2006-01-01

The Sonic Representation of Mathematical Data

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The Sonic Representation of Mathematical Data

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A thesis presented to the Dublin Institute of Technology,
Faculty of Engineering and Faculty of Applied Arts,
For the degree of
Doctor of Philosophy

2006

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Abstract

Conveying data and information using non-speech audio is an ever growing field of research. Existing work has been performed investigating sonification and its applications, and this research seeks to build upon these ideas while also suggesting new areas of potential. In this research, initial work focused on the sonification of DNA and RNA nucleotide base sequences for analysis. A case study was undertaken into the potential of rhythmic parsing of such data sequences, with test results indicating that a more effective method of representing data in a sonification was required. Sonification of complex data such as DNA and RNA was found to require more verbose methods than pitch to parameter mappings, and so investigation was made into musical pattern sonification. Existing low level pattern design methods were next evaluated in an experiment concerning the use of musical patterns to represent data. This experiment suggested that while a musical pattern may be made distinct, it does not necessarily follow that it is memorable. This experiment also suggested that concurrent pattern representation was difficult to process, and so improved methods were required.

Improvements to pattern design were made with the introduction of contour icons, which allow detectable and memorable musical patterns to be designed using simple shapes. Testing showed contour icons to be significantly more effective than low level patterns in a sonification, and as such form the basis of the novel contributions of this thesis. Improvements in concurrent representation were considered by the use of harmonic combination, a method of defining intersections in a data set as harmonies of a single common musical pattern. Significant improvements were observed over non-harmonic concurrent representation, although limitations were observed due to constraints in the number of combinations available using a specific value. Harmonic combination has potential for further development, and is a novel contribution of this thesis. The organisation and grouping of data in a sonification using rhythmic parsing was also investigated. Rhythmic parsing uses rest notes within a musical framework to define sub-groupings in a data sonification. Tests showed rhythmic parsing significantly improved the comparison of values and intersections between groups in a data sonification, and is another novel contribution of this thesis.

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Declaration

The work undertaken during chapter 5 has been published as Cullen and Coyle at both ICAD 2004 [185] and ISSC 2004 [186]. Work in chapter 6 was published as Cullen and Coyle at ICAD 2005 [187], ISSC 2005 [188] and ICMC 2006 [190], while work in chapter 7 was published as Cullen and Coyle at IEE ISSC 2006 [189]. This thesis exploits only the parts of those publications directly attributable to the first author.

Acknowledgements

This research has taken a lot of work to complete, and none of that work would have been effective or even possible without the assistance of people to whom I owe a great debt. I would sincerely and earnestly like to thank Dr Eugene Coyle, who has been of incredible help and support throughout the research. This work would never have been started without him- and certainly would never have been completed without his efforts. I would also like to thank Dr Noel Russell for his support on the project, as his efforts were instrumental in its progression. Thanks must also go to Professor Brian Norton, both for his assistance and for his invaluable advice on academic matters. I would like to thank Dr Brid Grant and the administration staff of the Conservatory of Music and Drama, who have been very kind and supportive throughout the research. I would also like to make particular mention of Mr Ben Rawlins, who has been a true friend over the years- as is Dr Derry Fitzgerald who I would like to thank for proofreading the chapters. I would like to thank Mr Frank Duignan for all his programming advice- what could have been weeks became minutes! I would also like to extend special thanks to Dr John Donovan, who has been of great help in allowing this research to progress further. Thanks must also go to Mr Charlie Pritchard of the DMC, who has also been a huge help during the process. I would also like to thank Dr David Deamer, who was very helpful in his assessment of my efforts and provided many interesting suggestions. Special thanks must also go to Dr Martin MaCauley, whose support gave me the confidence to begin the PhD.

I would like to give special thanks to all my family, particularly my parents who have put so much time and effort into the lives of myself, my brother and my sisters. I am truly fortunate to have had such an upbringing, and am thankful for that which so many others are not lucky enough to have. I would also like to thank (in no particular order) Stephen Morris, Damien Greene, Gavin Whelan, Alex MacAleese, Paul Delahunty, Jean-Jacques Darniex, Dr David Dorran, John Moxey, Jag Kooner, Menzies Johnstone, Martin McLaughlin, Dr Mikel Ganza, Dan Barry, Marco Neumann, Keith Gardiner, Elmar Jung, Andrea Razzini, and Quintin Ahern.

Finally I would like to thank Clara, who makes all these efforts worthwhile.

1. Introduction

1.1. Motivation of the Thesis

The use of sound to convey information and data has been an active area of research for many years [1], with advances in technology offering new opportunities for research in the field. Many examples of such auditory displays [100] are used to enhance visual systems [2, 3], or as a completely non-visual means of conveying information [4, 5, 6]. Sound is effective in reducing visual demands [104] and [7] in 'eyes-busy' tasks, and offers a viable alternative in many situations to the focus dependence of visual systems [135, 136].

Sound possesses certain advantages over visual communication, notably in the faster response time in the brain for auditory (2 ms) over visual (100 ms) stimuli [8]. Sound is also preferred over visual stimulus in infants and children [9], perhaps due to its much earlier introduction in prenatal stimulus [61]. The use of sound is an important (and often overlooked) means of communication that has great potential for information delivery, particularly in an age when ever greater demands are placed upon existing visual methods.

The emergence of mobile devices such as cellphones and PDA's (Personal Digital Assistants) has led to the delivery of ever growing amounts of data to handheld devices, where the dimensions of both screen and device can make effective visual communication difficult. In such situations, the need for fast and effective communication requires new methods of information delivery that do not rely so heavily upon visual stimulus. Avenues of research have been pursued which consider the potential of audio information delivery, and the field of sonification [1] is an ever-growing area of such research.

Many different forms of data have been sonified, often as a means of providing an alternative (or augmented) perspective for data analysis. Graph and chart data [119] has been investigated using pitch to value mappings, while sonifications have been performed using seismic [118] and rainfall information [132]. DNA sequence sonification is another active area of research [126, 127, 131], and this type of data forms the basis of a case study performed in the initial stages of the work of this thesis. An extension of existing DNA sonification methods [128] was proposed during this case study, alongside the means of grouping and structuring the data involved using musical rhythm. Although no conclusive method was produced, work performed in the case study served as an indicator for the progression of the rest of the thesis.

While many different forms of data sonification exist, it is often difficult to convey information purely in terms of scalar quantities such as pitch to value mappings. Other forms of information delivery using sound have considered the use of musical patterns [143, 148, 150] to provide the listener with more verbose means of detection. Earcons are a notable example of the use of musical patterns to convey information in a purely abstract manner, and though earcons are not used during this thesis the pattern design guidelines [145] developed for their use served as a basis for investigation into effective pattern design. This thesis approaches pattern design on the basis that a detectable pattern may not necessarily be memorable [46], and the effective design of distinct and memorable musical patterns was the impetus for original work carried out during the development of contour icons in this thesis.

Concurrent auditory display [111] describes the process of rendering several different streams of audio [80] in tandem, as a means of increasing the overall data bandwidth in a sonification. This is a more powerful method of sonification than single stream data delivery, but has the associated drawback of complicating the auditory scene which can adversely affect performance. Original work undertaken during this thesis investigates the means by which concurrent musical patterns may be effectively rendered, with the use of harmonic combination being suggested as a potential solution.

The organisation of events in a sonification is crucial to effective rendering of data, particularly in concurrent presentation. Existing work has considered the use of axes, tick marks and labels [121] to provide context within events in a sonification, and this structuring of data suggests means by which grouping information may be conveyed. Although the use of discrete time intervals to separate events has been investigated in data sonification [100, 144], no comprehensive investigation into the use of musical rhythm as a means of conveying structure has been performed. Work performed in this thesis utilises musical rhythms to highlight grouping and structure by a process called rhythmic parsing, which is similar in application to the use of punctuation in literature. Although a discrete time interval may serve as punctuation between events, musical rhythm is capable of far greater levels of hierarchical structure. It is the implementation of such structure that is considered in this thesis, suggesting a method which can be used to group and structure information within an overall data set.

1.2. Aims of the Thesis

1.2.1. Thesis Statement

Conveying complex data or information using sonification is difficult, particularly during concurrent presentation of multiple variable data. Existing methods of musical pattern design define patterns which are distinct for the purposes of detection, but do not adequately consider the means by which such patterns may be made memorable. Rhythm in sonification is often constrained to a single discrete time interval between events, and so is not capable of conveying structures or sub-groupings within multiple variable data sets.

This statement will be defended through work answering the following five research questions:

RQ 1: What effect does rhythmic parsing have on the understanding of structures within a data set?

RQ 2: Do present methods of pattern design (notably earcon design guidelines) produce patterns which are not only distinct but also memorable?

RQ 3: Can present methods of pattern design be used to efficiently render concurrent streams of data?

RQ 4: What effect does musical contour have on the recognition (and identification) of musical patterns used in data representation?

RQ 5: What effect during concurrent presentation does harmonic combination have on the identification of features and intersections in data streams?

This thesis seeks to investigate the effectiveness of current musical pattern design methods and to consider the potential of musical contour as feature of pattern design. Concurrent patterns are also considered, to determine whether individual features and intersections can be detected within a multiple variable data sonification. Conveying grouping and structure within a data sonification is also considered, to determine what role musical rhythm can play in data sonification.

1.2.2. Contributions of Thesis

The research questions listed above will produce several original contributions to the field of data sonification:

1) *Contour Icons*- abstract musical patterns based on high level visual shapes
2) *Harmonic Combination*- a method of highlighting intersections of interest during concurrent presentation.
3) *Rhythmic Parsing*- a method of grouping and structuring data in a sonification using musical rhythm.

These contributions will form the basis of future investigation into effective multiple variable data sonification, and as such represent novel work in the field.

1.3. Contents of the Thesis

The work of this thesis is contained within the following chapters:

Chapter 2: Sound and Perception- this chapter of the thesis reviews the basics of sound and its detection by the human hearing mechanism. Pitch, harmony, timbre and rhythm are considered, alongside the cognitive processes by which humans detect and analyse sound and music. Auditory scene analysis is also investigated, with the gestalt grouping categories determined as part of a checklist for effective musical pattern design.

Chapter 3: Data Sonification- this chapter details some of the existing work in the field of data sonification, from early developments in audio information delivery such as sonar through to audio alerts and alarms. Auditory display is considered, alongside concurrent presentation of multiple variable data in a sonification. Representations of graph and chart data using pitch to parameter mappings are investigated, through to sonification of complex data such as stock market figures or DNA nucleotide sequences. Auditory icons and earcons are documented, notably the definition of earcon design guidelines as the basis of detectable musical pattern design.

Chapter 4: Case Study: DNA/RNA Sonification- this chapter details the initial work undertaken during this research, investigating the means by which complex data such as DNA or RNA nucleotide base sequences may be sonified. Rhythmic parsing as a means of grouping events was also investigated, with test results suggesting that a more verbose means of representing data than pitch and interval parameter mapping was required.

Chapter 5: Low Level Pattern Design- this chapter investigates the potential of musical patterns designed using existing earcon design guidelines in data sonification. Test results indicated that whilst a pattern may be distinct (and thus detectable) it may not necessarily be memorable. Testing also showed that concurrent presentation is difficult for listeners, and suggested that more effective means of representing features in multiple variable data sonification was required.

Chapter 6: Contour Icon Pattern Design- this chapter details the process by which contour icons were developed, in response to the requirement of making musical patterns both distinct and memorable. Simple visual shapes were used as the basis of pattern design, providing listeners with high level representations of the patterns they were working with. Testing showed that contour icons were more effective than low level patterns in data sonification, by employing the higher level cognitive feature of melodic contour.

Chapter 7: Harmonic Pattern Combination- this chapter documents the implementation of harmonic combination in multiple variable sonification. Harmonic combination seeks to reduce the cognitive processes involved in detecting and analysing a specific combination of discrete values from different variables by representing that combination as a single harmonious pattern. Testing demonstrated that harmonic combination was more a effective means of defining value combinations, though the method employed was limited to a single combination involving any value.

Chapter 8: Rhythmic Parsing in Data Sonification- this chapter details an investigation into the use of rhythmic parsing to group and structure data in a sonification. The DNASon case study undertaken in chapter 4 had suggested the potential of rhythmic parsing as a means of highlighting sub-groups within a data set. Testing in chapter 8 showed that rhythmic parsing was an effective means of representing groups in a data sonification, while suggesting that future work could employ markers and labels to augment the structures defined by parsing.

Chapter 9: Conclusions- this chapter contains a summary of all work undertaken during this thesis, detailing why each aspect of the research was performed. A statement of the original contributions of the thesis is also made, alongside suggestions for future work to develop these contributions further.

The work performed during this thesis led to the contributions listed in (1.2.2), and is therefore structured in the following manner (Figure 1):

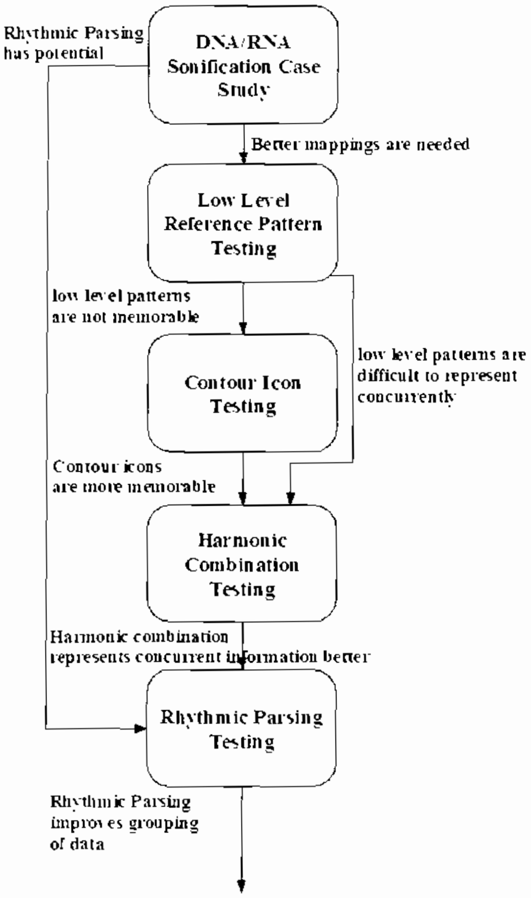


Figure 1: Diagram of overall thesis structure

2. Sound and Perception

The previous chapter introduced the main research undertaken during this thesis, specifically the use of contour icons (chapter 6), harmonic combination (chapter 7) and rhythmic parsing (chapter 8) to represent data for the purposes of analysis. In order to adequately investigate such topics, due consideration must first be given to the mechanics of sound and its perception and interpretation by human listeners. As contour icons are based on musical principles, the cognitive processes by which music is perceived by a listener are also of importance. Further, effective rhythmic parsing employs rhythmical structures to convey groupings within data sets, and so the role of rhythm in music is of importance.

This chapter first considers the basic physics of sound and its detection and perception by the human hearing mechanism. The low level attributes involved in detection (such as pitch and timbre) are next investigated. As this thesis concerns the use of musical patterns in the conveyance of information, the following sections detail a discussion of the higher level cognitive processing that is required by music. This processing is considered in two respects- the notes (or pitches) that are heard, and the rhythmic structures by which they are organised temporally. Musical events are rarely heard in isolation, and so more complex multiple stream detection and the principles of Auditory Scene Analysis [80] are also investigated. Higher level cognitive processing of sound is of great importance to this thesis, and forms the basis of the novel work presented in chapters 6, 7 and 8.

2.1. The Physics of Sound and Loudness

The physical properties of sound determine how they are detected and perceived by the human auditory system. Sound, as described by Moore [10] is "*the motion or vibration of an object. This motion is impressed upon the surrounding medium (usually) air as a pattern of changes in pressure*". A waveform can be described by three basic quantities- frequency, amplitude and phase (Figure 2.1).

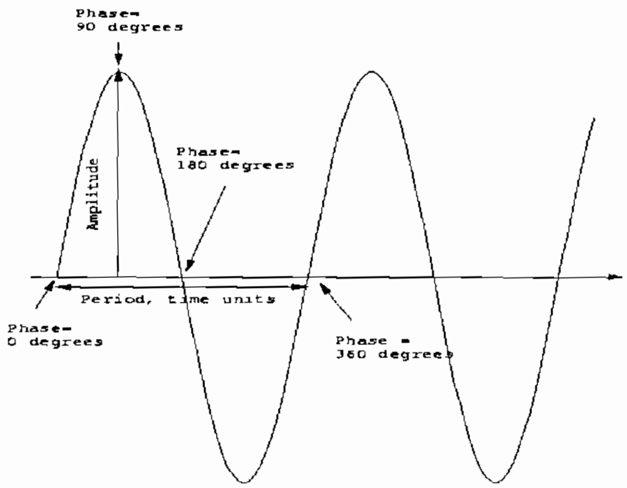


Figure 2.1: Example of a basic sinusoidal sound wave, adapted from Moore [10]

Frequency is the number of times a waveform will repeat itself in 1 second (defined in Hertz), such that a 2 Hz waveform will repeat twice a second. Amplitude is the level of pressure exerted by the waveform, and this pressure is perceived by the human auditory system as loudness. Loudness is defined as the rate of acoustic energy at a point [11] - i.e. the acoustic power (in Watts) delivered by a source to a given location. Loudness is expressed as intensity (watts/m^2), which is the power per square meter of a sound source. In the human auditory system the detectable intensity range is enormous. The threshold of hearing (lowest intensity detectable by the ear) is in the region of 10^{-12} Watts/m^2, while the threshold of pain can be as high as 1 Watt/m^2 in the average listener (depending on the frequency components of the sound source). With around a trillion values in the range of perception of human hearing [12], the unit of Intensity (Watt/m^2) is largely impractical for definition, and so Sound Intensity Level (SIL) and Sound Pressure Level (SPL) are often preferred.

SIL is calculated as a logarithmic ratio value with reference to the threshold of hearing (10^{-12} Watts/m^2), as a means of defining a scale of values for loudness that can be quantified and understood. If one sound has intensity I_0 and another has intensity I_1, then the intensity of the second sound relative to the first can be expressed logarithmically in bels (the unit bel being named after Alexander Graham Bell):

SL (bel) = 10 log(I_1/I_0)

This relation gives a definition of the human audible range (in bels) as [13]:

SL (bel) = 10 log(1/10^{-12}) = 12

now usually defined in an increment of 0.1 as the decibel (dB).

Useful practical values for SIL include the value for doubling of intensity (+3db), or an increase by a factor of 10 (+10db) and 100 (+20db). It is also of note that the more common unit of definition for practical purposes is Sound Pressure Level (SPL), which relates to the average power deviation of the sound in Newton/m^2 [14]. SPL can be expressed as:

SPL (decibel) = 20 log(P/P$_0$)

In most circumstances SPL and SIL are identical, but SIL cannot express any value for a standing wave (as there is no change in intensity) and so SPL is usually preferred for most calculations.

The phase [10] of a sound can be described as the offset in time between two sound waves (or a single wave from a reference point). This factor is important when considering the binaural nature (2.2.4) of human hearing, in that the difference in phase of a waveform due to the extra distance travelled around the head is believed to be part of the means by which a sound source is located. Having considered the basic physical properties of a sound wave, the method by which such waves are detected (and subsequently processed) by the human auditory system is also of importance.

2.2. Human Perception of Sound

The previous section considered the amplitude range that the human ear can comfortably detect. This range is not processed linearly however, and the frequency of a sound can have great bearing upon its perception.

2.2.1. Frequency Response

The perception of loudness is greatly dependant on the frequency of the sound source being considered, and this principle is of fundamental importance to any aspect of acoustic theory or practice. The human ear does not regard all frequencies within the audible range equally, rather certain frequency bands are perceived as louder (or quieter) than others. The perception of loudness is therefore a subjective measurement based on observation, and a set of experiments carried out by Fletcher and Munson [13] have been used as a benchmark by acoustic engineers since the 1930's (Figure 2.2):

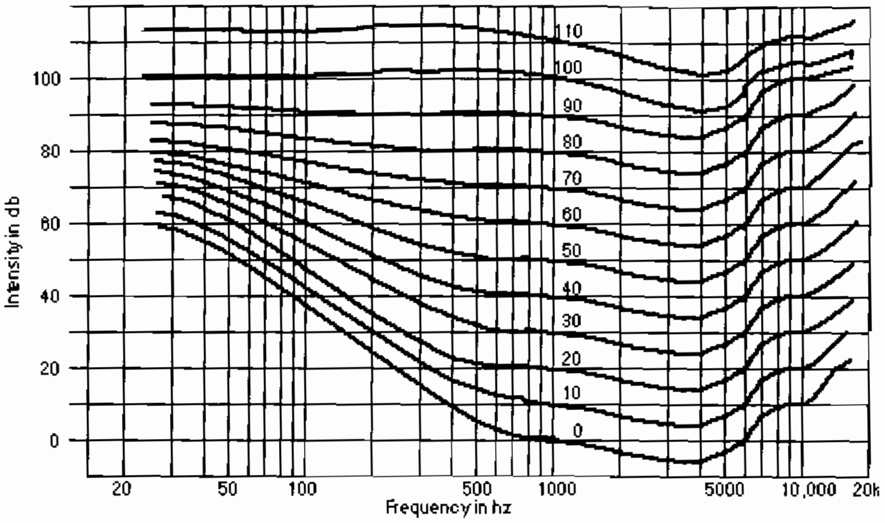


Figure 2.2: Fletcher Munson Curves for Equal Loudness, taken from Howard and Angus [13]

The experiments involved asked participants to define the relative loudness of two tones of different frequency, with the averages of these results being used to produce the equal loudness contours shown above. The axis of the graph define the perceived intensity (db) of a sound relative to its frequency (hz) and serve as a means of defining the relative frequency response characteristics of the human auditory system.

The typical frequency response of the human ear is usually in the range of 20Hz to 20 kHz for a healthy individual, although significant reductions in response can be engendered by age or environmental conditions [14]. The numbers labelled on the above graph (0 -110) are defined in Phons, which is a unit of measurement used to denote perceived loudness. The graph shows that human perception would define a 30Hz signal at 60 db as having the same loudness as a 1kHz signal with an intensity of 0db (on average).This pattern of behaviour is important to definitions of perception and thus the design and implementation of audio systems. The findings of Fletcher and Munson clearly show that the relative amplitude of bass frequencies must be far higher than those within the common speech range (500 – 2 kHz), if they are to be perceived as of equal loudness by the listener.

2.2.2. Critical Bands and Masking

Human audio perception is governed by factors of its design, such as the increased response characteristic around the human speech range- perhaps as a means of enhancing the ability to detect the vocal sounds of others (which is the essential primary function of human hearing). Another subjective characteristic of the human ear when in the presence of multiple tones or sounds is its variable frequency resolution, which is referred to as the Critical Bandwidth [15] relative to a particular frequency.

If two tones are sounded together with the same frequency a unison note is perceived by the listener, but if one tone is gradually increased or decreased in frequency then the changes in amplitude (due to the modulation of the slight changes in frequency) between the two tones are perceived as beats (Figure 2.3):

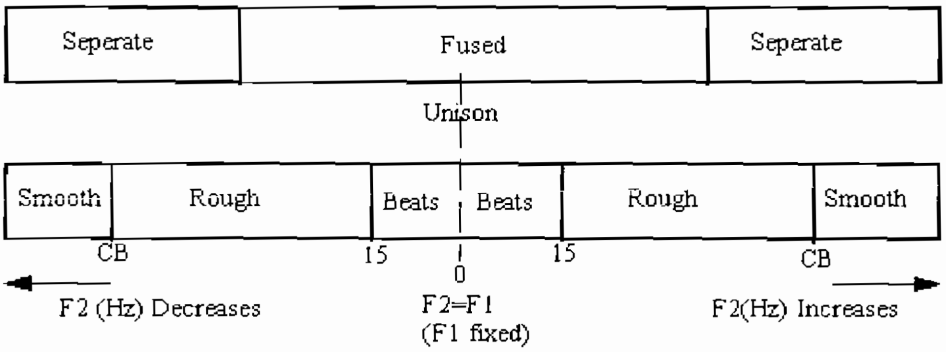


Figure 2.3: Perception of Beat Frequencies for 2 tones, adapted from Olsen [15]

Beat frequencies are practically defined as being detectable for a difference of less than 12.5Hz between the relevant tones, with a perception of consonance beginning for differences around the 15Hz mark (although these values will vary considerably between listeners [17]). The descriptive notions of rough and smooth in audio relate to subjective definitions of when tones can actually be perceived as separate (outside of the range in which beats can be heard), and again vary considerably on an individual basis -hence no absolute values can be defined.

Similarly, the range of frequencies at which beats are detected also varies over the human hearing range. This variation in the detectable frequency bandwidth is defined by Moore and Glasberg [16] using the equation:

Equivalent Rectangular Bandwidth, ERB = ing (Hz)

Where **fc** = centre frequency in Hz- **ERB** is valid for ($100<f_c<10{,}000$Hz).

This equation leads to typical bandwidth values of 47.5Hz at 200Hz and 240Hz at 2 kHz. These values determine that Critical Bandwidth increases with frequency- an important factor in the definition of consonance and dissonance and also in the masking of tones.

Masking is an effect produced by tones or audio signals from various sources drowning each other out- hence the notion that a sound must be louder than others in order to be heard. The effect of the Critical Band is that a sound or tone of the same frequency or higher than a reference tone can mask that reference tone to a much greater degree than a similar tone of lower frequency (Figure 2.4):

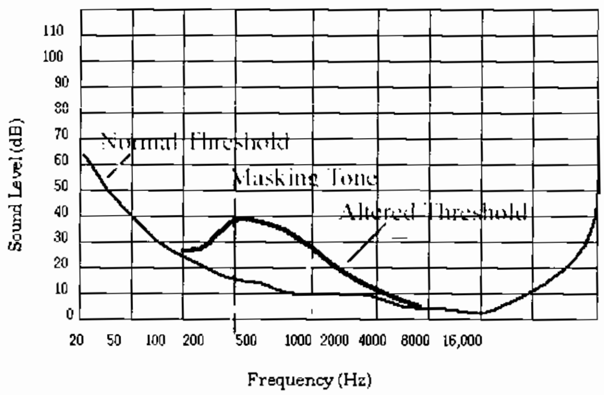


Figure 2.4: Masking Effect on Hearing Threshold, adapted from Howard and Angus [13]

The masking phenomenon is used extensively in noise reduction and digital audio compression systems, as a means of assuming that noise of certain frequencies will be masked if a similar signal component exists.

2.2.3. Just Noticeable Difference and the Missing Fundamental

Although Critical Bandwidth defines the range within which two tones can be regarded as fused or separate, it does not define the frequency resolution of the human ear. The detectable frequency difference between two tones is known as the Just Noticeable Difference (JND) and concerns the minimum change in frequency that can be perceived by the human ear. As with Critical Bandwidth, this value varies across the frequency spectrum, with a reasonable approximation being a JND equivalent to one thirtieth of the Critical Bandwidth.

The impact of Critical Bandwidth and Masking effects becomes more apparent in the context of real instruments, when considering the combination of complex tones and their associated timbres (2.2.6) - it is of importance to define what can or cannot be perceived due to physical restrictions and acoustic phenomena, rather than lack of musical knowledge.

A pure tone is considered as a single sinusoidal wave of a certain fundamental frequency, but in reality sounds are usually a combination of tones known as harmonics that occur at relative frequency and intensity to the fundamental. Harmonics usually occur at octaves [13] to the fundamental and their relative intensity is believed to have great bearing on the perception of instrumental timbres. In practice most listeners can differentiate between 5 to 7 Harmonics [17], while the combinations they create give the auditory system more information to work with in perceiving the individual timbre of a sound.

An interesting facet of this mechanism is demonstrated when a complex tone is generated and the fundamental frequency is subsequently removed from the signal over time [18]. This phenomenon is described as the missing fundamental, where even in the absence of the fundamental frequency the same pitch is still detected by the listener. Although the fundamental pitch is still perceived as present, a change in timbre is nevertheless observed (supporting the notion of timbre as a function of harmonic structure). This phenomenon suggests that the pitch of a sound (2.2.5) is calculated with respect to its harmonic series, rather than its fundamental frequency (which physically dictates the series in the first place).

2.2.4. Binaural Localisation

When considering the complexity and capabilities of the human ear it is often prudent to remember that each human being has two such devices (separated by approximately 18cm) for the purposes of detection and analysis. One of the most useful aspects of the human auditory system is the capability to discern the position and direction of a sound source relative to the position of the listener. Several different factors are involved in this process, mainly the difference in time (and potentially phase) taken for a waveform to reach each ear relative to the source, known as the Interaural Time Difference (ITD) [19]:

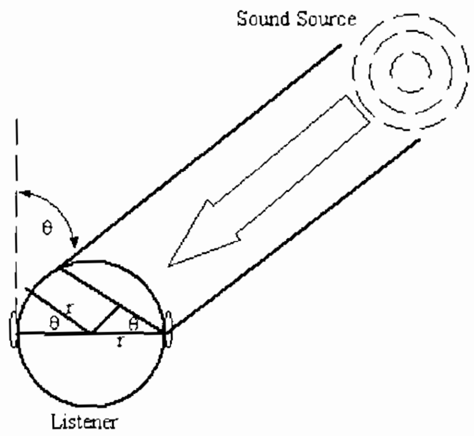


Figure 2.5: Diagram of Interaural Time Difference calculation, adapted from Gelfand [19]

The equation for calculating ITD must take into account not only the angle of arrival of the source and the distance involved, but also the time taken for the sound to travel around the head to the ear. By defining the quantities detailed in the figure above the full equation can be derived:

$ITD = r(\theta + \sin(\theta)) / C$

Where radius of skull, $r \approx 0.09$m, θ = the angle of arrival of the sound relative to the median (in radians) and c= the speed of sound (in ms^{-1}).

Although this delay is typically very small (maximum ITD at an angle of 90^0 is 673μs), it is of importance when determining the location of low frequency sounds in combination with assessing the phase difference of thc signals received by each ear. If the phase difference between both ears is defined thus:

Phase Diff (radians), $\Phi_{ITD} = 2\pi fr(\theta + \sin(\theta))$

Where f= frequency (Hz) and radius of skull, $r \approx 0.09$m.

For the maximum ITD angle (at which no phase ambiguity will occur) of 90^0 the corresponding maximum frequency of detection is 743Hz- although this value will be higher at smaller angles. This dictates that for frequencies above ≈743Hz a different method of detection must be employed.

The difference in sound intensity detected at each ear (due mainly to the presence of the skull shadowing the trailing ear) is defined as the Interaural Intensity Difference (IID) [20], and is used to categorise higher frequency signals. In this case the size of the skull (at least 2/3 of a wavelength) determines the minimum frequency at which it will reduce the intensity of the incoming wave due to shadowing. Thus the minimum frequency at which the skull affects intensity using the standard equation for speed ($c=344ms^{-1}$), distance ($d=0.18m$):

Minimum Frequency, f_{min} = 1/3 x (c/d) = 1/3 x (344/0.18) = 637Hz

It is of interest that a crossover exists between the maximum ITD frequency of 743Hz and the minimum IID frequency of 637Hz at around 700Hz, and for smaller angles this crossover will finally disappear at around 2.8 kHz – a frequency range in which experiments have shown direction is not as easily detectable [13]. Having considered the mechanism by which sound is detected by the human auditory system, it is now important to define the structure of sound and music as it is perceived by the listener.

2.2.5.Musical Pitch and Harmony Perception

This thesis concerns the design of musical patterns, patterns which are based on their relative pitch within a scale. For this reason, it is useful to define the basic music theory of pitch and scale. The American Standards Association [21] defines pitch as "*that attribute of auditory sensation in terms of which sounds may be ordered on a musical scale extending from low to high*". Pitch defines specific musical notes within octaves divisions that can subsequently be grouped in scales. The major scale [22] (Figure 2.6) is the most commonly known (and used) group of notes in western music and is the reference from which all other scales are defined.

Figure 2.6: The C Major Scale (Root to Octave)

With the use of a flattened 3rd in the C major scale (Eb rather than E) the natural minor scale can be similarly constructed (Figure 2.7):

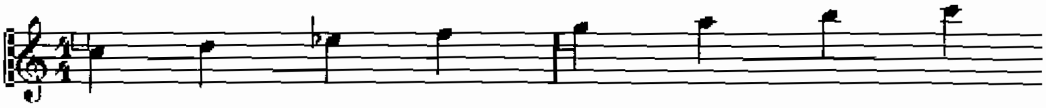


Figure 2.7: The C Minor Scale

The natural minor scale is enharmonically equivalent to the major scale starting from the 6th note, so in the case of C major the natural (or relative) minor is A (Figure 2.8):

Figure 2.8: The A (natural) Minor Scale

This relation is the basis of modality [23], the process by which the major scale is used as a template for other modes which begin (and end) on different degrees of that scale (Figure 2.9):

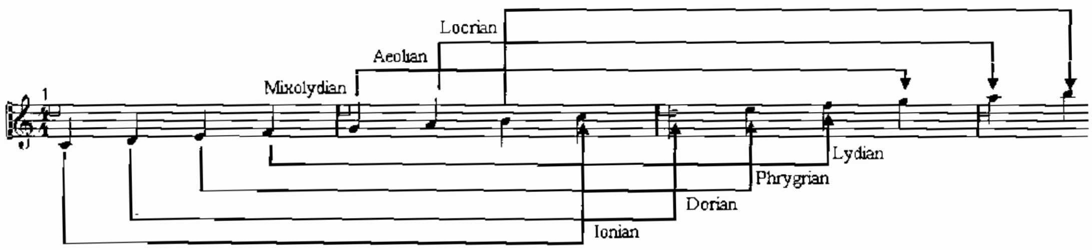


Figure 2.9: Modes of the C Major Scale, adapted from Routledge [23]

The relationships between musical pitches within the octave form the basis of harmony [24], which considers 2 (or more) pitches sounded together. Each harmonic interval (Figure 2.10) from 2nd to octave has a unique signature, such that different intervals can be considered consonant or dissonant [22] depending on the key signature and chord progression used.

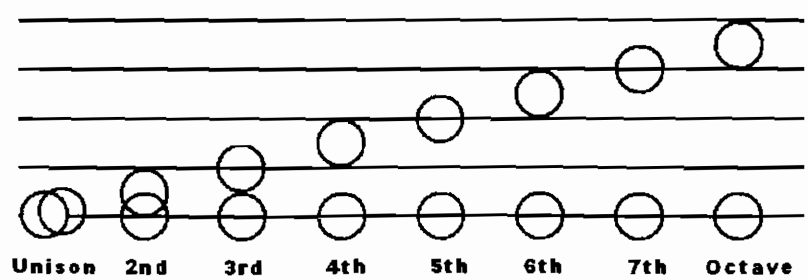


Figure 2.10: Intervals from Unison to Octave, adapted from Warburton [24]

These 8 intervals are also determined by their 'quality' [22] such that a 3rd may either be major or minor (when the 3rd of the scale is flattened by one semitone). The quality of an interval outside of the major or minor (diatonic [24]) is referred to as a chromatic interval, and denotes the use of notes in the octave which are not found in the major or minor scale (such as the #4th). Definitions of consonance and dissonance in harmony have changed throughout the history of western music [25], but the use of major intervals (such as the 3rd, 5th and 7th) remains the basis of consonance in music.

In western music, triads [24] are defined as a root note combined with the 3rd and 5th notes above it, and as such are the basis of chord theory. Each degree of the major and minor scales can be used as the root of a triad (Figure 2.11):

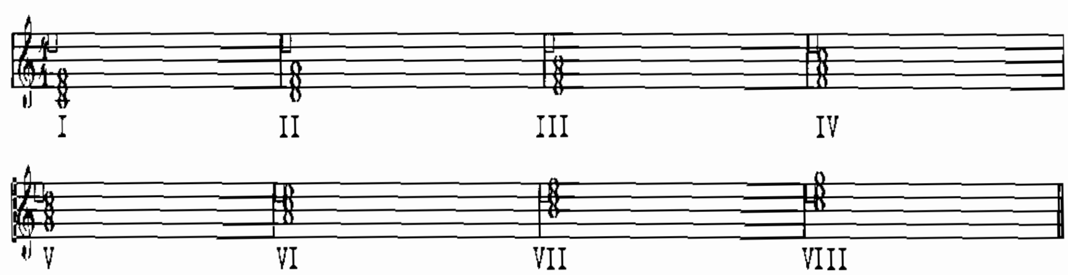


Figure 2.11: Major Scale Triads (numbered by Scale Degree), adapted from Taylor [22]

Each triad takes its name from the degree of the scale on which it is based (Table 2.1), and these triads are referred to by the roman numeral corresponding to their scale degree:

I tonic	**II** supertonic	**III** mediant	**IV** subdominant
V dominant	**VI** submediant	**VII** leading	**VIII** octave (tonic)

Table 2.1: Major scale triads and their names, adapted from Taylor [22]

This numerical representation is a useful tool for musicians (including those who cannot necessarily read or write a score), whereby they can construct chord progressions denoted by differing roman numerals to define a piece of music. The extensions of the basic triad define the nature of a particular chord, from 7th chords (which form the basis of traditional jazz and blues [75]) through to more exotic extensions taken from other degrees of the scale above and below the octave of the root. The use of differing chord families is a powerful means of changing the mood and tone of a composition, with the use of 6th or 7th suggesting a completely different character from a 9th, 11th or 13th.

These definitions are necessary when seeking to produce musical patterns, as the basic principles of music theory are essential to the design of such patterns. Cognitive disciplines such as Auditory Scene Analysis (2.5) consider the interaction between different sound events, and music theory suggests methods by which musical events may be effectively combined. If musical patterns are required to be delivered concurrently (3.2.1), they must be designed in a manner that will allow them to harmonise effectively. Pitch cannot be considered a comprehensive method of describing a musical pattern in isolation, as few people possess the ability to determine the absolute pitch [26] of a tone without reference. The additional problem of detecting the true fundamental (2.2.3) means that pitch is an ineffective means of distinction in isolation. For this reason, other more obvious factors such as harmonic consonance and dissonance must also be employed.

2.2.6. Timbre

Another distinctive aspect of a sound is its perceived timbre [27]. The definition of timbre is a subjective one, considering the acoustic characteristics of a particular instrument or sound. Descriptive notions of what constitutes a particular instrumental timbre often range into the emotional and allegorical, with preference and taste being important considerations. As a result of this, it is often difficult to adequately quantify even the most basic and obvious differences between instruments. The perception of timbre is an important consideration in sonification, as it defines many of the boundaries within which data representation can accurately take place. In seeking to define timbre, the first consideration is the acoustic variations inherent in any musical instrument either real or synthesised- variations that give each instrument its own unique signature. No physical instrument produces a pure single sinusoidal tone (Figure 2.12), and for most pitched instruments the individual character of the instrument is reliant upon additional components within each tone produced. A waveform can be regarded as periodic for the purposes of frequency analysis, but in reality the constant changes within the output waveforms have a finite span that makes them aperiodic for any other purposes.

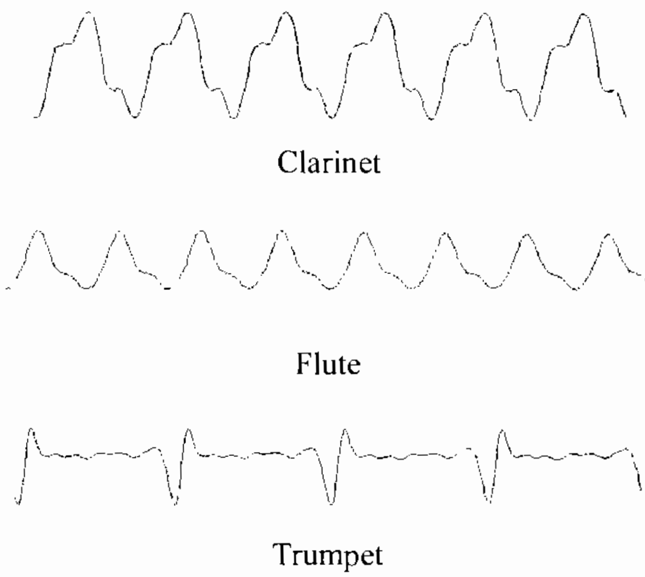


Figure 2.12: Time domain waveforms for clarinet, flute and trumpet, adapted from Seashore [27]

Most of the fluctuations and changes that occur within one period of a waveform can be attributed to the effect of harmonic components in the sound- components that are ideally related to the fundamental frequency that the instrument is trying to produce.

In the waveforms shown in (Figure 2.12), the fundamental frequency of each wave defines the nature of the additional harmonic components present in the wave as multiples of the fundamental frequency itself. Thus within each waveform of fundamental frequency $\mathbf{f_0}$, it is possible to find harmonics at frequencies $2\mathbf{f_0}$, $3\mathbf{f_0}$, $4\mathbf{f_0}$ and so forth depending on the acoustic limits of the instrument itself.

The harmonic components of an instrument waveform usually occur at different intervals in the wave, and this is perhaps the singularly most individual and psycho-acoustically definable aspect of any musical instrument. Different physical attributes of each instrument will cause harmonics to be generated at different times and at different amplitudes, and in doing so create the potential for a virtually limitless harmonic configuration- even within different examples of the same instrument.

For most sonification work, the use of some form of synthesis is required. Due to the computerised nature of most sonification tools, the output is often MIDI information which must be reproduced in some form. Because of this, General MIDI (GM) sounds

[153] that are usually available as standard on most devices are often favoured in reproduction. The major problem with GM synthesis is indeed its inherent generality, with many of the standard sounds available being poorly synthesised by the modules rendering them.

Another common problem in GM synthesis is the poor correlation between the sounds produced and the instruments they are claimed to represent. Many examples exist (particularly with generic PC soundcards) of instrument timbres which bear little relation to the sounds they are purported to describe. This problem was considered by Rigas and Alty [28] using a Roland MT-32 synthesiser to test timbre perception (Table 2.2). Although the MT-32 has long been surpassed as even a budget synthesiser, the notion of its use in defining a 'worst-case scenario' is of value- especially in comparison to most PC soundcards.

Family	Instrument Timbre
Piano	Piano, Harp, Guitar, Celesta, Xylophone
Organ	Organ, Harmonica
Wind	Trumpet, French Horn, Tuba, Trombone, Saxophone
Woodwind	Clarinet, English Horn, Pan-pipes, Piccolo, Oboe, Bassoon, Flute
Strings	Violin, Cello, Double Bass
Drums	Drums

Table 2.2: Instrument timbre groupings, taken from Rigas and Alty [28]

The findings of this study suggested that only seven distinct timbre definitions can be made by a listener using GM sounds with a basic soundcard. Vickers [137] further suggested that this leaves an effective range of 6 distinctive timbre families, with drums or percussion sounds being considered separate.

However, the main inference of the study is the lack of accuracy of many GM sounds on budget soundcards and synthesisers. This is not a factor which will affect the design of a musical pattern in abstract, as it will allow the melodic features of patterns to be assessed without the presence of significant tone colours. If listeners can distinguish between patterns rendered using limited timbres, then those patterns used could be considered valid in their own right. This would then allow even more distinct patterns to be created using the higher quality timbres available on many modern synthesisers.

2.3. Audio Cognition

Although the basic features of distinction are crucial to designing robust musical patterns, the higher mechanisms by which such patterns are processed in the human brain are also of importance. Audio cognition is ingrained into human behaviour as deeply as any visual or other sensory input, as a means of understanding and interacting with the world around us. In infants it has been found that a distinct preference exists for auditory stimuli [9] - indeed in competition to and often to the exclusion of visual stimuli. Once a child has reached the relatively young age of three or four years of age it will process both auditory and visual stimuli in exclusion [29], but still exhibit a preference for the audio modality when a choice is offered. This pattern of behaviour only reverses at the end of childhood, with adults showing the capability to process both modalities simultaneously (but now displaying a preference for visual stimuli over auditory information).

This reversal is interesting when considered relative to the faster response time in the brain for auditory (2 milliseconds) over visual (100 milliseconds) stimuli [8], which is believed to be even more pronounced in infants and young children. As a child develops, they are increasingly exposed to visual rather than audio stimuli as part of their education, and so are perhaps forced to compensate by developing visually instead. Most education revolves around the use of some form of written media, which would have a major influence on the learning development of a child. Recent studies have shown that the capability of a child to discern and express musical timing has direct bearing on their academic achievement [30] [31] and [32], with subsequent improvement being observed in all mental and physical skills.

2.3.1. Feature Detection

The innate audio processing capability of all humans (and indeed most animals [33]) is amply demonstrated by the ability of infants to discriminate between pitches [34], melodic contour [35] and rhythm [36] as well as an adult can. This ability even extends to the segmenting of melodies [37] into smaller phrases, and the association of music with other events [38] in a similar manner to adults. The mechanism for such processing is musically specific, with certain neurons directly responsible for pitch perception, rhythm and melodic contour [39, 40] being found only in the right hemisphere of the brain [35]. In this way, the detection and perception of musical sounds and structures is performed separately from language or audio in general. Further evidence for this behaviour is suggested by the fact that the left hemisphere of the brain processes mostly verbal information [41], except in the case of musicians, who are thought to use both sides of the brain in response to music [42]. This perhaps serves to highlight the analysis that musicians perform on what they hear as a matter of course, rather than regarding music as a purely creative or aesthetic medium.

The factors that allow human beings to perform this function are potentially related to the auditory system, the human speech production system and high-level perceptual and language processing - although no conclusive study has been performed. The important point of this effect as regards sonification is its existence rather than its mechanism, in that the ability of human beings to discern audio information at such a level of complexity is something largely taken for granted (rather than acknowledged as an important method of data analysis). In recognising patterns there is importance in considering structure, with a view to defining relations between different lower level instances and their subsequent combinations. Various studies have been performed [43] which suggest that criteria of perception and physical factors must be considered as important in understanding how the process takes place.

Perception is a subjective manner of assessment, as by definition differences in perception account for subjective opinion and hence do not easily conform to standardisation. The pitch, loudness or location of sounds can help define their similarity- as can their individual timbres. Also, the temporal variations of sounds (such as modulations over time or even their initial onset) can lead to sounds being perceived as grouped or separate- relative to their occurrence and subsequent change [80].

Physically, the fundamental frequency of a sound (and its associated harmonic series) are important in distinguishing between separate sources, as sounds of different fundamental frequency will be detected as separate rather than fused. The rhythmic components (2.4.1) of a source also play a major role in its detection [44] and recognition, and different rhythmic patterns allow sounds of often similar timbre and pitch to be perceived as separate rather than fused [80].

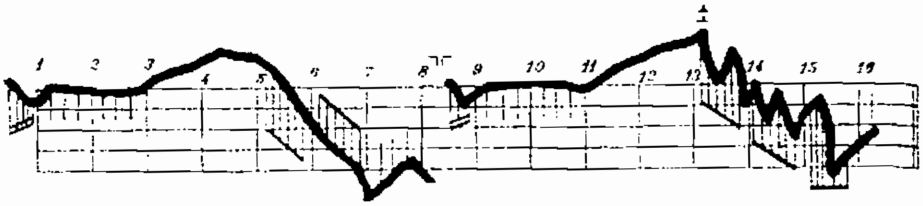
As considered with the cocktail party problem [45], the important aspect of human pattern matching as regards initial work in this research is its existence rather than its mechanism. However, it is of benefit to consider relevant factors such as pitch, rhythm, timbre and location when seeking to design a system for sonification- and any work undertaken in the field is likely to profit from such considerations.

2.3.2. Pattern Recognition and Recall

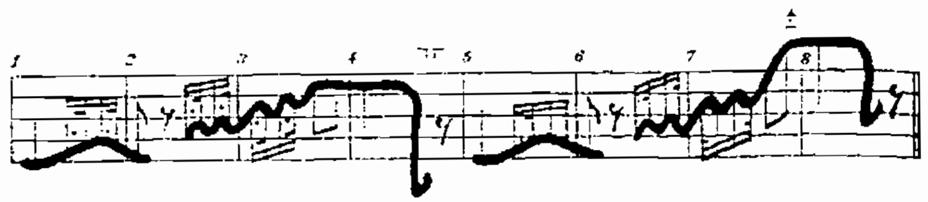
Studies of the mechanics of human audio perception suggest that differences exist between the processes of pattern detection and pattern recognition. A study into the matter has been performed by Herbert and Peretz [46], who claim that the requirements for detection and recognition of melodic patterns are indeed different. Their experiments suggest that long-term memory pattern recognition is biased more towards melodic factors than the rhythmic elements required by pattern detection. Although not an arrhythmic condition by any means, a definite preference is exhibited for melodic criteria when testing the ability of participants to recognise previously introduced patterns.

2.3.3. Melodic Contour in Detection and Recognition

Melodic contour has been considered by many musicologists as a means of defining relative changes in pitch [47] (with respect to time), rather than the definition of absolute values. In this manner, the shape, direction and range of a melody can all be summarised by its overall contour. Graphical contour representations were considered by composers such as Schoenberg [48] as a means of supplementing a musical score (Figure 2.13).



Menuetto, String Quartet in D, K. 575, mvt. III, mm. 1-16



Andante, Symphony 39, K. 543, mvt. II, mm 1-8

Figure 2.13: Contour graphs of selected Mozart compositions taken from Schoenberg [48]

Schoenberg regarded these contours as waves, a sentiment echoed by Ernst Toch [47] who regarded melodic patterns as combinations of waves and breaks of differing amplitude. This use of graphical notation to compliment (and analyse) the traditional score was taken further by ethnomusicologist Charles Adams [49], who used contour as the principle classification in his study of Native American melodies.

Adams suggested that a contour could be defined in terms of 4 minimal boundary pitches: initial pitch (I), highest pitch (H), lowest pitch (L) and final pitch (F). The relations between these 4 boundary pitches were summarised in 3 categories:

1. Slope, S- slope defines a comparison between the initial (I) and final (F) pitches as either ascending, level or descending.

2. Deviation, D- changes in direction between boundary pitches specify levels of deviation. Thus if all four pitches are equal then the deviation is zero, with subsequent disparities between any of the 4 giving different levels of deviation.

3. Reciprocal, R- The direction of the first deviation (either I to H or I to L) is referred to as its reciprocal, dictating the direction of the overall contour.

Using these features as a template, Adams defined 15 basic contour shapes for melodic classification (Figure 2.14).

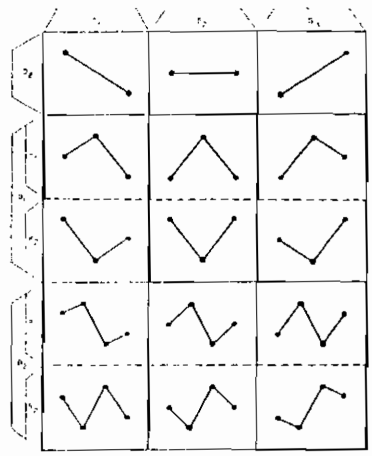


Figure 2.14: 15 Contour graphs taken from Adams [49]

This approach performed well for defining melodies that had been reduced to groups of 4 salient pitches, and allowed Adams to define the similarities and differences between music from 2 separate Native American tribes.

In his research, Vickers [137] noted that participants used melodic contour as a useful aide-mémoire for melodic patterns. Although further testing in that research suggested that this feature was of little interest to listeners, it was noted that musically trained listeners used contour [50] when defining similarities between patterns. This aspect of a patterns definition gave rise to broad possibilities for visual representation, and so a more exhaustive investigation of the cognitive processing of melodic contour was performed.

Contour can be considered an important part of musical memory. Dowling [51] suggests that contour information functions separately and independently from scalar information in memory. Experiments by Edworthy [52] showed that single pitch alterations in a melody could be detected by participants as changes in contour- even when they were unable to define what pitch had been actually altered in the pattern. This capability is believed to be present in infancy [53] (around 5 months), at a stage of development where changes in pitch cannot be recognised. It has also been shown that different brain cells are used in the processing of melodic contour [54] than are used in the detection of temporal or harmonic [55] components of music. This aspect of neural activity would again suggest that different parts of the brain are used [56] in the detection and recognition of musical events: rhythmic factors being paramount in detection, while melodic contour and range [57] and [58] being more important in the recognition of familiar and recently learned melodies.

With this in mind, it is suggested that the use of contour could be developed significantly in the design of effective musical patterns. Although rhythmic factors (alongside pitch and timbre) appear vital to the detection of an individual pattern, it could conceivably aid subsequent recognition if factors used by long-term memory were also employed. The interactions between patterns can be considered in terms of their ASA components (2.5), but it is also useful to consider the musical structures that allow different melodic events to interact effectively (2.2.5). The rhythmic grouping of musical patterns (2.4.3) defines higher level structures within a piece of music, and so the temporal interaction of patterns as used in this thesis will also require such grouping.

2.4. Rhythm

The two main areas of research undertaken in this thesis concern both how a pattern can be made distinct and memorable, and also how combinations of such patterns can be distinguished effectively during analysis. In considering combinations of patterns, the application of rhythmic structure is of importance. Rhythm is a fundamental building block of musical composition [22] that serves to group various events within a piece for aesthetic purposes. In this research, rhythm is similarly employed to group patterns used to represent data for analysis so that they may be more efficiently processed by the listener. In order to adequately assess the importance of rhythm in music, it must first be considered within the wider context of general human behaviour. It is argued that rhythm is a fundamental component of all human interactions [59], and so is similarly fundamental to the communication of effective musical patterns to a listener.

2.4.1. Rhythm in Infant Development

The capabilities of all mammals to naturally detect and reproduce musical structures [33] are genetically predefined. The abilities of infants compare with those of adults (2.3.1) to such an extent that the entire mechanism is observed to be ingrained in human biology (rather than learned or trained). However, the skills required to accurately quantify and convey audio information must be learned in the same manner as a child learns to crawl or walk- even though they possess the physical ability to do so from birth.

In the case of infants, the role of rhythm is the most fundamentally important aspect of early cognitive development [60], and is believed to begin in the womb (where the child is often observed to move in response to rhythms in speech or music [61]). The interplay between mother and child is defined most basically at a rhythmic level [62], with both subconsciously adapting and tailoring their own rhythms to facilitate communication with the other [63].

Infants display several common rhythms [64], which are used to seek attention from their parents or other adults. This use of rhythmic patterns is both frequent and essential [65] in the communication between infant and adult, communication that is dictated by a pulse common to all parties. Indeed, the variation or absence of such rhythmic components is observed to engender disinterest and negative responses from the child involved [66].

Infants and children synchronise to the rhythms of behaviour they are involved with [63], and rhythm is an essential part of the education and development of a child (2.3). Rhythm also dictates the interactions between individuals and groups from as early as the school playground [67], where complex patterns of interaction between seemingly unrelated groups of children are organised on a subconsciously rhythmic basis.

These behavioural patterns suggest that rhythm is a core element of human genetic makeup, and thus human behaviour in general. It is important to consider the importance of rhythm as an organisational factor in everyday life, with most of the common (and indeed unique) events that human beings experience being catalogued chronologically.

2.4.2. Rhythm in Speech

Motor functions such as walking and running are all dictated by rhythm patterns [68], and the detection of such patterns is ingrained just as firmly in human speech. Prosody [69] can be considered as the rhythm, accent and intonation of speech, with the associated changes in each of these factors having major bearing over their comprehension. It has been shown that the location and duration of pauses in a sentence has a major bearing [70] on the perception of its meaning. It has also been shown that the different prosodic character of a sentence [71] (such as the emphasis or pause associated with a particular word) has a similar effect on its perceived meaning.

The consequence of this is that the rhythm and punctuation of a group of words dictates what type of sentence it will become (if at all). These spoken rhythms are also culturally specific, and serve to distinguish between different languages and dialects at a largely subconscious level. Native speakers of rhythmically similar languages will perceive (and hence segment) spoken communication in the same manner as they would with their own language [72].

When a language of different rhythmic structure is presented, the listener will still attempt to segment it using the rhythmic patterns of their own native tongue. In this way, the effect of rhythmic structure can be seen to go right to the core of spoken communication. Without rhythmic cues and markers both speech and written communication (which is a visual mimic of speech) become incomprehensible- just as with music.

2.4.3. Rhythm in Music

Rhythm dictates the structure of a piece of music, from the individual sequence of notes to the hierarchical groupings of different musical phrases or passages. The ability of musicians to detect and convey complex structures [73] within a piece is a direct result of training and experience, the lack of which reduces rhythmic patterns to sequential processes. This means of structuring music relies heavily on the metrical organisation [74] of such rhythmic patterns into regular frameworks, utilising the time signature of the piece to define different sections.

Rhythm allows a piece of music to be organised into sections- sections of differing levels of complexity. By defining the bar (or measure) in terms of the beat (Figure 2.16) the basic organisational structure of a piece of music is decided. When this bar structure is then further organised into sections (such as the simple verse and chorus of popular music) it allows differing pieces of related musical information to be conveyed in a structured manner. Rhythm is one of the most fundamentally important aspects of music. The tempo, time signature and rhythm of a group of notes can dictate its style- and indeed its content. The tempo of a sequence of notes is specified by the length of a beat- the definition of a crotchet note (Figure 2.15) in musical time.

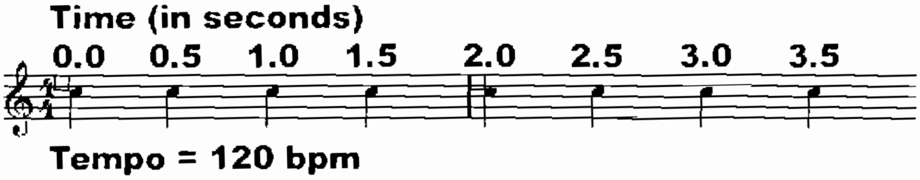


Figure 2.15: Length of crotchet note for tempo of 120 bpm (in seconds)

The tempo of a particular piece of music is considered as the number of beats per minute (bpm) that occur in sequence, each one being referred to as a crotchet note. The divisions of musical time (Figure 2.16) are often based around the crotchet [22], with greater (or smaller) durations being considered relative to the beat.

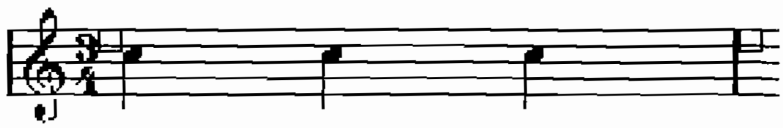
Figure 2.16: Common note lengths, adapted from Taylor [22]

The durations of the most common notes are as follows:

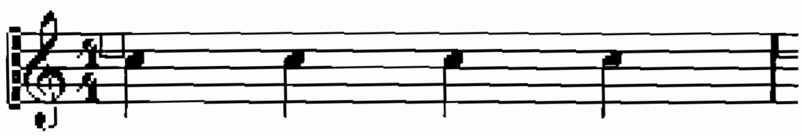
1. *Semibreve* (whole note) - 4 crotchets.
2. *Minims* (half note) - 2 crotchets.
3. *Crotchet* (quarter note).
4. *Quaver* (8^{th} note) – half crotchet.
5. *Semiquaver* (16^{th} note) – quarter crotchet.

This division can be continued as required, with many common sequencers now offering resolutions of 128^{th} notes or less. A musical composition is structured by the regular hierarchical groupings of notes in divisions of bars. The number of notes in a bar specifies the time signature of the piece (Figure 2.17), and has great influence over the overall pace (and movement) of the music.

2/4 Time Signature



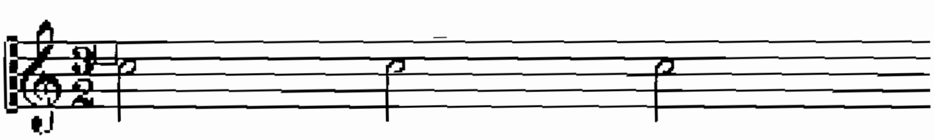
3/4 Time Signature



4/4 Time Signature

Figure 2.17: Common time signatures and their associated number of beats, adapted from Taylor [22]

The two numbers in a time signature (to the immediate right of the clef) denote the number of beats in the bar (numerator) and the length of a beat (denominator). Although the crotchet defines a musical beat in most common circumstances, there are many occasions when it is useful to quantify a musical beat with another note length. This relation allows more complex time structures to be used (Figure 2.18), where the division of a musical beat does not necessarily refer to a crotchet (such as a minim beat in 3/2, or a quaver beat in 6/8).



3/2 Time Signature

6/8 Time Signature

Figure 2.18: Complex time signatures with non-crotchet divisions, adapted from Taylor [22]

In this manner, complex groupings of note patterns can be specified as the overall division of the piece, with the beat acting as the common delimiter. Most popular music is usually written (and performed) in 3/4 or 4/4 time, with more complex time signatures often being found in jazz, classical and some traditional folk music [75].

The use of organisational structures such as the verse and chorus is a simple example of the potential for hierarchical complexity that rhythmic definition within a composition affords. A section of music can be repeated using the coda [75], which allows the inclusion of different endings or movement into other sections of the piece. In this manner, simple sections of music can be organised modularly like building blocks, which can be reused as required to form more complex musical structures.

Alongside organisation, rhythm is fundamental to the perception of movement (and hence emotional content) in a piece of music [68]. Changes in tempo and time signature can suggest differing emotional characteristics in a piece, allowing the mood of a piece to be defined at a much lower level than associated harmonic contrasts (such as change of key or scale). Emotional responses to music are often displayed physically by the listener, from simple repetitive movements in synchronisation with the beat to the complex patterns of movement found in dance.

The reactions of human beings to the beat (or pulse) of a piece of music is a fundamental factor in their musical preferences. The preference for different ranges of tempo is believed to be related to age [76], largely as a consequence of the physical faculties of the listener. The physical behavioural patterns of a listener (such as walking rate and speaking rate) also have an effect [77] on tempo preference, and in this manner the psychological makeup of a listener is expressed to a certain extent by their rhythmic preferences.

As with speech, rhythmic structures are highly cultural, with different time signatures and beat patterns being specific to certain cultures. The role of rhythm in suggesting the geographical or ethnic [78] context of a piece serves to highlight its fundamental role in music. The underlying rhythmic structure of a piece music dictates much of its style and frame of reference, with similar harmonic constructs capable of being conveyed in completely different styles due to their rhythmic patterns.

It is suggested that musical rhythmic structures allow patterns to be rendered more flexibly to the listener than by allocating static time increments as are often used in sonification [79, 100, 144]. The structure of music is tempo independent, in so much that a piece of music can be played faster or slower as required. This allows information to be delivered at a speed which is comfortable to the user, rather than by imposing a specific interval that may be too fast or slow for them to deal with effectively. Structures can also be designed using existing methods of grouping such as the beat and bar, which allow effective distinction to be made between events. In this manner, more complex information can conceivably be rendered using musical patterns.

2.5. Auditory Scene Analysis

Although the process by which individual sounds or pitches are detected is important, in most practical situations such sounds are rarely heard in isolation. Musical structures allow for more effective delivery of multiple events, but such distinctions are also made cognitively. Auditory scene analysis (ASA) can be considered as a study of the interactions of concurrently presented sounds. The Cocktail Party problem [45], seeks to identify why human beings can selectively listen to one particular conversation of relevance in a room full of similar ongoing conversations- often with the option of also changing this selection based on incoming information from these other conversations (such as another source calling the subject by name). If an alarm sounds on a busy street it is still perceived as separate from all the other audio signals present. This is a prime example of the complexity of the human auditory process, in that the grounds on which different audio events are given priority are not easily quantifiable.

Bregman [80] considers an audio stream as "*a perceptual unit that represents a physical happening*" and so defines the basic classification of an audio stream. If a song is heard from a radio while an alarm clock also sounds then they would be considered separate streams. This distinction is apparent to any listener, but the reasons why are less straightforward. The main factors of ASA are important to the musical pattern design techniques submitted in this thesis, and can be considered in relation to aspects of visual Gestalt psychology [81]. These factors can be considered as a checklist of requirements for effective pattern design [144], which if fulfilled will ideally engender distinct and memorable patterns.

2.5.1. Familiarity

Prior exposure to an audio source or pattern is a major factor in its subsequent detection. Familiar voices or songs are recognised far more efficiently in multiple streams than those which have not been previously introduced to the listener. In the case of music, previous exposure improves recognition [82] even within the context of unfamiliar sources. When seeking to design musical patterns for detection and recognition, it is important to note that prior exposure may improve performance.

2.5.2. Similarity

Audio components which would be considered to have similar attributes are consequently more likely to be grouped together. Differences in timbre can have an effect on stream detection [83], with a listener considering instruments of same (or similar) timbre being part of the same stream. The converse also holds, with experiments showing that differences in timbre can significantly improve pattern recognition [84]. Musical pattern design must therefore take into account the effect of distinctions such as timbre (and other major discriminatory factors) on two concurrent streams if such patterns are to be effective.

2.5.3. Good Continuation

Streams which retain (or change) attributes in a consistent manner will often be grouped together. This factor is particularly demonstrable when considering 'glides' in frequency (continual increase or decrease in frequency) that have been altered deliberately to introduce anomalous pitches [85] or noise [80] within the glide. The alterations serve to segregate the stream, thus suggesting that higher level features of the pattern (such as its contour) affect its recognition.

2.5.4. Belongingness

Belongingness defines the conditions under which an audio component will be perceived as being part of a stream due to its previous definition within that stream.

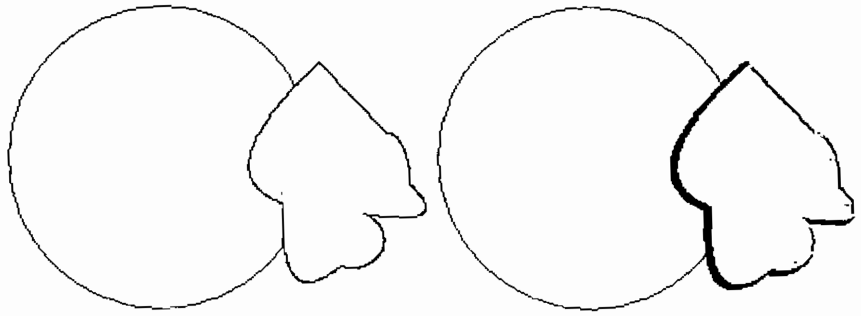


Figure 2.19: An example of belongingness, adapted from Bregman [80]

The above diagram (Figure 2.19) shows how part of a line in a circular shape (highlighted in second shape) can be considered as part of another shape under certain conditions. In situations where such ambiguity arises, the human auditory system will eventually resolve a component into a particular stream. Once a component is part of a stream, it will be perceived within that stream until it changes sufficiently enough to warrant reclassification.

2.5.5. Proximity

Components with attributes that can be considered close to each other are likely to be grouped together. This grouping by proximity is based on frequency, temporal or spatial (2.2.4) characteristics. In frequency proximity, greater difference between the frequencies of the components [86] involved will tend to segregate them into separate streams. When segregating by temporal distinctions, the variation in onset of components [87] will also serve to separate them into different streams. Finally, the spatial position of a component [88] will also serve to group it with other components in that position. In this manner, streams which are either close in terms of frequency, onset or position will be grouped together at some level by a listener.

2.5.6. Articulation

Articulation can be considered as the amount of attention required of a subject when determining different audio streams. Stifelmans work on the cocktail party effect [89] shows that a listener is often required to select a particular stream due to similarity (a group of voices), which would not necessarily be the case if music was played among the voice streams. Care must therefore be taken when working with similar streams (such as musical patterns rendered through a common synthesis device) to engender the maximum difference possible between them, so that accurate identification may take place.

The principles of auditory scene analysis help to define a method of cognitive processing as yet only partially understood. In seeking to design effective musical patterns to represent data, the methods by which such patterns can be made to effectively interact is of great importance when considering more than one data stream. The main categories listed above can be considered as higher level guidelines [144] for musical pattern design, suggesting qualities which will give maximum disparity between patterns.

2.6. Discussion

This review chapter first considered the physical properties of a sound wave and its subsequent detection by the human auditory system. Investigations into frequency response, critical bands and just noticeable difference help to define the typical limits of the human hearing mechanism, as did a consideration of the binaural nature of human hearing. This thesis investigates the use of musical patterns in the delivery of information, and so a brief overview of pitch and harmony was presented to show how sound events are grouped in hierarchical structures. Although pitch is not a good discriminatory factor in isolation, the use of harmonic structures provides the listener with more information about each event (and their interactions) and so are considered worthy of further investigation during this research. The location of a sound relative to the listener is also an important discriminatory factor, and so effective sonification will implement means of placing sounds at different locations to help the listener distinguish between them.

The definition of a sound's timbre was next assessed, as timbre can be a very important discriminatory factor. It was concluded that although timbre is a good means of discrimination, the limitations of synthesis methods on many pc soundcards can often preclude effective distinctions of timbre. For this reason, timbres used in this research will be employed in a worst case scenario method, which will ideally allow the effectiveness of musical patterns to be ascertained by their construction (rather than sonic qualities). It is suggested that well designed patterns will be distinct without recourse to comparisons of timbre, and so can then be utilised even more effectively with high quality sound palettes.

As pitch is not considered sufficient for the purposes of distinction, an investigation of higher level cognitive features was next undertaken. It was shown that complex musical structures can be discerned by infant and adult alike, with the capability to process higher level audio information being present from birth. The infant preference for audio over visual information was also considered, as this can be seen to augment the case for auditory display as a viable alternative to visual methods. This section of the review also suggests that two separate conditions must be considered when seeking to design effective musical patterns. The means by which a pattern can be detected by the human auditory system is essential to a robust pattern design method, but this is not fully effective unless a suitable means of making such patterns memorable is also provided.

Cognitive research has shown that melodic contour plays a major role in pattern memory. For this reason, pattern design methods using musical contour as a feature were investigated during this thesis. Although not argued as a solely discriminatory factor, it is argued that an effective and memorable musical pattern would utilise strong contour related features in its construction.

Rhythm is a fundamental building block of all forms of human interaction and communication. Rhythm in music performs a similarly crucial role, providing means of synchronising and organising musical events into complex structures that can be more readily understood by the listener. For this reason, the use of rhythm as a method of grouping and segregating musical patterns in the conveyance of information is investigated in this thesis.

Auditory scene analysis considers the interactions between audio events within an overall 'scene'. The main factors which determine the grouping or segregation of two events are important when seeking to convey multiple streams of data at once (as is the case in this thesis). For this reason, the six main Gestalt categories for effective stream segregation were detailed as a checklist for effective pattern design. Although subjective in some respects, if a method of designing musical patterns can be determined which satisfies all of these criteria then it is suggested that such patterns will be effectively determined within the auditory scene.

2.7. Conclusions

In this chapter, the mechanisms by which sound is detected and processed by human beings have been considered. The physical properties of sound waves were analysed, followed by the nature of their detection in humans. This detection process was investigated in terms of frequency and then musical pitch, alongside the associated quality of timbre. The process by which higher cognitive features (such as melodic contour) are determined was also investigated, alongside the means of grouping sound and musical events in structures through rhythm. Finally, the main Gestalt categories used in Auditory Scene Analysis were given consideration.

Knowledge and understanding of each of these principles is essential to this thesis, which investigates the means of concurrent presentation of musical patterns for analysis. Effective patterns will be discernable in terms of spatial location, pitch and timbre, alongside more high level characteristics such as melodic contour. The means of organising patterns using rhythmic structures found in music is very important when seeking to effectively deliver significant amounts of information through sound. The interactions between sound events (musical patterns) are also of vital importance, and the six Gestalt categories listed in 2.5 are defined as a checklist for pattern design. If effective pattern designs are to be produced, due consideration must be given to the constraints of the criteria detailed in this chapter.

The next chapter will consider existing work in the field of data sonification, specifically that which involves the use of musical patterns and structures. This work will form the basis of comparative analysis performed during this thesis to determine what improvements can be made to pattern design by the inclusion of high level cognitive features, and how best to render those patterns within the Auditory Scene.

3. Data Sonification

This research investigates the means by which musical patterns can effectively be used to represent data or information. The use of sound and music to convey information is an existing principle, with many forms of audio alert and display being implemented in a variety of situations. To adequately assess how best to convey information using musical patterns, a review of existing methods must first be undertaken.

Sonification [90] can be defined as "*the use of non-speech audio to convey information*". Many methods of information delivery utilise some form of audio component, often without due consideration of its function. It is suggested that sound can convey significant amounts of information [91], and thus could be of great benefit in the analysis and understanding of data sets. This delivery of information could perhaps occur in tandem (in some instances) with associated visual techniques, as a means of further enriching the perception and understanding of existing data structures. Some of the existing examples of sonification are largely unacknowledged and undefined yet generally pervasive in all walks of modern life, and as such require more rigorous study with a view to cultivating an overall framework for their practical application.

This chapter of the review strives to document some of these examples, by way of justification of the principle of sonification. The review next considers the auditory display, which is defined as the means by which information in a computer interface may be delivered to the user using audio. Many of the principles used in auditory display (notably concurrent presentation) are of importance to this thesis, and so are considered separate to the information that may be conveyed by the method. An effective auditory display should conceivably be able to deliver any type of data that existing visual methods can accommodate. For this reason, several specific types of data sonification were considered in order to determine which would be best suited for investigation in this thesis. Many methods of sonification (such as graph data) utilise a specific mapping that cannot easily be translated to other types of data. As a result, a review of the more prominent higher level mapping systems was also performed.

Earcons were of particular interest, as they represent a cohesive investigation into the use of musical patterns for the means of conveying information. Although this thesis does not directly utilise earcons, it does implement the design guidelines [145] suggested for their effective use. These guidelines are considered as a good means of creating detectable symbolic musical patterns for information delivery. As this thesis focuses on the creation of memorable musical patterns for data sonification, it is essential that these patterns first be detectable. The chapter concludes by detailing the data sets chosen for initial investigation in this thesis (and why). It also specifies the direction of investigation into the implementation of effective musical patterns for data sonification.

3.1. Existing Sonification Mechanisms

There are many examples of existing techniques and operations that utilise what could be defined as sonification – often without adequate definition or even acknowledgement of the term itself. As previously mentioned, there is a general lack of awareness concerning the level of audio information processing involved as a consequence of normal human interaction and behaviour. This could perhaps give some explanation towards a similar lack of recognition when regarding systems that utilise this aspect of the human auditory system. By considering examples, it is intended to show how common (and indeed integral) a part of daily life the principle of sonification has become.

3.1.1.Common Sound Events

We are aware of vast amounts of audio information at some conscious level as a fundamental part of our daily lives. The recognition of a persons' voice on a telephone or a song on radio or television is a good example of audio recognition and pattern matching, and serves to illustrate a process we perform on a regular basis-often at a subconscious level. Another interesting aspect of audio recognition is the associations we make with different patterns or events as they occur, for example when we hear birdsong we instantly make a judgment as to the size and weight of the bird (based on the pitch and timbre of the sounds they generate). This is an important aspect of audio analysis with respect to sonification, in that it suggests an existing method of conveying complex data based on associations made in memory.

When a mechanic works on a car, he or she will often run the engine to diagnose the fault- rather than by observation alone. If someone wishes to make an estimation of the current volume of a closed containcr, they will often tap on the surface and listen for the pitch (and timbre) of the sound as an indicator of occupied volume. Similarly, if a structural engineer wishes to make a quick assessment of a wall or floor he or she will often tap on the surface to determine the presence of damp of dry rot. Although not absolute measurements, these methods demonstrate how the measurement of certain physical quantities can be estimated by the sounds they generate.

By recognising musical fragments delivered via a plethora of modern media (from broadcast through to personal devices,) we navigate through the information that they are intended to convey often without any realisation that we are doing so. At an emotional and psychological level, this is also true for sounds that occur as a consequence of other actions rather than as distinct events in their own right (such as the sounds of machinery or traffic contributing to stress and fatigue). We process audio signals throughout our lives, yet often do not recognise or appreciate this as an invaluable means of information retrieval and analysis.

3.1.2. Sonar and the Geiger Counter

Sonar [92] is a system that uses the transmission and reflection of sound waves in an underwater environment to measure distance or detect and locate submerged objects. A Sonar device will transmit a subsurface sound-wave, with the purpose of detecting returning echoes of that sound that have been reflected by objects in its path. The reflected sounds are relayed to operators via loudspeakers or headphones that allow the sounds to be analysed for the purposes of detection (Figure 3.1):

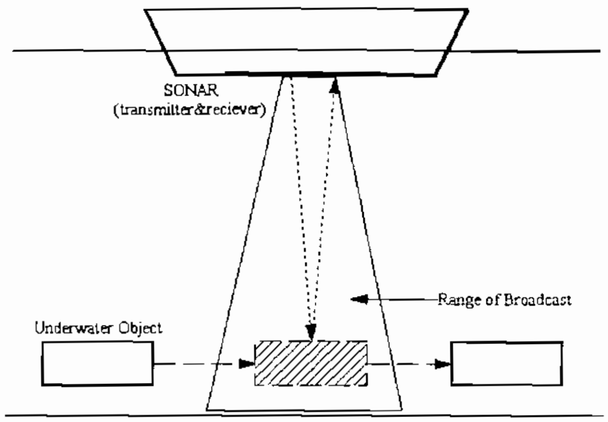


Figure 3.1: Basic SONAR operation example, adapted from Waite [92]

The Geiger counter [93] was invented in 1908 by Hans Geiger and Ernest Rutherford, as a means of detecting the fast electrons and ions emitted by radioactive materials. A Geiger counter (Figure 3.2) works on the principle of attracting electrons and ions to a high potential wire (around 1000V) inside a gas filled metal tube and then measuring the fluctuations in current they cause:

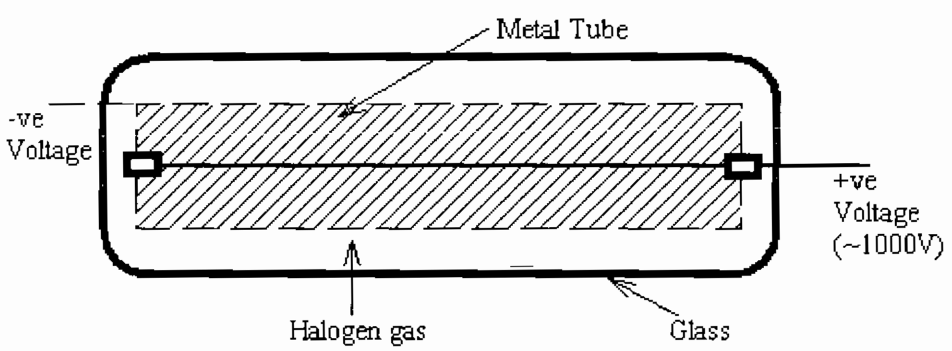


Figure 3.2: Basic diagram of a Geiger counter, adapted from Kleinknecht [93]

These changes in current are conveyed to the user by a sonic representation of the fluctuations in radiation through headphones or a loudspeaker. It is now common to define the presence of radioactive material by the noise of a Geiger counter, and as with Sonar this is perhaps one of the most common and important demonstrations of practical sonification.

3.1.3. Sirens, Alarms and Computer Alerts

In the case of sirens and alarms the need for fast and accurate sonification is essential. Any audio alarm or siren is ideally instantly recognisable as being specific to a particular type of alert- either as a static event that may signal a fire or theft or as a mobile broadcast signifying the presence of an ambulance or fire engine.

Modern sirens as used in emergency vehicles have now come to include localisation features [94], designed to improve upon existing systems that were considered inadequate as a means of safely warning drivers of the presence and location of an emergency vehicle. With a typical siren, the frequency spectrum could be considered between 500- 1500Hz [95] and thus gives the brain very little information to work with when trying to determine the location of the source. By including richer harmonic components in the sounds and spreading them further across the audio spectrum, the brain can be given enough information to accurately pinpoint the location of the sound source. By utilising such sonic design techniques, it is possible to equip road users with a far more accurate means of judgement when dealing with an emergency vehicle.

The proliferation of home and vehicle security alarms has served to demonstrate the problems that can occur if the information content being delivered by the alarm is not rendered accurately enough. In normal practice, very few car or house alarms engender the level of response they are designed to instigate- often to the extent that a common reaction is to be more concerned with attenuating the alarms' output rather than inquiring into the event that triggered it. In situations such as this the sonification of the information involved (that there is a problem concerning some aspect of the home or vehicle) has not been considered to a degree where it performs its correct function, and thus largely ceases to function in the correct manner at all. Many alarm manufacturers are becoming increasingly more aware of the pitfalls and benefits of sonification systems, and are consequently striving to develop better means [96] of delivering warning and alert information as accurately as possible.

Alarms are also an integral part of any home computer and indeed the principle of using audio to diagnose BIOS [97] issues dates back to the early days of computing development, where programmers and engineers would tune a radio to detect the AM interference produced by a computer, predating the use of a simple speaker system to indicate BIOS conditions. In 1965, researchers at TNO Physics and Electronics laboratory developed a system for debugging computer programs that used an automated telephone answering system [98] to relay audio codes from an Eliot NCR803B computer to a remote operator- signifying different operation and termination conditions as audio signals. This technique was developed further using the Power On Self Test (POST) routines of modern personal computers such as the IBM 5100 [99], which was one of the first PCs to signify POST errors as combinations of audio tones broadcast through a small speaker attached to the motherboard case.

By showing how commonplace existing sonification systems are in daily life, it is intended to justify their structured use in the delivery of information. The following sections of the review will consider how such mechanisms have been developed, detailing examples of information delivery using sonification.

3.2. Auditory Display

McGookin [100] defines an auditory display as "*the use of sound to communicate information about the state of an application or computing device to a user*". The roots of auditory displays can arguably be traced back to alarm and alert mechanisms, seeking to inform the user of an important or urgent condition. Such displays utilise many of the advantages of audio information delivery, notably the operation of an 'eyes-free [101]' interface. Focus independent systems of information delivery have been implemented in situations such as flying a plane [102] or driving a car [103] as an essential means of processing information, and in so doing highlight on of the main advantages of auditory display.

Similarly focus independent situations occur with the operation of mobile devices [104], which often occur in conjunction with general physical tasks and activities. Several investigations into the use of auditory displays have been performed [105, 106], notably Brewster's [107] use of audio feedback during a data entry task performed while walking. This study showed that the addition of sound to the interface allowed a significantly greater amount of information to be entered by the user whilst performing a physical task (walking).

Auditory displays also possess the advantage of faster information delivery [8] than any visual mechanism can offer, and so are well suited to situations requiring alerts or alarms. Audio is also largely unavoidable [108] and so is again ideal for alert or alarm information, unlike the focus dependence of visual systems which may often be ignored by the user.

Having said this, auditory displays often suffer spatially in comparison to visual displays. It is far more difficult to present significant amounts of information concurrently (3.2.1) using audio than by visual means, that allow many different pieces of information (such as application icons) to be rendered to the user quickly and accurately. The issue of accuracy is also an important one in auditory display, with the consistent detection and recognition of information delivered using audio [109] being more difficult than with visual methods. Persistence of information also requires far more of a listener's short term memory than with visual systems, as audio is a temporally dependent medium. Effective use of auditory displays requires the strict observation of these boundaries, understanding that audio affords far quicker 'eyes-free' information delivery over a far narrower and more transient bandwidth than with visual methods.

3.2.1. Concurrent Auditory Displays

Concurrent source auditory displays [110, 111] offer advantages over other auditory displays due to the increase in data they convey. A concurrent display achieves a greater data bandwidth by using multiple sources and so gives the listener access to more data in the same length of time. This higher information rate is augmented by the potential for the user to focus on specific aspects of the data [105, 112] at any time by using auditory scene analysis [80]. In this manner, information rendered by a concurrent auditory display can be analysed either wholly or in part by the listener as they require.

Because of this, concurrent auditory displays are potentially one of the most useful methods of delivering data using audio as they provide a means of delivering several related data sets in tandem. Brown [113] considered the potential of two sonified graphs presented in tandem as a means of detecting intersections of interest. Results showed that this method of representation significantly reduced the time taken to determine intersection points, without reducing the accuracy of responses compared to sequential (individual) presentation. Such intersections can be better highlighted using more complex patterns such as earcons (3.6) as shown by Hankinson and

Edwards [114], who used compound earcons to indicate the validity of certain operating system tasks. The earcons used were designed with harmonious musical attributes based on valid operations, such that a copy earcon would sound harmonious with a file earcon but dissonant with a printer earcon. This method of concurrent representation suggests great potential when using musical patterns (7.7), as it affords the use of many of the traditional musical compositional techniques required of harmonic consonance [24].

3.2.2. Sound Mappings in Auditory Display

Auditory display requires that the information or data being displayed be mapped to particular audio attributes or events. The methods by which these mappings are implemented are crucial to developing an effective display. Speech is the most common form of auditory display, utilising the extensive linguistic capabilities that have been developed by human beings for communication. Sign mappings rely on cause and effect relationships, such as increasing pitch to denote an increase in the data value. Iconic mappings are directly representative of the information they convey, with an example being the sound of a printer denoting a print command. Metaphoric mappings such as those used by auditory icons (3.6) engage the listener's understanding of a sounds context [141], such as water being poured into a container defining a file copy operation.

Symbolic mappings are purely abstract and so have an arbitrary relation to the data conveyed. Symbolic mappings allow designers to define mappings for any quantity they wish- regardless of whether it has any iconic or metaphorical qualities of description. The main disadvantage of symbolic mappings is also their abstract nature, requiring the listener to learn each mapping before it can be utilised. Because of this, it can often prove difficult to provide an effective mapping that is both data independent and easy to learn. This is of importance to the research of this thesis, which seeks to define a symbolic mapping system (chapter 6) that does not require extensive exposure prior to use.

Having considered some of the more pertinent issues of effective presentation in auditory display, the next sections will investigate some of the types of information that have been presented. The choice of data source is important when seeking to determine an effective method of sonification, as complexities in a data set can engender problems unrelated to the method by which they are rendered.

3.3. Sonification of Graph and Chart Data

The notion of sonification as a means of representing a set of data (in the same manner as a visual graph or chart), is probably the most obvious application for audio display outside of existing systems. The principles involved in the representation of a set of data vary widely between different types of data- much in the same way that a pie chart is more useful than a line graph in some situations (and vice versa). Thus the definition of an overall framework for data sonification is still a matter of much research and debate.

Unlike existing systems of sonification (3.1) that have developed largely organically in response to a particular problem or requirement, auditory display and data sonification have arguably stemmed from sources such as the algorhythmic composition techniques of modern composers like John Cage [115] and Karl Heinz Stockhausen [116]. Cage's work 'Music of Changes' [115] used the tossing of coins to obtain musical events, by mapping the results of each toss to a musical parameter such as pitch, amplitude rhythm and timbre. In this manner, Cage was using mathematical data (the boolean results of each coin toss) as the basis for composition. From this position, it is only a minor change of emphasis (from the aesthetic to the analytical) that defines such techniques as sonification. Origins aside, the field of research is a growing concern and practical applications are becoming ever more prevalent, as the appreciation of potential benefits becomes more and more apparent. The main aim of much current sonification work (including this research) is the development of frameworks and techniques for the sonification of data sets, with a view to ultimately defining a means of sonifying data in general- in many ways specifying the audio equivalent of the principles of the graph or bar chart.

In considering simple data sets the notion is largely to define the principles under which the most effective sonification can occur, rather than in the analysis of the data itself. The principles defined by such sonification are ideally the basis of more extended frameworks for the sonification of complex data sets and patterns, much in the same way that a graph or chart is altered and tailored to cater to the data it is required to represent. In defining principles for basic sonification, many different approaches have been considered and it is of import to examine the different aspects and merits they provide.

One of the most fundamental differences between sonification principles is the types of mappings that are used [117]. Parameter mapping specifies the musical events that represent data values and so is the greatest source of diversity within sonification. The data values concerned can either be regarded numerically or as data objects (depending on source), and so scope exists for mapping data as musical events- scope that has led to many different theories on how best to define data using sound. One of the earliest and most common types of data sonification was direct mapping to frequency, whereby each value was allocated a specific frequency value on a scale relative to the data itself. This technique was also the basis for sonification wherein data of certain ranges (e.g. light absorption frequencies or seismic data), was scaled into the audio waveband for synthesis and playback [118]. Using this method, a large array of data values could conceivably be represented by a single synthesized instrument capable of frequency based output. One of the main drawbacks of such a system is that while the mapping may be technically specific, the human auditory system can have difficulty perceiving the exactitude of each variation in frequency. Although a listener may discern a change in frequency, it is a very different matter to ask them to accurately quantify it. Sonification in this manner still proves very useful for trend analysis of large data sets (such as rainfall data and seismic data), with a view to detecting overall changes in aspects of the data over a period of time. However, in some ways it can be considered too broad a representation for certain types of data.

3.3.1. Pitch Parameter Mapping

A more common technique is the use of MIDI synthesis to assign values to notes within the MIDI range (0 -127). For practical purposes this range is often truncated [119], (due to the perceived limitations of most synthesisers) in an effort to render an accurate and definable note at all times. The basic premise of pitch mapping is that some form of scaling relation present in the data set can be represented as corresponding changes in musical pitch, by assigning individual data values to individual notes on a purely numerical basis (Table 3.1):

Student Number	1	2	3	4	5	6	7	8	9	10	11	12	13
Score	48	53	58	61	50	67	73	56	49	62	59	65	60

Table 3.1: Example listing of student exam results

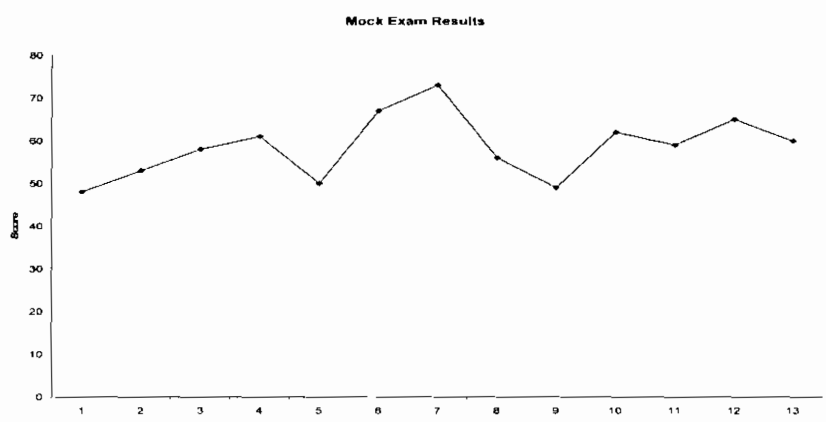


Figure 3.3: Exam results from Table 3.1 rendered as visual graph

Figure 3.4: Possible output sonification of exam results from Table 3.1

In the previous example (Figure 3.3 and Figure 3.4), a fictitious list of examination results are sonified on a purely numerical basis, with individual exam score defined by MIDI note number. With such a relation, some form of manipulation must ideally be performed on data that falls outside this narrow range of MIDI values, and so much like a visual graph the scaling of the data is largely dependent on the data itself (and what is considered of importance within it).

Perhaps the main advantage of this technique is its ability to very quickly convey transitions within the data (such as an increase or decrease in magnitude) corresponding to a similar change in pitch. Another advantage is the ease of implementation of a system that requires only basic MIDI note frameworks, rather than extensive signal processing or calculation. Having said this, a major drawback of such a system is its lack of pliability, in that major changes must often be made to the input data sequence in order that it can be represented within the MIDI note range. It is often counterproductive to unduly colour the input data of a sequence by manipulation, in order that it can be tailored to fit the medium- rather than considering methods by which the medium can adequately convey the data instead.

3.3.2. The Audio Abacus

One such innovation intended to address the problem of accurately conveying values with pitch parameter mapping is the Audio Abacus [120] (Figure 3.5), which seeks to convey both the specific data *and* the trends within the data itself as part of an overall sonification. In its most basic incarnation, the Audio Abacus uses 3 notes to convey each individual digit in a three digit number- in the same manner as the traditional abacus:

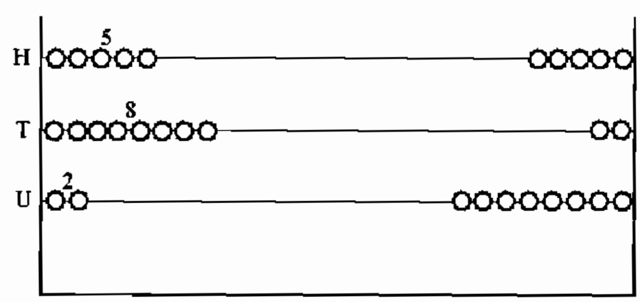


Figure 3.5: Traditional abacus representation of the decimal number 582

Each decimal number (0-10) is defined within a range of MIDI notes, such that the range of MIDI note numbers 60 through 70 could be used to define each decimal increment (60 for 0, 61 for 1 and so on). If the range were extended between the MIDI notes 60 through 80, the decimal increment would similarly increase to 2 MIDI notes (60 for 0, 62 for 1, 64 for 2 and so on). In the example below (Figure 3.6), the number 582 has been rendered as MIDI notes, within the Audio Abacus range 60 (0) through to 70 (10):

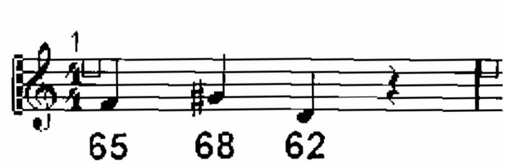


Figure 3.6: Audio Abacus representation of the decimal number 582 and its associated MIDI note numbers, adapted from Walker et al [120]

By using this system a far greater range of values can accurately be conveyed in a single musical event and provision has also been made for decimal values (Figure 3.7), wherein a percussive cymbal sound is used to denote the decimal point- hence the value 58.2 could be rendered thus:

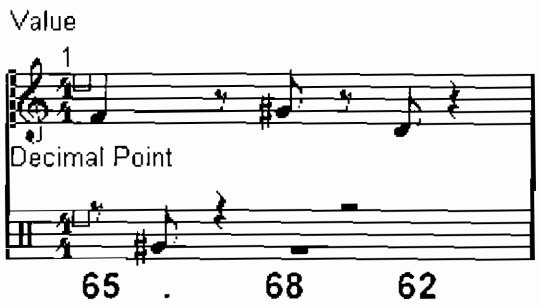


Figure 3.7: Audio Abacus representation of the decimal number 58.2 and its associated MIDI note numbers, adapted from Walker et al [120]

The Audio Abacus is perhaps one of the most interesting innovations in an ever growing field of research and endeavour, in that it seeks to address one of the most common problems in both audio and visual display systems alike- the definition of point data within overall trend analysis. Other approaches have produced results that are interesting and useful within the framework of the specific data they relate to, but often suffer when applied to other types of data. In this manner, the principles of the Audio Abacus suggest a very powerful innovation in the area of pitch to parameter mapping.

3.3.3. Markers, Axes and Labels

Another important development in the sonification of graph and chart data (and indeed in data sonification in general) is that of context and markers [121]. In order to define the transition between specific events in a sonification, an audio tick mark of some form is of benefit in allowing the user to determine where they are within the data they are listening to. By using percussive sounds at regular intervals in the sonification to denote some form of index in the data, a more defined representation of that data can be achieved- much in the same manner as the tick marks on the axes of a visual graph help specify the value of the information that the graph displays.

Tick marks provide resolution and location information to a sonification, which is of importance for both defining point data and trend analysis. If changes in pitch are considered as the resolution of the Y axis on a visual graph (usually denoting a magnitude of some form), then audio tick marks can be considered as performing similar function on the X axis (Figure 3.8):

Figure 3.8: Example pitch parameter mapping of Table 3.1 exam results with additional percussive tick marks

In the above example, each sonified student result can be identified by its position relative to a percussive cymbal sound, and so the addition of audio tick marks allows the listener to discern the exact position within the data being sonified. More verbose information can be conveyed by the addition of further audio ticks and marks (corresponding to the data being sonified) and these take on the function of additional labels within the audio graph. An important practical point is the appreciation that adding too many ticks and labels serves only to unduly clutter the data being sonified- much in the same way as with a visual graph or chart. It is important when seeking to deliver information that as little extraneous or irrelevant material is included, and so further work must be done to adequately define a framework for markers and labels within sonification.

The ultimate goal of data sonification is the accurate and efficient delivery of audio graphs and charts for the purposes of analysis and understanding, and to this end no fully effective solution has been achieved thus far. The potential for audio displays and rendering techniques is becoming more and more apparent in a data-driven world that seeks to convey as much information as possible in the shortest time interval. Data sonification is a source of great promise in the endeavour to find new techniques and principles for information delivery, and so the determination of a comprehensive framework for basic data analysis is of prime importance. Although graph and chart data sonification focuses on simple data for the purposes of analysis of the method itself, many other investigations in data sonification have involved highly complex data. In these cases, the sonification method is often employed in an attempt to extract meaning from data whose complexity precludes effective analysis using visual methods.

3.4. DNA/RNA Pattern Sonification

Music from DNA and RNA sequence data has been a growing field of composition in recent years. The notion of conveying the complex structures contained within a nucleotide sequence through music has fascinated musicians and biologists in equal measure. In considering a data set that is still largely functionally undefined, the possibility of decoding certain features or operations with a sequence using sound or music is of huge potential benefit. However, with a data set as complex as DNA some prior knowledge of the data itself is required- as detailed below.

3.4.1. DNA, RNA Transcription and Translation

Deoxyribonucleic acid (DNA) [122] chains consist of four chemical bases, which provide a code for all life on this planet. These chains are grouped in complimentary pairs of purines (adenine and guanine) and pyraMIDInes (cytosine and thymine). The bases are usually referred to by their first letter within the actual code sequence for brevity (e.g. ACGT), and each binds to a sugar (deoxyribose) and phosphate molecule in order to create a nucleotide (Figure 3.9). These nucleotides then form chains of specific base sequences that make up the code of DNA.

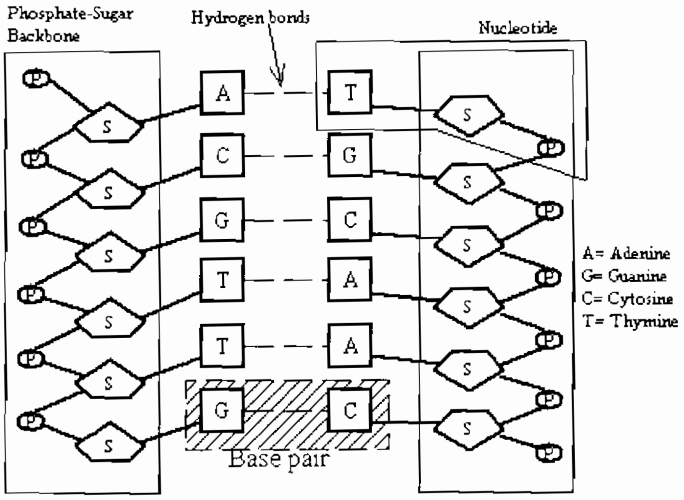


Figure 3.9: Base pairs within a DNA nucleotide sequence, adapted from Watson and Crick [122]

DNA within a gene is double-stranded, and the chemical properties of the bases cause the strands to twist into the coiled double-helix that is DNA. Each base on one strand is paired with a complimentary base on the other (adenine with thymine and guanine with cytosine), and in this way, each molecule of DNA contains its own template that is passed to a new molecule after replication for future decoding and duplication.

Transcription of DNA involves the creation of single stranded RNA [123] (ribonucleic acid) from a DNA (deoxyribonucleic acid) template. In the case of RNA, the purine Adenine is paired to the pyraMIDIne Uracil instead of Thymine as in DNA (thymine does not code in RNA). The end result of the process is a strand of RNA that contains the same information as the original strand of DNA, and this strand can then be translated into amino acids (and hence protein).

Translation of RNA utilises a large complex of proteins and ribosomal RNA (rRNA), which are collectively known as a ribosome. Each strand of RNA can be broken down into groups of three bases known as codons [124], with each codon specifying a particular amino acid. The ribosome pairs each codon with its associated amino acid, and the resulting polypeptide chain will eventually fold into protein. It is interesting to note that although there are 64 possible combinations of codons (Table 3.2), there is a three to one redundancy when translation takes place (19 amino acids and a stop codon).

	U	C	A	G	
U	Pheny -lalanine	Serine	Tyrosine	Cysteine	U
	Phe	*Ser*	*Tyr*	*Cys*	C
	Leucine	*Ser*	STOP	STOP	A
	Leu	*Ser*	STOP	Tryptophan	G
C	*Leu*	Proline	Histidine	Arginine	U
	Leu	*Pro*	*His*	*Arg*	C
	Leu	*Pro*	Glutamine	*Arg*	A
	Leu	*Pro*	*Gln*	*Arg*	G
A	Isoleucine	Threonine	Asparagine	Serine	U
	Ile	*Thr*	*Asn*	*Ser*	C
	Ile	*Thr*	Lysine	Arginine	A
	Methionine /START	*Thr*	*Lys*	*Arg*	G
G	Valine	Alanine	Aspartic acid	Glycine	U
	Val	*Ala*	*Asp*	*Gly*	C
	Val	*Ala*	Glutamic acid	*Gly*	A
	Val	*Ala*	*Glu*	*Gly*	G

Table 3.2: Codon combinations and their corresponding amino acids, adapted from Hayward [124]

Amino acids all consist of the same 8 atom structure with attached side chains of differing atomic clusters. These side chains dictate whether an amino acid is suited to water (Hydrophilic) or oil (Hydrophobic), whether they carry a positive charge or none at all and also whether the amino is acidic or alkaline in nature.

These differences in characteristic are of prime importance when constructing a protein, in that they will allow chains of different function to be constructed from amino acids of differing properties as required. Having said this, the biological processes involved in the decoding of DNA into final protein are far too extensive to be covered here in any great detail, but the basic premise of DNA as a biological code is central to the sonification of DNA and RNA nucleotide sequences.

3.4.2. DNA Sonification

Having considered the basic principles of DNA, the means by which such information has been sonified must next be investigated. One of the first documented suggestions of DNA sonification is attributed to Douglas Hofstadter [125], who likened the transcription of RNA into amino acids as similar to magnetic tape passing through the playback head of a tape recorder (Figure 3.10). In the case of RNA, the playback head is the ribosome and the amino acids are notes, with pieces of music being defined as proteins.

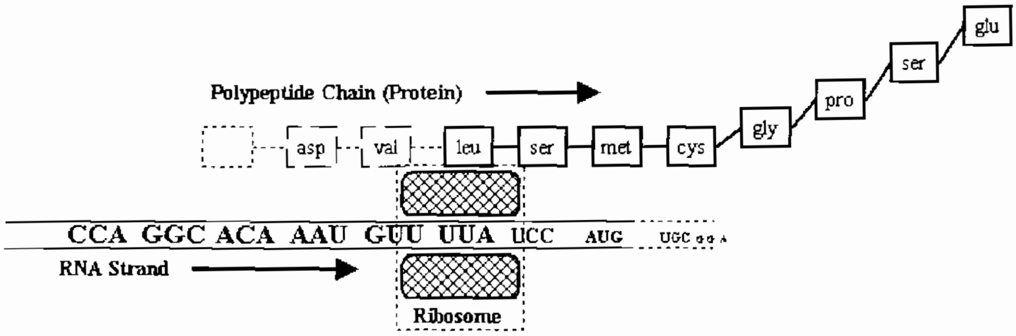


Figure 3.10: A representation of RNA translation as akin to a tape recorder, adapted from Hofstadter [125]

The notion of DNA and RNA as a code that defines the complex structures of proteins is a rich vein of data for analysis that has attracted researchers from many different fields- not least that of sonification. By taking the bases and their properties as data, sonifications can be produced representing various aspects of the original codes both for compositional and analytical purposes.

Initial works by artists like John Dunn and biologists like Dr. Mary Anne Clark [126] have stimulated an area of research among musicians and biochemists which is proving increasingly fruitful. Mary Anne Clarks' original research was based on the premise that DNA proteins and genes were pattern based, much like a musical score. Her collaborations with John Dunn centred initially around haemoglobin, where although the protein is different among species, the common theme remains- much like an orchestral work. A method of actually representing DNA sequences by pitch substitution was first defined by Nobuo Munakata and Kenshi Hayashi [127] in 1984, with the suggestion that the four bases of DNA could be allocated pitches within the interval of a fifth (Figure 3.11).

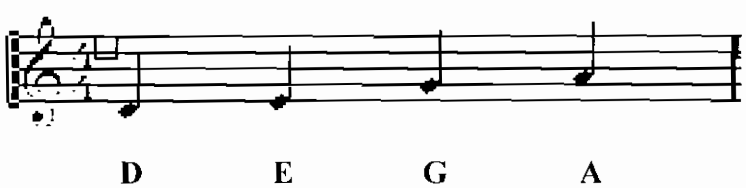


Figure 3.11: Example nucleotide bases to musical pitch mapping, adapted from Nubuo and Munakata [127]

In the previous diagram (Figure 3.17), each of the four nucleotide bases is allocated a pitch from the cycle of 5ths (D is the 5th of G, A is the 5th of D and E is the 5th of A) within an octave range. It was also suggested by Munakata and Hayashi that the corresponding amino acids coded from RNA sequences could be represented by pitches within the same output sonification [128], but no clear guidelines for such mappings were suggested. With these basic tenets as a guideline for the sonification of DNA/RNA sequences, many other composers have produced works using DNA/RNA as a template.

The sonification of different enzymes and proteins is now an area of research, with new works appearing from the likes of Susan Alexjander [129] and Dr. David Deamer which relate to both the physical behaviour of DNA base pairs and also the musical coding of such. Susan Alexjander's compositions are based around the relative light absorptions of different base pairs, which when scaled down into the audio waveband produce very musical relations. Dr Deamer has also published DNA suite [130], a series of compositions based around the human insulin gene and alu consensus- a 300 nucleotide repeating sequence that comprises over 10% of the human genome. Dr. Ross King and Colin Angus developed the software Protein Music [131] in 1996 to set DNA sequences to music. The output music details the base nucleotide sequence and properties of the amino acids they code for (such as water solubility, charge and size). The software also suggests changes in the structure of the proteins the amino acids code for by changes in the tonality of the piece.

Although research has been performed using DNA sonification, no conclusive method has yet been produced. The vast complexities of the data require extensive consideration when determining which aspects of the information present should be rendered in a sonification. The huge amounts of information present effectively preclude a complete analysis of any sequence, and so care must be taken when editing for the purposes of sonification. DNA and RNA are by no means the only candidate for sonification of complex data, and so other data sets used in sonification were also considered.

3.5. Other Sonification Data Sources

The impetus of sonification for analysis purposes has progressed from initial compositional work (using data sequences such as DNA or seismological information) into an ever growing field of research. The desire to use data from existing fields of analysis as the basis of sonification has provided many works (utilising meteorological data such as rainfall statistics [132], or even stock market trading figures [135]). The analysis of weather records [133] for different months and years, allows a comprehensive observation of trends and patterns in the weather to be performed using sonification. By allocating musical patterns to temperature, rainfall and snowfall statistics a representation of weather records over time can be achieved.

Another method of sonification in this area is the delivery of specific weather reports [134] for a period of time, in much the same manner as conventional media such as newspapers and television already provide. The weather forecast for a particular day can be represented as synthesized sounds designed specifically for the purpose (such as wind sounds created using resonant filters and white noise) and this technique affords a far greater degree of control and flexibility over the timbre of sounds than with general MIDI mechanisms.

In analysing data obtained from stock market trading figures, a new and potentially very powerful field of research has been growing in popularity over the past few years. The MarketBuzz system [135] allows traders the opportunity to monitor the movement of stock prices in real time, as means of augmenting and often replacing existing visual methods. One of the main problems facing traders is the amount of information that they are required to keep constant track of, and to this end the average traders' workspace contains several computer monitors for the purposes of information delivery. When information about certain relevant stocks was sonified and delivered to the traders via speakers, it was found that it became much easier to monitor the information they required.

Experimental tests of the framework have suggested a far greater degree of accuracy when using integrated audio and visual systems or even with audio as the only stimulus. The application of sonification to an area where multitasking is essential, has proven one of the distinct advantages that sonification systems provide- the ability to integrate and co-exist with other data delivery systems in real time.

Network monitoring [136] is another new area of sonification where systems are being introduced to convey information about various aspects of a data networks performance. The potential for rendering audio information to a network administrator while they perform other tasks has great benefit, particularly in a field similar to stock trading in its level of information delivery. Pilot studies have suggested great potential for such a system.

Taken one step further, several forays have been made into the area of debugging computer software using sonification- most notably the Caitlin project [137]. The Caitlin project developed software to represent simple Pascal code routines as audio in order to assess the ability of novice programmers to debug them. The research obtained results suggesting that participants performed better when debugging code using both visual and audio means in tandem. This serves to highlight an important role of sonification as an augmentation or compliment to existing methods- also referred to as an equal-opportunity interface [138].

Many other examples of sonification exist for both composition and analysis, and it is often more difficult to determine which is the overall aim than to appreciate the potential benefits of either or both. In the case of Cellular Automata sonification [139] emerging trends and patterns within the system are of analytical importance, while the intricacy of the patterns themselves is also of aesthetic interest to many researchers. Existing visual systems designed to represent the state changes of a cellular automaton generate complex and interesting structures from a given set of rules for each automaton and the patterns created are of great interest to mathematicians and philosophers alike. This method of sonification is interesting in that it provides potential for simulated analysis, predicting what a given set of rules will do in a system using sonification to render the data.

Having considered some of the data sets used in sonification, it is now important to investigate the best methods by which these may be rendered to the user. Simple pitch mappings (as used by graph and chart data sonification) are often inadequate means of conveying anything more than trend information. The audio abacus seeks to solve this problem by concatenating pitches into musical pattern events, and in so doing becomes part of a higher level form of auditory display. The use of metaphoric or symbolic sound events- is they audio, music or a combination of both- are a far more robust way of communicating information than by methods which only relate to the specific data they represent. In seeking to produce effective musical patterns for data sonification, the existing methods used are of great importance to further work.

3.6. Auditory Icons

Auditory icons [140] are real sounds (or synthesized imitations of them) that are used to represent different actions or objects that they relate to. Auditory icons increased rapidly in popularity with the advent of the personal computer, as a means of conveying information about objects within an operating system and the operations associated with them. Graphical User Interface (GUI) designers and programmers in general discovered an increase in functionality when sounds were used to convey information in tandem with visual cues and so rapidly began to build them into applications as a matter of course.

The basic nature of an auditory icon is now familiar to most users of personal computers running a major operating system such as Windows or Mac OS. The auditory icon can be the sound of a printer indicating a print command or the sound of liquid poured into a receptacle to denote a file copy. From its initial implementation in applications such as SonicFinder [141] and SharedArk the auditory icon enhanced GUI functionality by defining events and processes in a manner familiar to the user.

Although the popularity of the auditory icon has now secured its place as part of every major operating system, it has been found that many users find the additional information to be obtrusive when too verbose, and so often the level of audio information delivered is relegated to simple alarms and notifications. Auditory icons also suffer from their metaphorical mappings, in that a particular sound is required to convey a particular piece of information. This requires that distinctions can be made between these sounds, as Mynatt [142] states "*although the sounds of a copier and printer may be quite distinct, it may be difficult to correctly identify them when they are both used in the same interface*". In many instances this can prove difficult, and so distinct mappings are often elusive.

3.7. Earcons

Earcons are defined by Blattner et al. [143] as "*non-verbal audio messages used in the user-computer interface to provide information to the user about some computer object, operation, or interaction*". This definition is taken further by Brewster [144], who describes earcons as "*abstract, synthetic tones that can be used in structured combinations to create auditory messages*". Earcons have been considered as an alternative to auditory icons in both their implementation and application, in that they are intended to convey information without relying on the contexts of the sounds themselves. To this end earcons are defined musically rather than as audio events, and so can ideally be learned in abstraction without reference to a specific sound.

The construction of earcons focuses on the use of a motive [143] as a basic building block for more complex musical structures. A motive is defined as a short series of pitches intended to be individual and distinct relative to other similar motives designed for the same purpose. In defining a motive several characteristics are considered of prime importance, notably the pitch, timbre, register and rhythm of the resulting motive. The pitch and rhythm of an earcon define the basic characteristics of the motive, while the timbre and register provide means of altering these characteristics to convey different information. Earcons fall into four distinct categories– one-element, compound, hierarchical and transformational- depending on their overall function.

3.7.1. One-Element Earcons

One-element earcons convey a single piece of information using a single motive. They are similar to auditory icons in that a distinct mapping is required between earcon and data on a one to one basis, although in the case of earcons no metaphoric information relates them to the data. A one-element earcon can be as simple as a single pitch (or rhythmic pattern), and this dictates that each earcon and its associated data mapping must be explicitly learned for each data set encountered. This lack of pliability means that large data sets require similarly large sets of sounds to be learned by the user, and so become an unduly complex method of conveying information. To circumvent such large numbers, other types of earcon which convey more information are employed.

3.7.2. Compound Earcons

In a compound earcon (Figure 3.13) different motives (Figure 3.12) are concatenated to provide information about an overall event:

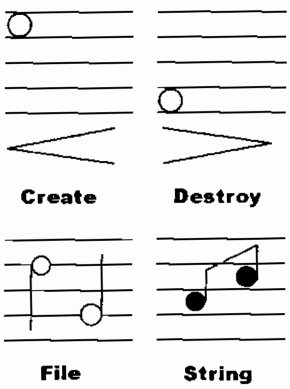


Figure 3.12: Four motives 'create', 'destroy', 'file' and 'string' taken from Brewster [144]

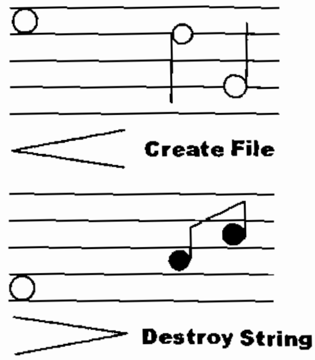


Figure 3.13: Combining motives to produce 'create file' and 'destroy string' compound earcons, taken from Brewster [144]

In the above examples, the bass note defines a create or delete action (in this case relative to a melody specifying a file object). In each combination, the initial action is conveyed followed by the object it applies to as a means of creating an association for the listener, and in so doing becomes a compound of individual motives used to convey more complex information. One drawback of compound earcons is the time they require, with even short earcons requiring up to 2.6 seconds [144] to complete. In many instances, the time taken to deliver information is critical and so may preclude the effective use of compound earcons as a means of data representation.

3.7.3. Hierarchical Earcons

In hierarchical earcons the different characteristics of an earcon (rhythm, pitch, timbre and so on) are introduced at each level (Figure 3.14)- to denote a further refinement of the information to be conveyed:

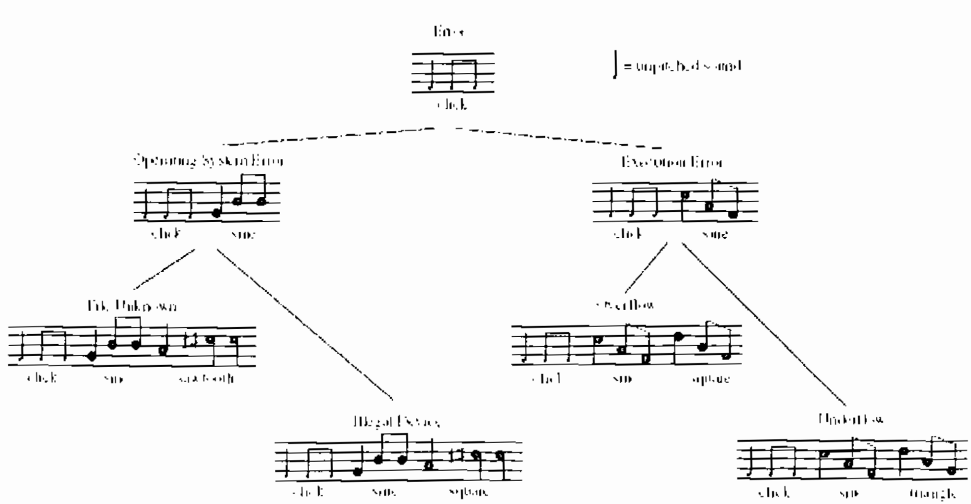


Figure 3.14: Hierarchical earcons used to represent computer error messages, taken from Blattner et al. [143]

In the above example an initial click sound is used to define the rhythm of the motive (and hence its structure), before the addition of pitch information in the second level rendered by a sine tone (assumed to be neutral or colourless for timbre purposes). In the third level a square or sawtooth wave is used to define the timbre of the motive, and so three different pieces of information are conveyed. However, hierarchical earcons still require a similar length of time to execute as compound earcons. For this reason, the additional information present in a hierarchical earcons makes them as temporally expensive as their compound counterparts.

3.7.4.Transformational Earcons

Transformational earcons (Figure 3.15) provide a solution to the problem of completion time, with the different levels of motive being omitted in favour of the final hierarchical earcon.

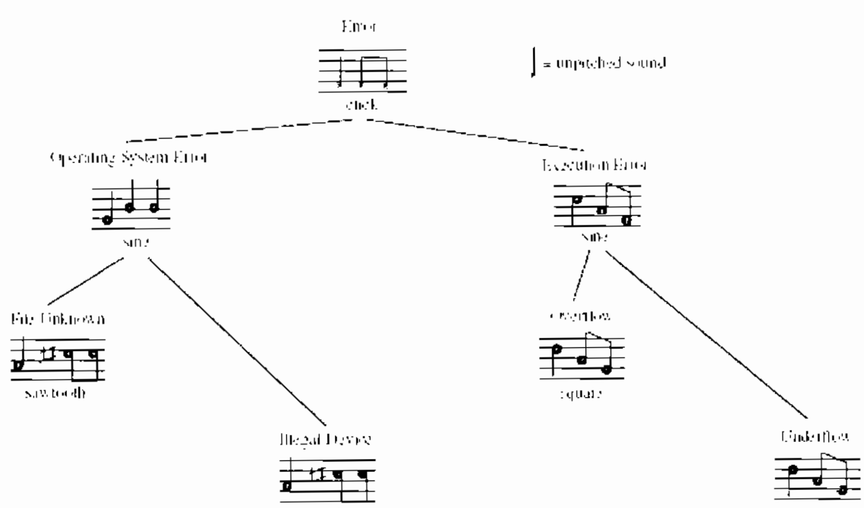


Figure 3.15: Transformational earcons based on error messages from Figure 3.14, taken from Blattner et al. [143]

In the above example, the omission of the various 'construction' stages of the earcon allow for a far shorter rendering time than with any of the previous methods. This form of earcon is suggested for 'expert users' [143] who are already familiar with the grammar of earcon construction. In this manner, an earcon containing several pieces of information can be rendered in a far shorter time than with any of the other earcon approaches.

3.7.5. Earcon Design Guidelines

Specific guidelines about the construction of earcons have also been offered by Brewster et al [145], to provide a more cohesive method for their utilisation. The guidelines consider different musical attributes in turn to define an overall system for earcon creation:

- *Timbre*: Musical timbres with multiple harmonics should ideally be used to allow straightforward judgements to be made between them. The choice of timbre must take the specifics of the synthesiser into account- i.e. two sounds which are expected to have different timbres and tonal characteristics may not be significantly different when implemented in General MIDI for example. Also, the envelope of the sound must be considered to determine whether the sound produced is continuous or discrete. Discrete sounds are ideal for short, rhythmic patterns but may not be sufficient for longer events such as chord intervals or drones.

- *Register*: Register denotes the octavc of the patterns used. It is recommended that register is not a singularly reliable means of differentiating between patterns. If used, it is suggested that gaps of 2 or 3 octaves will lead to better recognition.

- *Pitch*: the pitch range used should ideally fall in the range 125-150Hz up to 5 kHz. As with register, pitch is not a reliable means of recognition in isolation, but can be utilised effectively along with rhythmic patterns. Care must also be taken to ensure that the pitch range used is within the scope of the timbre selected- e.g. a violin sound will not deliver well at low pitches. If a wide range pitches are to be used, a timbre such as organ or piano should be considered.

- *Rhythm and Duration*: Rhythmic patterns used should ideally be as different as possible. The use of different numbers of notes in patterns has been found to be very effective. A recommended guideline suggests a note length of no less than 0.0825 seconds, although in short patterns (of no more than 2 or 3 notes) notes as short as 0.03 seconds can be considered. It is also suggested that earcons containing up to 6 notes in 1 second can be used as patterns.

- *Intensity*: Intensity is considered by the guidelines to be the main source of annoyance in a sound. The relative volumes of patterns should be kept within a narrow range (between 10 and 20dB above the background threshold) and indeed intensity should not be considered as means of differentiating between earcons. The exception suggested is the use of a slightly louder (accented) first note in a pattern to emphasise its rhythmic qualities.

- *Spatial Location*: Spatial location can either be defined by a standard left-centre-right panning attribute, or by more complex spatialisation hardware or software as available. Spatialisation is considered a very useful means of differentiating between parallel earcons and even as a means of augmenting the differences between serial earcons.

These guidelines are used throughout this thesis as a means of defining detectable musical patterns. Although earcons themselves are not directly employed, the principles of musical pattern design detailed by the above guidelines are essential to any robust method. The next section will consider aspects of data set selection and pattern design detailed in this review, with a view to specifying how work in this thesis must progress.

3.8. Discussion

This chapter of the review investigated existing methods of sonification. Many methods of sonification have developed without recourse to the term itself, and so some of the more common examples were reviewed by way of suggesting the potential of effective sonification. A particularly common method is the auditory display [111], which provides focus independent information to computer users.

This research considers methods by which different (related) streams of data may be effectively rendered to the user, and so work performed in this area by designers of auditory displays is important. As higher level methods of recognition are of interest, the use of harmonic relations between patterns [114] is also considered an interesting method of concurrent display.

3.8.1. Data Structuring Using Rhythm

Investigation into the use of rhythm as a means of structuring musical events had also suggests an area of sonification that had not been adequately considered. Although rhythm is considered the most important factor in the design of a pattern, less consideration has been given to rhythmic organisation of such patterns. Brewster [144] noted that short gaps of around 0.1 seconds allowed users more time to process events in a manner common to speech [146]. This gap is an example of how separation of individual patterns is possible by effective use of rhythmic intervals, but does not adequately investigate the potential of such structured representation. Smith and Walker's use of percussive tick marks [121] suggests a far more robust means of segregating data in a tempo independent manner. A physical definition of time is tempo-dependent, and so suffers from a lack of pliability when seeking to provide an effective method of organising musical events.

By employing musical rhythms, the tempo of a sonification can be altered to suit the pace of the listener (if so desired) without affecting any of the information contained therein (or it structure). It is suggested that rhythm can be used to segregate different levels of grouping among events in a sonification. By using different lengths of rest notes in a sonification it may be possible to convey structures within that data. This use of rhythmic parsing can conceivably allow the user to organise the data they hear in a more efficient manner.

3.8.2. Initial Data Set Specification

Choosing the type of data to be sonified is crucial to producing an effective means of designing musical patterns. The review considered several of the more prominent data types undertaken in existing work, and as a result it was decided to investigate the potential of DNA/RNA nucleotide sequence data in sonification analysis. This data source was considered for the following reasons:

- DNA/RNA sequences are a rich and interesting source of data and so lend themselves to comprehensive study.

- The hierarchical structures of DNA and RNA were considered to be very similar to the structures found in music (as suggested by Hofstadter [125]) and so the use of one to convey the other was perceived to be an interesting avenue of investigation.
- Previous sonification of nucleotide sequences has largely been for compositional purposes, and so no definitive method exists.
- The combination of nucleotide bases and their corresponding codons would benefit from concurrent streaming, ideally using more robust high level musical features than existing work [128].

Although this form of data was specified for initial conditions, several other factors also had to be borne in mind:

- DNA/RNA is a huge, highly complex and largely unknown type of data that may prove too cumbersome for effective sonification when no truly viable method currently exists in any modality [147].
- Effective rendering and analysis of such data sets may require extensive training in genetics.
- Exotic data such as DNA/RNA could conceivably affect the assessment of any pattern design method.

As a result of these factors, it was decided that DNA/RNA sequences would be used as part of an initial case study into the merits of their sonification. The methods suggested by Nubuo and Munakata [128] could conceivably be improved upon if other factors were employed, but complexities in the data could also preclude effective assessment of the sonification method itself. Having decided upon an initial data set for sonification, the method by which that data would be rendered was now considered.

3.8.3. Pattern Design Methods

The mappings used in sonification are also of great importance when seeking to determine an effective method. As a consequence of the review, it was decided that pitch to quantity mappings did not supply the user with enough information (2.2.5) upon which to make effective distinctions. A possible solution to this problem has been suggested by the Audio Abacus [120], but it is argued that such methods of pitch to value mapping are effectively patterns in themselves.

Consideration was given to existing higher level methods of mapping such as auditory icons and earcons. As this thesis investigates the use of musical (and hence iconic) patterns, auditory icons were not felt to be a useful direction of investigation. Earcons were investigated in their various forms, with particular interest in the construction of transformational earcons. This type of earcon is potentially a very effective current use of a musical pattern as a means of conveying structured information, although the method obviously requires significant previous training and exposure (in common with all iconic pattern methods).

Having said this, the patterns used by earcons are distinct in as much as they are different in detectable ways, but do not contain specific guides as to how these patterns were determined as more efficient descriptors than others. The grammar used in constructing earcons often relies on low level mappings (3.7.1) which may not necessarily be memorable to the listener. Work by Hankinson and Edwards [148] has considered the use of more distinct musical phrases in earcon design, suggesting that "*a vast amount of more complex, highly-structured information can be easily expressed musically in a considerably more stylised way and with greater design freedom ....beyond the limitations of the earcon guidelines*". Other research [149, 150] has also been performed on the use musical phrasing in earcon design patterns, and suggests that musical structures can benefit the design process. It is suggested that a truly effective pattern must be both distinctive and memorable (2.3.2), and so creating such patterns is potentially a prerequisite to other methods of pattern sonification.

This research aims to produce musical patterns which are both detectable and memorable, for use in the sonification of information. In producing detectable patterns, the earcon design guidelines suggested by Brewster, Wright and Edwards [145] are considered an essential first principle. Although earcons are not used, the methods by which they are made discernable are employed throughout the rest of this thesis. It was decided that effective, memorable patterns were an important consideration that required greater investigation than in existing work. As a result of the review, a set of research questions were derived:

RQ 1.What effect does rhythmic parsing have on the understanding of structures within a data set?

RQ 2. Do present methods of pattern design (notably earcon design guidelines) produce patterns which are not only distinct but also memorable?

RQ 3. Can present methods of pattern design be used to efficiently render concurrent streams of data?

RQ 4.What effect does musical contour have on the recognition (and identification) of musical patterns used in data representation?

RQ 5.What effect during concurrent presentation does harmonic combination have on the identification of features and intersections in data streams?

3.9. Conclusions

This review has shown that great potential exists for sonification, with existing mechanisms demonstrating that one of the main areas of development required is awareness of the technique itself. It can also be argued that although significant investigation has been performed in areas such as DNA sonification, much potential still exists for further work. It was intended to perform a case study into the merits of DNA/RNA nucleotide sequence sonification, and this was seen as the ideal opportunity to employ higher level rhythmic groupings as a means of organising the data. As stated in (3.8.2), DNA/RNA is a complex type of data which may cause difficulties other than those caused by pattern design. Part of the impetus for the case study was to assess how difficult it is to sonify large and complex data, with a view to then improving the method to a level capable of sonifying such data. It is argued that complexities in the data may require separate consideration from the methods by which they are rendered to the listener, and hence results obtained from testing would serve as an indicator to development in future work.

4. Case Study: DNA/RNA Sonification

4.1. Overview

As a result of the sonification review, it was decided to investigate the possibilities of DNA and RNA sonification as part of a case study. Existing work in the field (3.4) had suggested various means of DNA and RNA sequence sonification, and it was intended to build upon the principles of these methods. The work of Nubuo and Munakata [127, 128] was considered the most straightforward method of DNA/RNA sonification, and hence the most applicable to testing. Improvements were proposed, although comparison with the existing method was not the focus of testing. The viability of the data set, and its segregation using rhythm were the areas of interest to this research.

The first stage of the investigation focussed on defining what elements of DNA or RNA sequences would be used in sonification, and in what manner. Initial studies showed that RNA sequences were a less complex form of data than full DNA sequences, as well as being far shorter than the 3 billion bases found in a human DNA sequence. For this reason, it was decided that RNA sequences would be used when developing a sonification framework, allowing any positive results to be considered with DNA at a later stage.

The next area of investigation considered what elements of a nucleotide sequence would be used in a sonification. The hierarchical structure of RNA (from base to protein) was found to be too complex in its entirety, with no definitive work detailing the entire process available at time of writing [151]. As a result, the complexities of protein folding [152] structures are considered as completely separate from the sequence that created it, and so a full analysis of the entire process is not possible at this time. With this in mind, it was decided to examine the relation between nucleotide base sequences and the amino acid chains they code. This was of particular initial interest, in that the 64 different combinations possible from a 3 base four-digit code (4x4x4) are mapped to 19 amino acids (and a stop codon). With such redundancy present, this research sought to ascertain whether different codon combinations occurred in different sequences of the same protein- and if so why.

With the frame of reference for the data set defined, it was next considered how best to approach the analysis of such a data set using sonification. To this end, the combination of basslines and chord intervals was seen as an intuitive means of representing both sequence and product, as the relations between the two allow each to be analysed individually or collectively as required. This approach differed from previous work [128] that had merely assigned a single pitch to each amino acid, rather than considering more complex combinations of tones. It was felt that the use of chord intervals allowed far greater contrast to be created between amino acids than with a single tone.

The use of rhythmic parsing to sequence events was also of particular interest, as much existing work in sonification has not adequately considered this function. Although significant work has been performed [144] using rhythm within patterns (or events), it was felt that rhythm plays a far more fundamental role in musical structure than previous sonification research has investigated. Specific time intervals between events (2.4.3) do not allow for the flexibility of musical rhythms, which are tempo independent and more complex in structure. For this reason, it was intended to investigate the application of rhythm as a means of organisation within a sonification, in this case as a means of highlighting the structure of RNA sequence data.

A piece of software (DNASon) was developed that would allow RNA sequence sonification to be performed as required. After the software had been completed, it was intended to test the proposed sonification method, to assess its potential as an analysis technique. This testing would ideally highlight any potential (and drawbacks) of the RNA sonification method, thus allowing further redevelopment to follow. The development schedule was therefore defined:

1. Develop a method of RNA sequence sonification based on that of Nubuo and Munakata [127] and [128].
2. Develop and test an RNA sonification application based on this method.
3. Perform user testing of the method using the application.

4. Assess results of testing with a view to developing the method.

4.2. Sonification Method

The first stage of the case study was the design of a sonification method for DNA/RNA sequences. This method would have to take input RNA sequence data, manipulate it within the parameters of a sonification and then output the sonification in a suitable file format for listening.

4.2.1. File Formats

It was decided at an early stage that Standard MIDI Files (SMF) [153] would be the best means of output for the processed data sequences. MIDI files are useful due to both their compact nature and also their ubiquitous migration across all types of sound and music synthesis. Format1 SMF files [154] can contain up to 16 separate tracks, each of which can hold MIDI data that can then be sent to a required MIDI channel. Indeed, SMF1 is the preferred format of MIDI file for most musical purposes [155], due to its capability of carrying information for more than one synthesiser voice.

Having specified an output file format, the format of the input data sequences now had to be determined. There are two main file formats for DNA/RNA base sequences- GenBank (.ncbi) and FASTA (.fasta) [156]. The FASTA file format (Figure 4.1) is a fairly simple and widely used base sequence format, wherein a header line(s) signified by a delimiter (>) is followed by the base sequence on subsequent lines:

```
>Test fasta sequence
actagcgcgatatcctctcgagatatcgctagcgcgatatatagcatgcgctagatatcggcatgcac
gtac
```

Figure 4.1: Example of a nucleotide sequence in FASTA format

The obvious advantage of the FASTA format is its simplicity, in that it contains little other than nucleotide base sequence data, which can quickly be obtained using basic file parsing.

4.2.2. Nucleotide Base Definition

Previous work in DNA sonification [128] had assigned pitches to individual nucleotide bases, with an interval of a 5^{th} between each note. In the case of the

DNASon software it was decided that the four bases adenine, cytosine, guanine and thymine (Uracil in RNA) would also be assigned a predetermined note from a scale, in order that all output files would have some form of harmonic cohesion. Further, the nucleotide base sequence suggested a relation to the bassline of a musical pattern, in that a bass melody underpins the actual music being conveyed by delivering information about the harmonic nature of the entire piece. In a similar manner, it could be suggested that a base nucleotide sequence performs the same function-conveying information about the amino acids and proteins it codes for. For initial purposes, it was decided that the major scale was both easiest for the listener to recognise and easiest to define algorithmically, and that the four bases would be assigned the root, third, fifth and seventh of this scale (Figure 4.2).

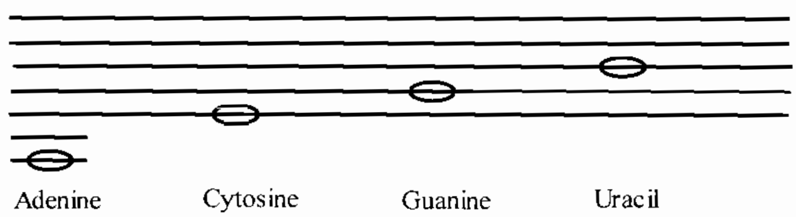


Figure 4.2: DNA base to musical pitch assignment

This choice of major intervals was reached in an effort to compliment the corresponding amino acid chords, without moving outside of a simple octave boundary. The octave is the most commonly regarded interval in music, and so was considered a good frame of reference for musician and non-musician alike. Pitches outside of a single octave on bass could prove distracting (3.7.5) in relation to the chords, and in certain circumstances could even directly conflict with the pitches in the chord intervals. The scale chosen by user would define the key of the entire sonification, with all elements being pitched according to the particular key of the scale selected.

4.2.3. Amino Acid Definition

The codons defined by the nucleotide base sequence were intended to be represented by chord intervals in the output sonification. By continuing the relation of base sequence to amino acid as being similar to that between bassline and chord sequence, it was intended to highlight the interaction and dependence of amino acids on the initial nucleotide combinations. In the output file, the amino acids corresponding to the input codons would be defined as chord intervals playing over a bassline consisting of the four major scale tones assigned to the nucleotide bases- in a key chosen by the user.

This definition of amino acids would require some form of user input, in that the intervals used to represent each amino acid would have to be defined in such a manner as to be meaningful to the listener. By giving the user a choice of 21 basic intervals (to correspond to each available amino acid and the final stop codon), it was intended to allow as much user control over the sonification as possible- while still remaining within the major scale framework. The available intervals were intended to be straightforward, and so were sequential in definition from 1st (root) and major 2nd, up to 1st and octave, then correspondingly from 3rd and 4th, to 3rd and major 7th and so on (Figure 4.3):

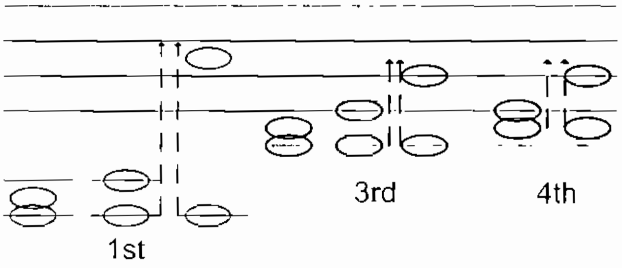


Figure 4.3: Interval choices from root C

Intervals of the 2nd and above are considered more difficult to interpret than those using the root [24], and so were omitted to avoid confusion among non musicians. Consequently, in order to obtain 21 distinct intervals (2.2.5), the intervals above the octave were used. These intervals also followed the same 1st to octave pattern as before, merely in a higher register. These intervals were specified for initial testing purposes, with a view to assessing the potential of bassline and chord interval sequence sonification. Further work could implement far richer chord intervals for allocation to amino acids once the viability of the method had been assessed.

4.2.4. Subdivision and Representation of Data through Rhythm

Any piece of music must have rhythmic segments or breaks in order that it can be better understood by the listener, rather than just a constant stream of notes without pause. In the sonification of data, rhythm is often overlooked as a very important and powerful part of the analysis process- often more so than the accompanying melody.

Also, rhythm is perhaps as great a source of variety as melody, yet it does not significantly alter the information being conveyed by pitch or contour [157]. A piece of music played slower (or in a different time signature) can often appear radically different without actually changing any of the data in that piece. Due to the three base grouping of a codon (Figure 4.4), it was initially decided that two time signatures should be available for user definition which would accurately reflect this grouping:

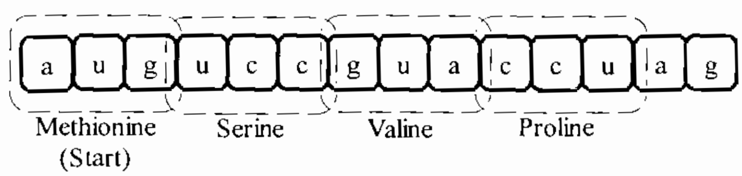


Figure 4.4: Codon groupings in nucleotide base sequence

3/4 time (Figure 4.5) was the most obvious time signature choice, in that it would allow for any group of bases and their associated amino acid to be represented as individual units within the rhythm of the overall piece:

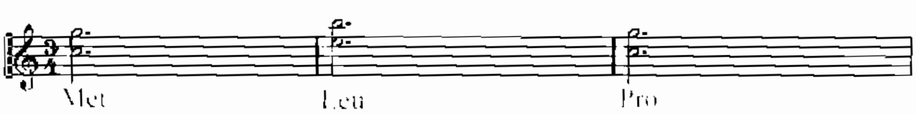


Figure 4.5: Amino acid representation of codons in 3/4 time

4/4 time (Figure 4.6) was also included, on the grounds that a three note crotchet group followed by a crotchet rest would also be a very good way of segmenting the data for analysis:

Figure 4.6: Nucleotide base representation of codons in 4/4 time

Although these two basic time signatures only scratch the surface of the information that a well rhythmically defined piece can potentially convey, it was felt that they were sufficient for initial testing purposes. Future development after initial testing (chapter 8) was intended to consider some of the different possibilities of tempo, signature and rhythm and their respective effects on a sonification, with a view to obtaining a more cohesive definition of how rhythm can best be employed in sonification.

4.3. Application Design

A software application was required to allow the sonification method to be properly implemented. The DNASon application was developed using the Visual Basic programming language. The front end user interface of the application was developed using Macromedia Flash (Figure 4.7).

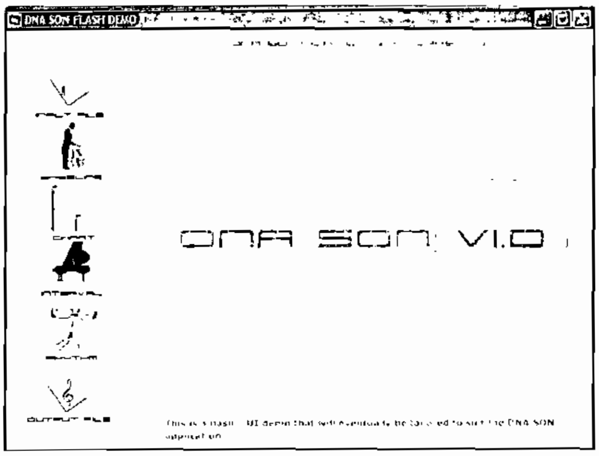


Figure 4.7: DNASon application front screen

Macromedia Flash [158] has provision to relay information obtained from user interaction to external targets via the FSCommand structure within its code. The FSCommand routines allow data to be sent from Flash to another application as required (and vice versa). Within this structure Visual Basic can be used as a backend [159] for a Flash GUI application, wherein the user interface is developed separately as one or more Flash movies that can then be launched within a Visual Basic application. The DNASon application allows the user to sonify an input nucleotide base sequence using a combination of musical notes and intervals to represent nucleotide bases and their associated amino acids. Each sonification can be parsed into one of two time signatures (3/4 and 4/4) as desired by the user. With a sonification method now implemented using the DNASon application, a set of tests were thus performed.

4.4. Experimental Design

4.4.1. Overview

The sonification method used by the DNASon software focused on the rendering of nucleotide bases as bass notes, with their associated amino acid codons represented by chord intervals. The output sonification was also parsed rhythmically, to help the listener group each codon combination within the overall sequence. In testing this method of sonification, the rhythmic parsing of a sequence was used as the basis of the test schedule. It was hoped that rhythmic parsing would allow the participants to compartmentalize the data more effectively and so achieve better results.

In evaluating the potential of a sonification method, it was also of interest to assess the effects of formal musical training on the ability to analyse a sonification. The overall goal of the testing was to ascertain whether effective RNA sonification could be achieved using the proposed method. If this was not the case, a combination of test observations and results would ideally indicate where best to improve the method.

4.4.2. Test Schedule

The test schedule (Table 4.1) sought to test participants about sonifications of various RNA test sequences, which had been intentionally created to contain specific features upon which a participant could be questioned. The schedule aimed to assess the effects of rhythmic parsing on RNA sonification, alongside a more general evaluation of the potential of the method itself.

Test Schedule	Session 1 (non-Rhythmic Tests)	Session 2 (3/4 Rhythm Template)	Session 3 (4/4 Rhythm Template)
Test 1	Point estimation	Point estimation	Point estimation
Test 2	Pattern matching	Pattern matching	Pattern matching
Test 3	Extended Pattern matching	Extended Pattern matching	Extended Pattern matching

Table 4.1: DNASon test schedule

The tests were conducted over 3 sessions, with the independent variable in each session being the rhythmic template used (no rhythm, 3/4 and 4/4 respectively). The dependent variables in each session were the number of amino acids and their combinations identified by the listener. As rhythm was the prime focus of the testing it was hoped to compare and contrast the results of two basic rhythm patterns with a non-rhythmical control set.

The 3/4 rhythmic pattern tests defined a grouping of 3 nucleotide bases (and their associated codon) per bar, in a time signature of 3/4. This would allow the participant to define each amino acid in turn by the rhythmic accent of the first beat of the bar. The 4/4 rhythmic pattern tests defined a grouping of 3 nucleotide bases (and their associated codon) with an additional crotchet rest per bar. In this case, the participant could define each amino acid and its associated nucleotide base sequence by the gaps in musical output created by each rest note. Each individual session was split into groups of questions based on the testing hypothesis.

4.4.3. Testing Hypothesis

In stating a hypothesis, the preferred procedure is the definition of the null hypothesis [160] (i.e. the existing condition that the testing seeks to challenge) as the basis of each set of tests. In considering each factor in this manner, a set of statements could thus be defined which would be the basis of analysis:

Hypothesis 1: Rhythmic parsing has no effect on point estimation. In considering this hypothesis the variance between non-rhythmic (session 1) and rhythmic (sessions 2 and 3) conditions must be determined. The first test of each session must be analysed to compare the control group (non-rhythm) to 3/4 and 4/4 rhythmic parsing patterns.

Hypothesis 2: Rhythmic parsing has no effect on pattern matching. This hypothesis will examine the variance between the second and third tests of each session. Again, the aim is to compare the variance between the non-rhythmic control group and the 3/4 and 4/4 rhythmic parsing patterns to assess the effect on pattern matching.

Hypothesis 3: Musicianship has no effect on sonification. This hypothesis seeks to consider whether the musical experience and qualifications of the participants have any bearing on their ability to use sonification. In this instance, the hypothesis must be considered relative to the results of hypothesis 1 and 2, so that any significant results obtained can be evaluated in terms of musicianship.

A set of questions was now developed for each of the testing hypothesis, to allow analysis of each factor separately within the results.

4.4.4. Point Estimation Test Questions

In the point estimation group a total of six, two-part questions (Appendix 1) were asked relating to the occurrence of specific amino acids in a nucleotide base sequence (of length 20 amino acids, less start and stop codons). In all questions, the first part asked whether the specified amino acid occurred in the sequence (Figure 4.8).

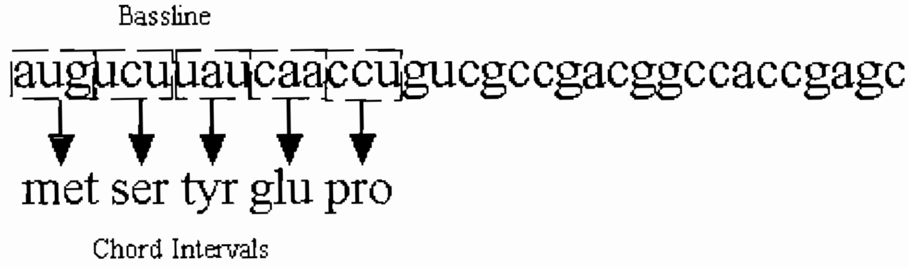


Figure 4.8: Excerpt from point estimation test sequence (session1freq.fasta in Appendix 2)

If the subject felt that the particular amino acid did occur at some point during the sonification, then they were asked to give the number of occurrences as the answer to part two of the first four questions. The marking scheme for these questions was 2 marks each (4 marks total), with a correct definition of an occurrence yielding two marks and a following two for the correct number of occurrences. Participants who were inaccurate were awarded one mark if they were within one amino acid of the correct tally, otherwise no score was given.

Questions five and six again concerned the occurrence of a specific amino acid, but in these cases the underlying codon combination was also studied. An amino acid can often be coded from different combinations and so the particular codon responsible is of great interest to geneticists, often when considering the evolution of a species and its particular codon/amino patterns. The second part of questions 5 and 6 asked whether a particular codon was always used for a specific amino acid (yes/no answer). In these questions the second part was scored as 1 mark for a correct yes or no, on the grounds that no specific information about the codon(s) involved was required.

4.4.5. Pattern Matching Test Questions

The second set of three questions (Appendix 1) in each session focused on the ability of participants to discern combinations of amino acids within a sequence of 20 codons (again discounting start and stop codons). For each question, the subject was required to indicate whether a specific 2 amino acid combination occurred in the sequence (2 marks) and subsequently how many times the combination was detected (2 marks).

As before, inaccurate answers were awarded half marks for the second part of the question if the value was within one amino acid of the correct count (and none if a greater disparity was observed). The detection of 2 amino acids in combination was regarded as the first step towards advanced pattern matching within a nucleotide base sequence (Figure 4.9).

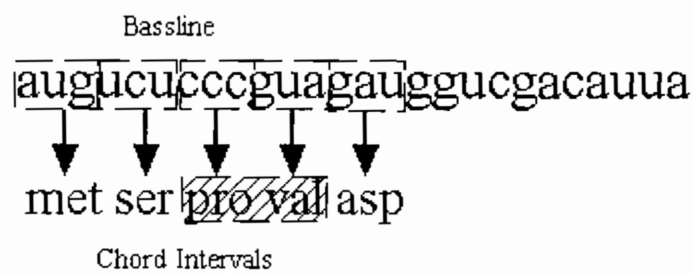


Figure 4.9: Excerpt from pattern matching test sequence (session1combi1.fasta in Appendix 2)

In considering the potential of DNA and RNA sonification the ability to accurately define point estimations is of relatively little use, unless it is as a means of assessing particular amino acid sequences or groupings. The potential for mutation due to a single base change in a sequence means that certain combinations of amino acids can produce radically differing polypeptide chains from others. In detecting a particular combination the potential exists to discriminate between the correct combination and a mutated derivative, and thus detect errors in a nucleotide sequence.

4.4.6. Extended Pattern Matching Test Questions

The third set of three questions (Appendix 1) in each session sought to develop the potential for pattern matching of amino acids by extending the patterns to 3 amino acid combinations. In this case the relevant sequence file contained a nucleotide base sequence of 30 codons (less start and stop codons) in order to adequately accommodate the larger combinations. As with all of the tests, the first part of each question asked whether a particular 3 amino acid combination was present in the relevant sequence file (2 marks). If the subject detected the relevant combination they were then required to define how often the combination occurred within the sonification of the sequence (2 marks).

In this manner a gradual increase in amino acid pattern combinations was introduced to each subject in an effort to define what level of pattern matching could be performed with relatively short exposure to the method. If a significant number of participants could define the patterns then it would suggest that further training would enable participants to detect more complicated sequences of amino acids.

4.4.7. Test Groupings

Each subject was first asked to complete a brief questionnaire (Appendix 3) of 10 questions concerning their musical experience, qualification and preferences prior to testing, with a view to splitting the participants into two groups based on musicianship. This grouping was required to assess the validity of hypothesis 3 in regard to DNA/RNA sequence sonification. A total of 20 students were selected from various courses (both undergraduate and postgraduate), with 10 being deliberately selected from the BMus music course as the musicians grouping. The questionnaire was used to confirm that each student was indeed of one or other group, rather than discounting the obvious possibility of a qualified musician studying a non-musical discipline. The questionnaire contained several questions specific to a musical education (questions 5 through 7), and these questions were used to determine whether a subject would be placed in the musicians group (or not). The participants were initially selected on the basis of musicianship and musical knowledge, based on the results (Appendix 3) of questions 5 through 7 (Figure 4.10) in the questionnaire.

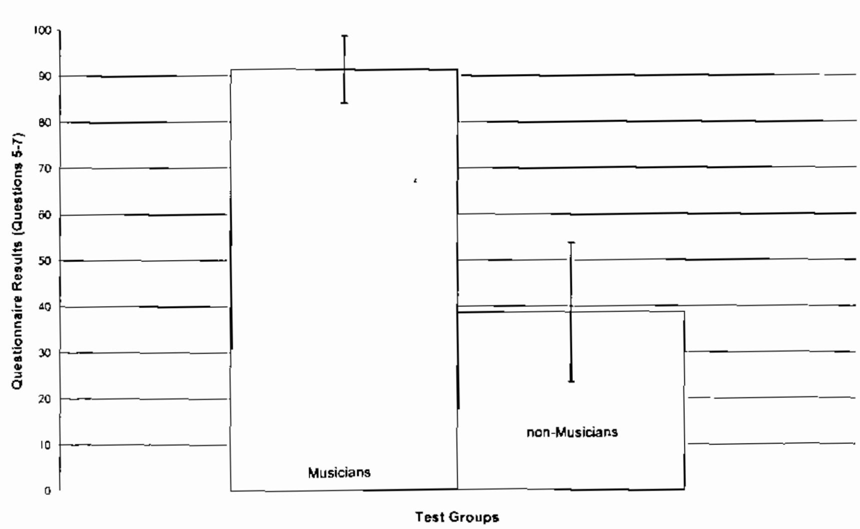


Figure 4.10: Graph showing average percentage results of musical knowledge questionnaire (questions 5-7), showing standard deviations

These results suggested that the overall scores for the predefined musician group were higher than those in the non-musician group, with the average for musicians being 91.33% compared to 38.67% for the non-musicians.

4.4.8. Training

A brief overview of the basic principles of DNA/RNA nucleotide sequences had been emailed to each subject a week before testing began, to allow them time to familiarize themselves with the principles involved. In several cases participants requested additional material and also expressed confusion with regards to the sonification of nucleotide sequences. For this reason, a similar document on the basic principles of sonification (as it related to the DNASon software) was also prepared and sent to each subject. These documents were intended to give the participants a basic knowledge of what was required of them during the tests, alongside providing an introduction to the method of RNA sonification.

All participants were also given a further tutorial (Appendix 5) on the concepts involved in testing after they had completed the questionnaire. The tutorial covered the basic principles of DNA/RNA nucleotide sequences and the relationship between bases and amino acids. The tutorial then explained the concept of sonification as it related to DNA/RNA sequences, detailing the method by which nucleotide bases and amino acids would be sonified during testing. Participants were then allowed time to ask any questions. Although no data was collated to confirm a trend, several participants found either DNA/RNA sequences or sonification to be confusing. This was a factor which had to be given thorough consideration when analysing the results of the test schedule, particularly in relation to (3.8.3).

4.5. Results

The test schedule was designed to assess the effects of rhythmic parsing and musical education on point estimation and pattern matching tasks. 3 test sessions were performed, with the results (Appendix 4) subsequently analysed in terms of musicianship and performance. Overall results (Figure 4.11) showed an increase from 52.17% in the control condition to 56.41% in the 3/4 and 55.43% rhythmic parsing conditions respectively.

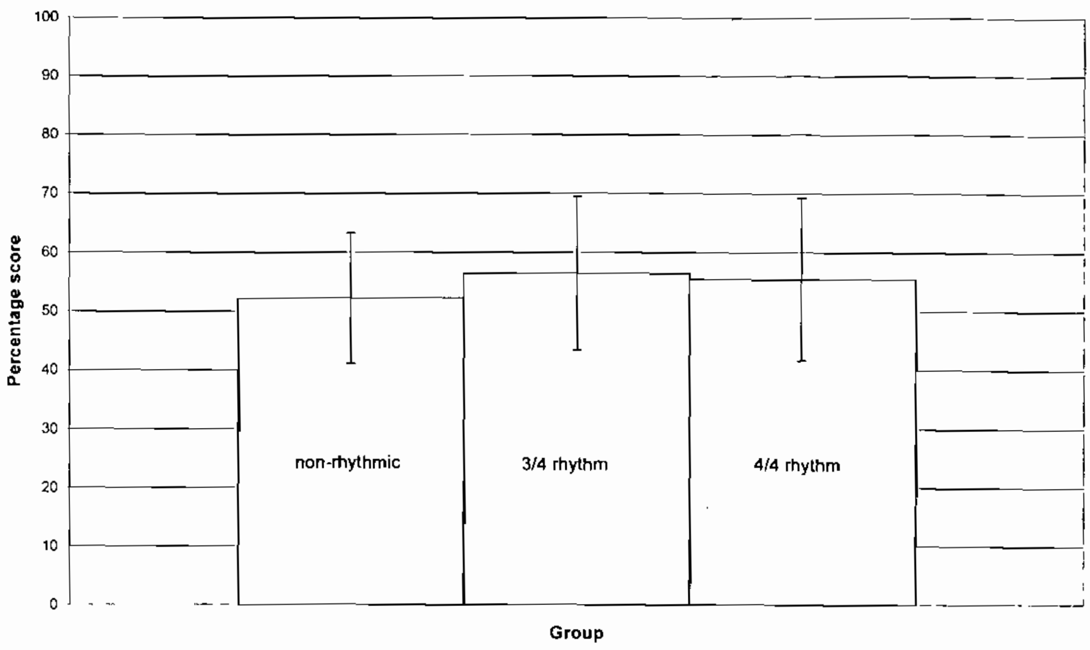


Figure 4.11: Graph showing overall average pereentage scores (by test condition), showing standard deviations

A 2-way between subjects Anova [162] was performed on all overall results, with session number and musicianship being the relevant factors. The results showed no significant difference between performance in each session due to either musicianship ($F(1,30)=1.663$, $p= 0.202$) or rhythmic parsing ($F(2,20) = 0.583$, $p= 0.562$). Because of these results all testing hypothesis were rejected. The DNASon testing had shown that many aspects of the sonification method required improvement, and these improvements were seen as the basis of further work undertaken during this thesis.

4.6. Discussion

4.6.1. Data Set Considerations

Many participants found difficulties in the complexities of DNA/RNA nucleotide sequence data- as previously mentioned in (4.4.8). It had been incorrectly assumed prior to testing that the basic principles of genetics could be understood after exposure to tutorial material and training. It was found during testing that many participants were still unfamiliar with the relation between nucleotide bases and amino acids, and thus were often more comfortable thinking of the data as a sequence of letters rather than a genetic code. This factor had not been given significant enough consideration when designing the experiment, and proved to be a problem during testing. Another set of tests was considered using geneticists to overcome the problems of understanding the data, but aspects of the testing had suggested other issues which would require consideration before such tests could be carried out.

The genetic data used (although synthetic for testing purposes) did not contain anything more than basic sequence information, and so the amount of useful data the sonification could hope to convey was limited. One misconception during experimental design was the relation between sequence and protein [124], which had been the initial aim of the method. Rhythmic parsing had been intended as a means of conveying the protein structure of a translated sequence, but the current absence of any such data [152] precluded its study. GenBank format data was again considered due to its more verbose content, but as mentioned other issues during testing suggested a different direction for future work.

It was found that effective RNA sonification was not realisable using the current sonification method. Complexities in training had largely precluded any effective assessment of the method itself, which was also not considered robust enough for application to a data set such as DNA/RNA nucleotide sequences. It had been shown in testing that a method for sonification would have to be developed prior to its application, particularly in relation to complex and exotic data sets. For this reason, future work would have to utilise far simpler data in assessment of a method. If this method could be shown as effective with straightforward data, it could then be assessed with more complex information.

4.7. Sonification Method Issues

The method used in testing was an extension of the work of Nubuo and Munakata [128], with the addition of intervals rather than single notes for amino acids. This method was considered difficult by many participants, who often complained they could not distinguish between intervals with any great accuracy. Future work would have to provide a more effective method of conveying information, utilising the higher level cognitive features [51] required in audio pattern matching.

Several participants had found the underlying nucleotide bass notes to be difficult to determine. As with the intervals, it was believed this was due to lack of information in the musical patterns used. It was realised that future work would have to utilise more verbose musical structures if effective communication was to be achieved. Many participants did not express any particular preference for one interval over another, and this was believed to be due to the sparseness of the intervals used.

This was in keeping with existing work [144] using static time intervals, but did not give any indication as to whether musical intervals were more effective. A lack of significant difference between the two rhythmic parsing conditions (3/4 and 4/4) suggested that no real claim could be made to the effectiveness of such parsing. Part of the reason for this may have been due to framing errors in the parsing of the data, where amino acid combinations were broken by rest notes. This had not been considered prior to testing, and so no effective data could be produced to show whether this was the case for accented rhythmic structures also.

4.7.1. Testing Method Considerations

The testing method used had not given due consideration to the data set being used, and so had not made adequate provision for its explanation. It had been incorrectly assumed that the technique itself would be better understood by users, and thus testing was slowed by explanations and discussions that had not been foreseen during development. Tutorial information had not been sufficient to overcome the apprehensions of some participants, who remained unconvinced about sonification after testing. Post session Task Load Index (TLX) tests [164] would have provided more information on the opinions of participants, and their lack of inclusion prevented proper assessment of the impact of the method. Future testing would have to consider the effects of the method used alongside the results it could produce, in order that a more effective evaluation could be performed.

4.8. Conclusions

DNA and RNA are a rich and fascinating source of data for any form of analysis, but the challenges they place upon any framework for such often outweigh the initial benefits. Even the smallest bacterial sequence runs into many thousands of bases (kilo-base pairs, kbp) and so choosing a region for analysis is an analysis in itself. Also, the level of knowledge required by the user can often preclude meaningful assessment of their performance in sonification. This factor is considered as part of the reason for the low test scores encountered, as much a reason as reticence by test participants to consider the possibilities of sonification itself.

The complexity of DNA and RNA sequences proved too large an area of research within which to develop a new sonification method. It was considered far more prudent to develop the method itself in isolation and then apply it to complex data sets such as DNA. It was hoped that by considering more straightforward data sources a better understanding of the mechanisms of sonification could be achieved. In this way such understanding could be used to construct a better sonification template for DNA and RNA sequences, rather than attempting to accomplish both at once.

The use of rhythmic parsing in testing had not fully assessed its potential. The lack of significant differences between the parsing templates suggested that neither could be considered effective in isolation, and so further work was required. It was decided that a set of tests would have to be developed (chapter 8) to examine rhythmic parsing in isolation with respect to RQ 1. It was also noted that as rhythmic parsing is used to group events in a sonification, the events themselves must first be considered.

The mappings used by the method had proven ineffective for most participants, who had often found it difficult to distinguish between them. It was realised that a comprehensive investigation into the effectiveness of patterns was required as defined in RQ 2 and RQ 3, patterns that could subsequently be used in sonification. If robust patterns could be developed, then they could feasibly be used in the representation of different forms of information of varying complexity (including DNA/RNA). For this reason, a thorough investigation into the design of effective and memorable musical patterns (chapter 5) for use in sonification was undertaken.

5. Low Level Pattern Design

5.1. Introduction

The DNASon case study had shown that robust musical pattern design was crucial to effective sonification of data or information. An effective sonification method would have to be developed before complex data sets such as DNA/RNA could be considered (4.6.1). Several other suggestions were considered, notably for the use of simple, easily understandable data during sonification testing. If users did not have to devote significant amounts of time to comprehending the data used, the patterns which represented that data could be assessed more effectively. The framework used in the DNASon development had also indicated that there was potential for multiple streams of data to be conveyed by sonification (nucleotide bases and amino acids), and this had to be considered more fully. As a result, a pattern design process was undertaken based on the third and fourth research questions of this thesis:

> RQ 2. Do present methods of pattern design (notably earcon design guidelines) produce patterns which are not only distinct but also memorable?
> RQ 3. Can present methods of pattern design be used to efficiently render concurrent streams of data?

In this chapter a set of reference patterns were created based on earcon design guidelines (3.7.5). Although these patterns were not earcons (as they did not convey any specific information), the means by which such patterns may be made distinct were considered a starting point for further development. By using low level patterns as a reference, further work could compare the effects of higher level auditory attributes on pattern recognition (chapter 6). A set of tests were carried out using the TrioSon software, which was developed for pattern sonification. These tests formed part of the design process for future patterns, and so were used to highlight areas of performance in which they could be improved.

5.2. Initial sonification Method

The process of pattern design sought to investigate the use of higher level cognitive features (notably melodic contour) as a means of improving recognition [58] and pattern recall. The first stage in this process was the creation of patterns using existing earcon design guidelines as a frame of reference for further work. Although the patterns created using these methods were not earcons themselves, the justification for their design was to highlight what information a listener could extract from lower level audio attributes. If a user could distinguish between such patterns effectively, then the process by which hierarchical information is built into patterns such as earcons would have a sound cognitive basis. It is the contention of this research that a detectable pattern may not necessarily be memorable (2.3.2), and that this can be a potential stumbling block in its implementation.

5.2.1. Musical Orchestration and Concurrent Auditory Display

Existing work [100, 110, 111] has considered the use of concurrent patterns in auditory display, but little consideration has been given to the use of standard musical arrangement techniques in such forms of display. Work with DNASon had suggested that multiple streams of data could be conveyed using standard musical arrangements of bass lines and chord intervals, and it was desired to explore this further. The common musical trio [165] (bass, chord and melody instruments) can take many forms and in many styles, but the basic capability of such an orchestration to convey complex musical information is well known. With only 3 sources, a huge wealth of melodic and harmonic combinations can be produced that far outweigh that which could conceivably be produced by one or two instruments (in similar context). In this manner, the trio format affords the potential for large amounts of information to be conveyed in a format that is familiar to most listeners.

The aim of sonification is to convey information, and the means of this conveyance should be as transparent as possible to all users. In considering a basic trio format for sonification, it was intended that such a format would be familiar to most users-regardless of musical background or preference. The interactions between bass, chord and melody (in most compositions) are one of the most fundamental (and indeed flexible) aspects of composition and performance. Listeners will often indicate their recognition of a piece of music by the isolation of a particular musical element within it (such as a bass line or melody), while still maintaining an overall grasp of the entire piece as a whole. In this manner, the hierarchical nature of music is definable by both musicians and non-musicians alike.

Hence, one of the goals of the development and testing was to explore the possibilities that a trio framework could provide to sonification [185, 186]. Of particular interest was how accurately multiple data streams could be conveyed, alongside determining the accuracy of comparisons performed between said streams. If different data parameters could be accurately rendered by index for the purposes of analysis and comparison, a robust framework for data sonification could be achieved.

5.2.2. Scales, Modality and Instrumentation

It was intended to assess the potential of different musical patterns and chords- and their subsequent interplay. Western music theory [22] allows for vast combinations of scales and chords, even within the basic major and minor scale formats. It was of interest to examine the effects of scales and modality [166] within sonification, as a means of conveying more information within a smaller number of melodic patterns. The patterns of bass and melody were also of interest as separate entities, the reasoning being that what can be considered a good bass linc would not necessarily be a good melody (or vice versa). Existing principles in earcon design (3.7.5) would be used as an initial guidelines for pattern design. Although the patterns involved would not be earcons, the specifications for the design of earcons (such as use of pitch, rhythm and timbre) can be seen to apply to musical patterns in general.

Instrumentation and timbre were also of interest, particularly with regard to the production of a useable sonification application that would be of benefit to users. General MIDI synthesised tones are useful for testing purposes, but ideally any final application would consider the use of better synthesis methods. An analogy can be drawn with the visual graph, and the many software applications that offer means of making such graphs and charts as aesthetically pleasing as possible. Although not as directly quantifiable a factor, the aesthetic design of available instruments and timbres was thought worthy of due consideration.

5.2.3. Initial Rhythm Design Considerations

Rhythm is considered to be an important factor [167] in audio pattern recognition. Various studies [168] have shown that the rhythm of a pattern (or the absence of) is crucial to its differentiation by listeners. To this end, the guidelines suggested for earcons stipulate that the rhythms used to define patterns should be as different as possible. The different rhythmic aspects of a pattern are what make it unique to a listener, often to a greater degree than any other single factor of that pattern. Initial conditions specified 4-note bass patterns and 8-note melodic patterns (Figure 5.1), with each pattern lasting for one minim (maximum).

Figure 5.1: Initial rhythm design template for bass and melody patterns

Within this 4 and 8 note template, each pattern was given a minimum resolution of a quaver for bass patterns and semiquavers for the melody. The time signature used was initially specified as 4/4 in order to best compliment the length of patterns involved. As the most common time signature in music, 4/4 was considered to be the most familiar to all users.

It was felt that the bass patterns should not be as complex as their melodic counterparts, in order to prevent the sonification from becoming too complex and cluttered. This was a facet of design that could only be fully considered and evaluated as a result of testing. The DNASon testing did not have the scope to consider the additional melodic components of a trio arrangement. For this reason, the results of user testing would be used as an indicator to future development. Having defined the rhythmic pattern template, different combinations of rhythms could now be tested to assess what were the most beneficial for recognition.

5.2.4. Initial Pitch and Register Design Considerations

The musical pitches used in a particular pattern are crucial to defining its unique tonal character, and at a higher level specify the scales and modes which are the aesthetic basis of most traditional music compositions. For initial testing purposes, it was decided to group each of the three instrument pattern sets into major, minor and chromatic families. The guidelines for earcon design stipulate that the register (octave) of a pattern is not a robust means of differentiation. In this sonification template, the interval gaps of more than one octave between bass, chord and melody patterns were considered sufficient (in conjunction with other factors) to allow segregation. Having said this, some freedom within a range of pitches would also have to be considered in order to provide an adaptable framework.

It was decided that for initial purposes the bass patterns would reside in and around the C0 to C1 octave range, allowing a broad gap between bass patterns and chord intervals (ranging from C2 to C4). Melodic patterns would be allocated the range around C4 to C5, allowing the purpose of register to be fully considered during testing. It must be noted that earcon design guidelines offer suggestions on the use of register rather than its effect. For this reason, it was felt prudent to test the patterns within these ranges, before considering amendment. The combinations of patterns of differing scales would only be fully effective if they could be pitched in different keys, allowing the modality of different chord and scale relationships to be examined. Thus, it was decided to allow the user to specify the key of each individual bass, chord and melodic pattern as required. An example would be the combination of a D minor bass pattern with a D minor chord and a C major melody (Figure 5.2), wherein the melody pattern would be regarded as a D Dorian [169] mode pattern.

Figure 5.2: Example of D minor bass and chord with D Dorian melody

These groupings were intended to give the user as much scope as possible when allocating patterns for sonification. It was desired to assess the potential benefits of modality in pattern matching, particularly as a means of augmenting the use of pitch in pattern design.

5.2.5. Implementation of Timbre in Mapping Schemes

As stated in 2.2.6, there is often a lack of adequate distinction between GM sounds on budget soundcards. With so little variety often available, testing using GM synthesis would ideally allow the patterns used to be assessed without the presence of significant tone colours. This was considered important to the success of musically designed patterns, allowing their assessment without significant use of other factors. If users could distinguish between patterns rendered using limited timbres, then those patterns could be considered valid in their own right.

5.2.6. Volume and Panning Considerations

The other important principle of earcon design is that of spatialisation [100]. By using stereo positioning of different sound streams, the user can be given as much audio information as possible when required to discern between said streams. In the case of the current sonification template, the panning of each of the three different instruments (bass, chord and melody) was considered essential to pattern recognition.

It was decided that users would be allowed to pan each instrument as they wished (or not at all). In this manner, it was hoped that by directly involving the user in the spatialisation process a more effective recognition of stereo location could take place. Users would be provided with a choice of speakers or headphones as desired, with the speakers involved being placed at an angle of at least 45° from the position of the listener. This was intended to cater both for individual preference and also for users with differing hearing characteristics (such as partial deafness), who although not able to work with stereo headphones would still benefit from the stereo location of sounds.

Each pattern (in a concurrent display) would require volume control, as a means of allowing the user to obtain an overall balance with which they were comfortable. Earcon design guidelines suggest that volume imbalance (either relative or overall) is the main source of potential annoyance for the listener. It was again intended to consider users with hearing problems, by allowing them to balance the instruments as they required for adequate perception. If a reasonable framework for sonification is to be achieved, it must take into account the less than ideal hearing response [170] of many potential users.

5.3. Trio Pattern Design

The sonification method used in testing was based on the instrumental trio of bass, chords and melody (5.2.1). This method was considered as a means of rendering concurrent music patterns in a format familiar to most listeners [165].

5.3.1. Initial Bass Pattern Design

As previously mentioned (Figure 5.1) the bass pattern template consisted of a maximum of four notes, within the time interval of a minim. A total of 48 bass patterns were created in 3 different families (major, minor and chromatic), in groups of 16 patterns for each family. The bass patterns were required to be rhythmically disparate, of differing pitch combinations and also suggest the scale they represented. The patterns created were intended to examine what factors would be more important to sonification, particularly in combination with the other instruments.

Various patterns had similar rhythms, pitches or overall contour, but not in combination. It was desired to investigate whether 2 patterns with similar rhythms or pitches would still be perceived as different by users-and whether sufficiently to consider them distinct. The effect of scale was also of interest as a means of differentiation, particularly between major and minor patterns. Although the difference between major and minor is considered one of the most common (and obvious) in most forms of western music, there is only 1 semitone of a difference between both scales (b3rd in the minor). It remained to be seen whether a listener would accurately judge between the two, particularly in cases where other more important cues (such as rhythm and timbre) were not present.

5.3.2. Initial Chord Construction

The implementation of major intervals in the DNASon software was now extended to more complex chords. One of the main suggestions from users had been the inclusion of better (i.e. richer) intervals than the 2 note combinations used in DNASon testing. For the current framework, a far more comprehensive selection of chords was given to the user for investigation. It was intended to assess the potential of different chord families and inversions from those families (within the register defined in 5.2.4), alongside progressions that could be created from various chord groupings.

For the intervals that would be used in testing, the use of 7th chords was considered a good basis of construction. It was felt that more extended intervals (such 9th, 11th and 13th chords), were not significantly different from basic major and minor inversions to warrant inclusion. Ad-hoc auditioning[1] of different chord families and progressions had shown that non-musicians did not reliably detect extensions above the octave, particularly when the chord was part of an overall progression. For this reason, the addition of a 7th (major, minor or dominant) was considered sufficient difference within the basic context of major and minor chord families.

The initial chord patterns were grouped by scale type (Figure 5.3 and Figure 5.5) and inversion (Figure 5.4), within the major and minor families. Unlike the 48 bass and melody patterns, 32 chord patterns (16 major, 16 minor) were made available to the user for testing purposes. In the major family, the chords were grouped by major, major 7th, dominant 7th and suspended 4th.

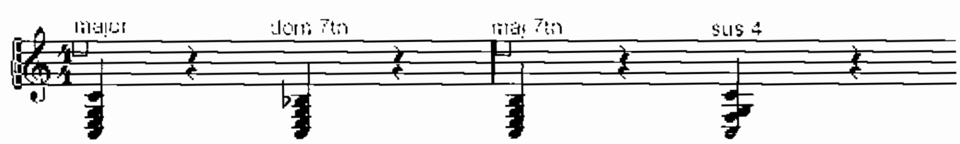


Figure 5.3: Major chord types (same inversion)

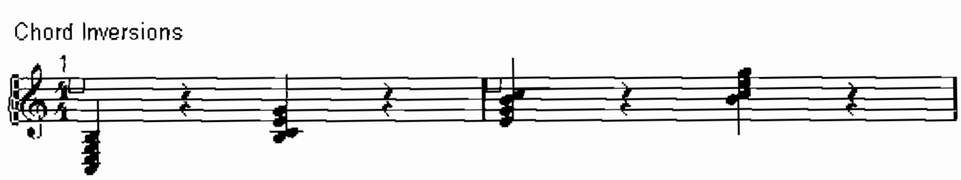


Figure 5.4: Example chord inversions (major chord family)

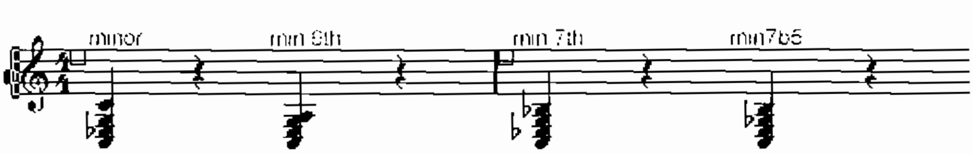


Figure 5.5: Minor chord types (same inversion)

In the minor, the groupings concerned were minor, minor 6th, minor 7th and minor 7b5 chords. It was felt that these groupings would provide enough harmonic variety for

[1] *No significant data was collated as a result of these auditions, instead they were used as part of the initial development process in an attempt to narrow the scope of the work undertaken.*

testing purposes. As with the bass and melody patterns, each individual chord could be assigned its own root note. It was intended to investigate the chord progressions that could be defined in this manner during testing, ideally as a means of providing harmonic structure to the entire sonification.

5.3.3. Initial Melody Pattern Considerations

The melody pattern template consisted of a maximum of 8 notes per pattern (5.2.3) within the time interval of a minim. As with the bass patterns, a total of 48 patterns were again created in groups of 16 patterns for each family (major, minor and chromatic). Each pattern was ideally required to be rhythmically disparate, of differing pitch combination and indicative of the scale family they belonged to. It was of interest to observe whether either the melody or bass patterns were more effective in sonification. If either type displayed dominance, it would hopefully provide suggestions as to why the other was lacking.

5.4. Application Design

To facilitate effective testing, an application called TrioSon [187] was developed. The requirements that the software had to fulfil were as follows:

1. Develop a sonification application for 3 instruments (TrioSon).
2. Implement a method to input a CSV data file for use in the sonification.
3. Implement a method of defining musical patterns to be used by the code.
4. Implement a method of specifying rhythmic patterns within the code.
5. Implement a method of allocating patterns and their parameters to the input data.
6. Implement a method of configuring the synthesised output of the code.
7. Implement a method of rendering a MIDI file of the sonification information for playback.
8. Implement a method of outputting a MIDI file containing the relevant information.

These requirements specified the basic aims the software had to achieve in order to be ready for testing. It was intended to reconfigure the application during testing as the pattern design stage progressed.

5.4.1. File Input and Output

The first area of focus was the input and output of sonification data in the relevant format. The DNASon testing had suggested that more straightforward data sets than DNA or RNA could be usefully employed, as a means of assessing the capabilities of sonification more thoroughly. The use of less complex data would allow a framework for sonification to be more adequately considered in isolation. The results of such observation could subsequently be used to create a better sonification framework, which could then be applied to more complex data sets such as DNA or RNA sequences.

One of the most commonly used sources of data is that produced by consumer survey, where individuals are asked to define their favourite style of music, film, literature or specify their favourite food, drink and so forth. This type of data has the advantage of being easy for any user to understand and hence relate to (most people will express some form of preference in such questions). For this reason, a series of small data sets concerning such parameters were constructed to be used in testing. Each data set was given specific numbers of different variables for each parameter, in order that frequency and combination questions could be developed about each set. The data sets were held in files of Comma Separated Value [172] (CSV) format (Figure 5.6):

```
Index,Parameter 1,Parameter 2
1,variable,variable
2,variable,variable
3,variable,variable
```

Figure 5.6: Typical format of a standard comma separated value (CSV) file

The CSV format was chosen due to its inherent simplicity, a standard file contains one row of header information followed by data on every subsequent row. Within this format, any spreadsheet data could be used as required. The CSV format is a popular choice in simple spreadsheet and database applications (largely due to its simplicity), and so was considered the ideal file format for sonification purposes.

In each file used, a specific variable (such as Colour, Food, Drink, Film etc.) would contain up to 4 values relating to that variable (such as Blue, Green, Yellow or Red for the variable Colour). Each file contained 10 data entries, allowing value frequency (e.g. how many people chose Rock Music) and combination (e.g. how many people chose Italian food and Coffee) questions to be asked about a specific file.

The header information (denoting the name of each parameter in the data set) had to be stored as mapping parameters (Figure 5.7), to allow each parameter to be allocated by the user at run-time. Each column of the data had to be parsed and stored in a multi-dimensional array as individual strings, again to be made available as mapping parameters.

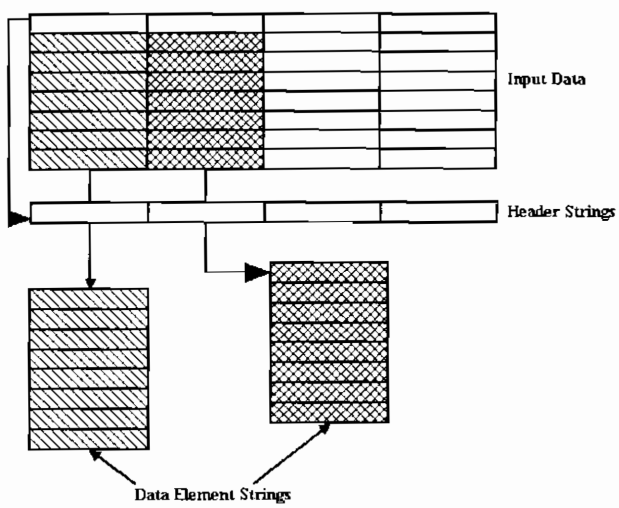


Figure 5.7: Operational diagram of input file parsing functions

With the input file parsed into header and data strings, each variable could be displayed by the GUI (Figure 5.8) for allocation to an instrument (bass, chords or melody). The GUI was configured for drag and drop of each header label onto an instrument target label, with the index for the sonification also available.

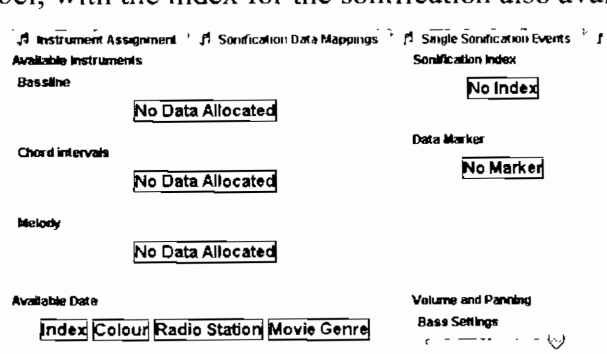


Figure 5.8: TrioSon screen for drag and drop header assignment

The index can be regarded as the delimiter (Figure 5.9) which defines the separation of each set of values over time, allowing each set of sonification patterns to represent a specific set of data values.

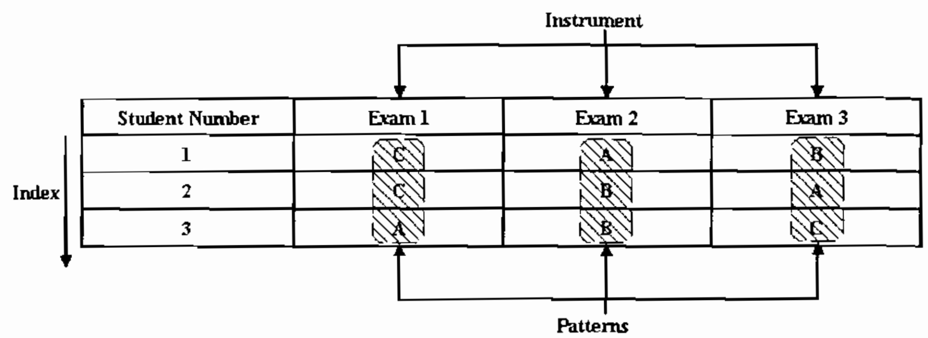


Figure 5.9: Example mapping scheme for sonification of fictitious student results dataset

In this manner, the subsequent rhythmic parsing of the sonification can be used to separate each set of values by index as required by the user. This method of allocation required that each index (i.e. each set of values) in the data set be listed under its own column heading, a heading that could be listed for assignment in the GUI.

5.4.2. Pattern Storage

The application was required to have provision for bass and melody patterns, as well as chord intervals. In considering the standard java MIDI classes contained within the java sound API [173] (Application Programmer Interface), it was found that the MIDI output functions were designed to take data of MIDI format (such as note numbers and message codes) without additional conversion. Thus, the application data model could be filled with the relevant patterns and chord intervals in a numerical format (Figure 5.10) for storage and rendering:

```
mValues[1][1]=0;mValues[1][2]=dsq;mValues[1][3]=sq;mValues[1][4]=2*sq;// start times
mValues[1][5]=3*sq;mValues[1][6]=0;mValues[1][7]=0;mValues[1][8]=0;//1-8
mValues[1][9]=dsq;mValues[1][10]=dsq;mValues[1][11]=sq;mValues[1][12]=dsq;// durations
mValues[1][13]=sq;mValues[1][14]=0;mValues[1][15]=0;mValues[1][16]=0;
mValues[1][17]=88;mValues[1][18]=84;mValues[1][19]=83;mValues[1][20]=77;// notes
mValues[1][21]=72;mValues[1][22]=R;mValues[1][23]=R;mValues[1][24]=R;
```

Figure 5.10: Sample melody pattern array in TrioSon data model

This allowed the development of the code to be kept separate from the pattern design work, enabling patterns to be composed externally using a standard MIDI sequencer and controller. Working externally on the patterns provided many opportunities to test various patterns and chords, without having to wait for the TrioSon development to finish. As a result, the pattern design stage was afforded a far greater focus than it had been in the DNASon development.

5.4.3. Instrumentation, Volume and Panning Configuration

Each instrument used in the sonification would require a General MIDI patch to be assigned to it, in order that a useable sonification could be produced. It was intended to include provision for external MIDI devices (such as Samplers and Synthesiser Modules) at a later stage, but for initial purposes it was felt sufficient to provide General MIDI timbres (Figure 5.11) via the onboard soundcard of the relevant machine.

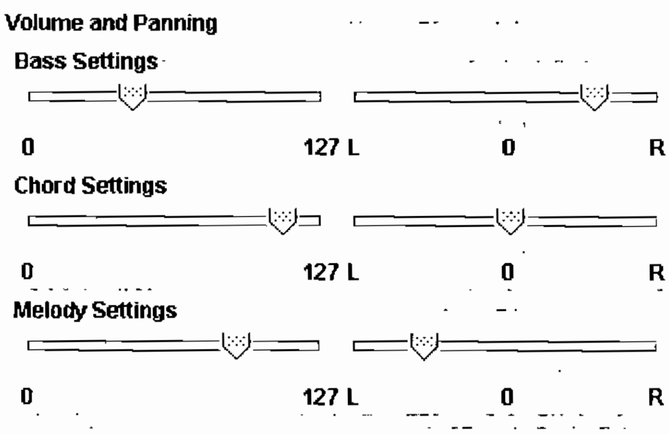


Figure 5.11: TrioSon instrumentation, volume and panning settings

The individual volume and panning settings for each instrument were also made available to the user. Spatialisation is considered an important part of the human hearing mechanism, and experiments [174] on its effect have shown it to be a very important element in pattern recognition. The guidelines specified for earcon design [145] also suggest that volume is an important factor in inhibiting perception or masking tones. For this reason, it was felt important to allow the user to set relative volume levels for each instrument that they were comfortable with.

5.4.4. Pattern Mappings

Once the instruments and index had been assigned, the individual bass, chord and melody patterns could now be assigned. For initial purposes, the user was given the choice (Figure 5.12) of 48 major, minor and chromatic patterns (in groups of 16) and 32 chord major and minor chord intervals (again in 2 groups of 16).

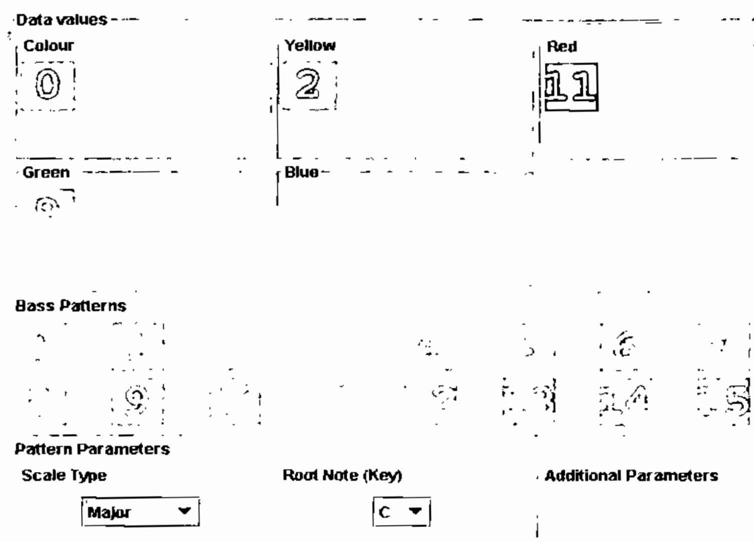


Figure 5.12: TrioSon screen for drag and drop pattern mappings

It was intended to give the user as much control over the parameters of each available pattern, in order that the choices they made could be observed during testing. To this end, each available pattern could be individually pitched in any key from C to the B below the next octave.

By changing the key of the pattern, it was hoped that the potential of different major and minor modes could be assessed in the sonification. As with the DNASon software, both pattern icons and drop target icons would play their relevant pattern (or chord) when clicked. This element of functionality was deemed essential to the user making informed choices about patterns, particularly when patterns in different keys were chosen for comparison. When each icon was dropped on a target representing a data value, the data model was updated with both the index and pitch of that pattern. In this manner, each index in the input array would now contain entries for the relevant pattern and its pitch as assigned by the user. With the patterns assigned, the user was now able to assess whether or not different patterns (and their combinations) were easily discernable within a sonification.

5.4.5. Pattern Combination Assessment

In order to provide the user with as much information as possible about the patterns they were required to detect, a pattern combination screen was provided (Figure 5.13).

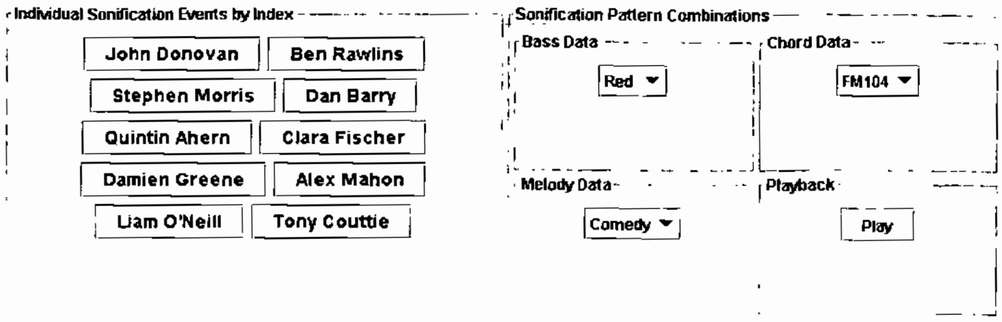


Figure 5.13: TrioSon single events and combinations screen

The Java combo boxes in the pattern combinations section allowed each individual bass, chord and melody mapping to be played by the user. This feature was added to provide the user with the means to learn specific combinations before they listened to the full sonification. In the above example, the user could preview the combination of the colour Red, the radio station FM104 and the film genre Comedy. In this manner, the user could define specific combinations of interest in a sonification and familiarise themselves with them prior to analysis.

The user could also compare each set of combinations by index, in the above case pertaining to the colour, radio station and film genre preferences of the survey group. The survey group was listed by name (index), with each java button playing the combination for that index. In this manner, a user could analyse a specific set of values by their index and compare them to all possible combinations within the sonification.

It was very important to the overall testing of the sonification framework that users were able to detect combinations of patterns, alongside single patterns for a given instrument. Comparisons between different data variables in a common set is potentially one of the most useful aspects of sonification and so required as much training as possible. It was hoped to assess the abilities of users to detect combinations of interest during testing and the pattern combinations section was designed to cater for this function.

5.4.6. Rhythmic Offset and Parsing Configuration

Much existing work has focused on the use of rhythm within a pattern, as a means of distinguishing one pattern from another. In the case of this research, it was desired to extend the use of rhythm as both a means of distinguishing patterns and also of parsing the data by index (chapter 8). To this end, a rhythm allocation screen was provided (Figure 5.14).

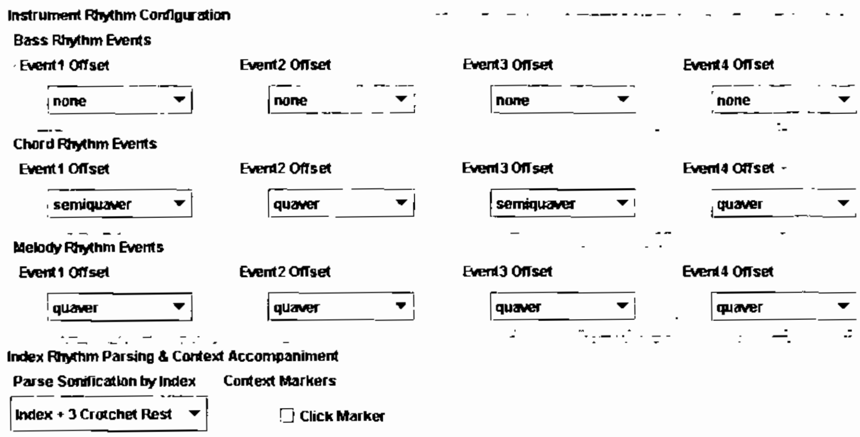


Figure 5.14: TrioSon rhythm configuration screen

In using rhythmic offsets to distinguish between patterns, the basic premise was to provide the user with a means of defining each pattern (or chord) for a particular index separately in time (Figure 5.15 and Figure 5.16).

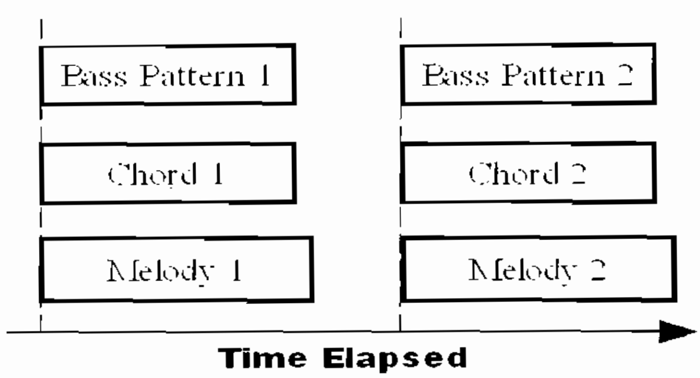


Figure 5.15: Sonification events without rhythmic offset (by index)

Without offset, the bass, chord and melody patterns for a given index would all occur in unison. It was hoped to assess the effect of separating each instrument in time within the same event. Ideally, a relatively small shift in time between instruments (say a crotchet or quaver) would allow the listener to detect the different patterns of each instrument in a much more accurate manner.

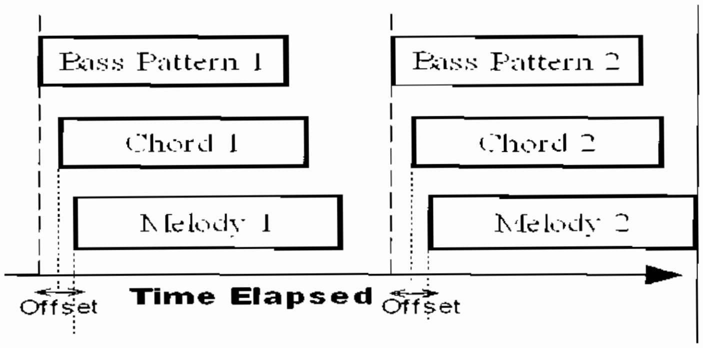


Figure 5.16: Sonification events with rhythmic offset (by index)

It was also desired to consider the effect of different time intervals between events within the sonification (Figure 5.17 and Figure 5.18).

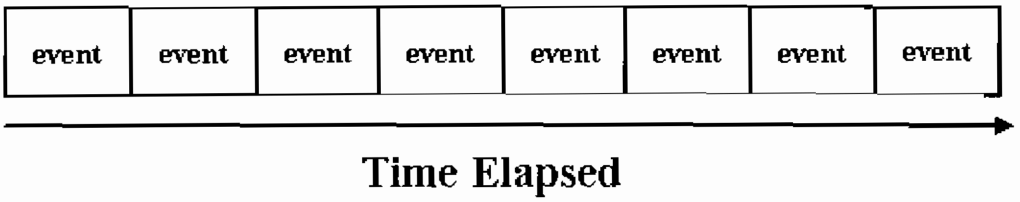


Figure 5.17: Sonification events with no rhythmic parsing (by index)

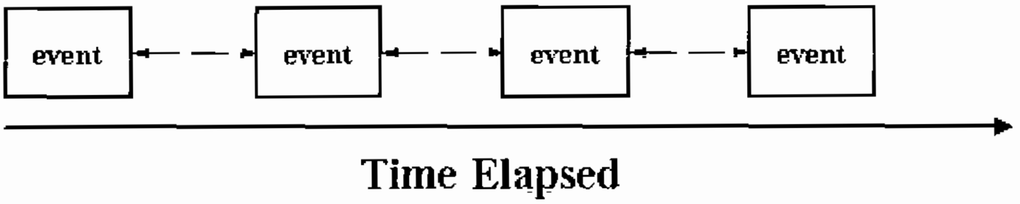


Figure 5.18: Sonification events with rhythmic parsing (by index)

In the same manner as the individual instrument offsets, a gap (3.8.1) between the events was also of interest. The gaps were intended as a means of segmenting events for individual consideration. In the TrioSon software, provision was made for different combinations of events and offsets. A single event could be accompanied by up to 3 minim rests, or 2 events could be accompanied by 1 or 2 minim rests. In each case, the event itself was desired to last for no more than 1 minim. Although a full set of tests were intended to assess rhythmic parsing in isolation, it was an integral part of the software development.

5.4.7.Sonification Rendering and Output

With all mappings and rhythmic considerations specified by the user, the output sonification would be ready for output. The Java Sound API provides functions for

MIDI input and output, alongside sample routines [175] for the creation of MIDI files. In the TrioSon application, it was decided that the development of a transport section should be of prime importance. As a functional element, the transport section was also given provision for tempo control and individual instrument muting (Figure 5.19).

Figure 5.19: TrioSon transport bar

A tempo slider and checkboxes for each channel mute were implemented. The entire transport section was embedded in a toolbar, which could be detached from the main GUI screen (by drag and drop) and relocated anywhere in the display area as required by the user. A sonification could be played and stopped as required, and the entire sonification could be written to file if desired. A reset button was also added, to allow the user to recommence work with a new data file as required.

With all main elements now in place, testing of the reference patterns could now be performed. The schedule for testing was designed to allow the implementation of such facets as user training, the redesign of patterns and the amendment of the application software as required. It was intended to take full account of each in order to develop a more robust method of sonification.

5.5. Experimental Design

5.5.1. Overview

The aim of the reference pattern tests was to establish a baseline of performance to serve as an indicator for further work. A set of patterns created from low level audio attributes would allow for comparison with higher level musical patterns in future testing. Testing low level patterns also allows for important observations to be made about the design process of such patterns prior to a comprehensive set of tests (chapter 6). Other observations about the testing method were also intended, in order that the means by which effective musical patterns can be utilised in sonification can be assessed as accurately as possible.

5.5.2. Test Schedule

The reference pattern tests were intended as an indicator of current methods, in that any subsequent improvements to the design or implementation of the patterns would be made as a result of assessment of testing. All participants sat a total of 9 tests over 2 sessions, with the point estimation and pattern combination questions (Appendix 5) occurring as required during each test. The point estimation tests sought to define how many values a subject could distinguish (from 2 to 4) and for how many variables (between 1 and 3). Each instrument was also assessed individually to define whether any difference existed between bass, chord and melody pattern matching.

5.5.3. Testing Hypothesis

The reference pattern tests were intended to investigate various aspects of sonification with a view to defining a more comprehensive framework for sonification using patterns. In testing such a framework for analysis and development, the initial test hypothesis had to be defined.

Hypothesis 1: Musicianship has no effect on point estimation and pattern matching. This hypothesis seeks to consider whether the musical experience and qualifications of the participants have any bearing on their ability to detect patterns in a sonification.

Hypothesis 2: Number of values has no effect on point estimation. This hypothesis seeks to consider the results obtained when assessing different numbers of patterns in a sonification. It is of interest to ascertain whether a variable which has 4 possible values will be more difficult to quantify than one with 3 or 2. The headroom at which acceptable levels of recognition break down is of great importance in defining the amount of data this type of sonification framework can convey.

Hypothesis 3: Number of variables has no effect on detecting pattern combinations. This hypothesis seeks to consider the results obtained when assessing different numbers of data streams in sonification. It is of interest to determine whether it is easier to detect combinations of patterns when other variables are present (such as analysing bass and chords in a sequence of bass, chords and melody). As with values, the headroom for acceptable recognition is of importance in specifying the amount of information this sonification framework can convey.

Hypothesis 4: Specification of instrument has no effect on sonification performance. This hypothesis seeks to quantify whether there is any benefit (or detriment) in representing data using bass, chord or melody patterns. If a robust framework is to be created, the representation of several variables must not show any particular bias for or against a particular instrument. If a certain instrument is more difficult to quantify it must be improved to meet the same performance as its counterparts.

5.5.4. Point Estimation Test Questions

The point estimation questions in each test were used to examine the validity of Hypothesis 2 and RQ 2 of the thesis. In each test, the point estimation and pattern combination questions occurred within an overall question related to a specific variable (such as bass, chord or melody). Each test file (Appendix 7) contained survey results of 3 variables in groups of 10 (Table 5.1), with various variables (such as favourite food, drink or film) being represented in different files.

Index	Colour	Radio Station	Movie Genre
1	Red	FM104,	Action
2	Blue	98FM	Sci-Fi
3	Yellow	98FM	Action
4	Yellow	98FM	Comedy
5	Blue	LyricFM	Sci-Fi
6	Green	FM104,	Romance
7	Yellow	SpinFM	Comedy

Table 5.1: Example test file of survey results for favourite colour, radio station and movie genre

Using these files, the subject was asked to sonify various aspects of the survey results for analysis. Initial questions concerned two conditions for a single variable, with later questions considering up to 4 conditions for all 3 variables in unison.

It was desired to assess the potential of different instruments relative to each other and in combination. For this reason, similar tests were carried out on bass, chord and melody pattern matching individually to assess whether performance differed between them. Participants were not informed of how many results were contained in each file, and were allowed to listen to each sonification a maximum of three times for single variable questions (rising to 6 for 3 variable questions). The capabilities of participants to retain differing quantities in memory was not considered the main focus of testing, thus the number of passes through each sonification was intended to allow each subject to pattern match as effectively as required. Participants were allowed to slow down (or speed up) the sonification as they desired, particularly at the beginning of testing. Although tempo is a very important factor in sonification, it was felt that each subject would find their own pace at which to work. It was noted from the outset that investigation of the effects of tempo would require further consideration in their own right.

5.5.5. Pattern Combination Test Questions

The pattern combination questions in each test were used to examine the validity of Hypothesis 3 and RQ 3 of the thesis. The pattern combination tests sought to determine whether linked quantities could be discerned from a sonification- as in how many times a certain value from one variable occurred in tandem with another related value from another variable (for up to 3 variables). This was considered a very important aspect of the sonification testing, as it would show what abilities (and limits) each subject possessed to detect pattern combinations. By detecting multiple values in combination, a data set of several related variables could be sonified for comparison and analysis. For example, if a census of favourite movie genre and beverage was taken by a cinema then the results could be used to determine which beverage would potentially be in most demand for films of that genre. In this manner, the use of sonification would allow a user to determine when certain important combinations occurred (and how often) with a view to assessing the importance of that pattern combination in the overall data set.

5.5.6. Test Groupings

Each participant was again given the questionnaire (Appendix 3) as used in the DNASon testing (4.4.7) in order to assess their musicianship as required by Hypothesis 1. It was hoped that the differences suggested by the DNASon testing (although not statistically significant) could be further explored. The questionnaire also served to highlight the areas in which each subject may be unfamiliar, as it was hoped to provide the relevant training on an individual basis (as required).

The musicianship groupings (Figure 5.20) were split according to their performance in the music education questions (questions 5 through 7) with students having already been selected from the BA Music course for the purpose. The non-musician grouping was drawn from a selection of staff and students of various courses with no musical background. It was felt that the effect of musicianship could only be fully assessed when juxtaposed against a completely non-musical background, a factor that the DNASon testing had overlooked. No participants involved had taken part in the DNASon testing, or would take part in any subsequent testing in this thesis.

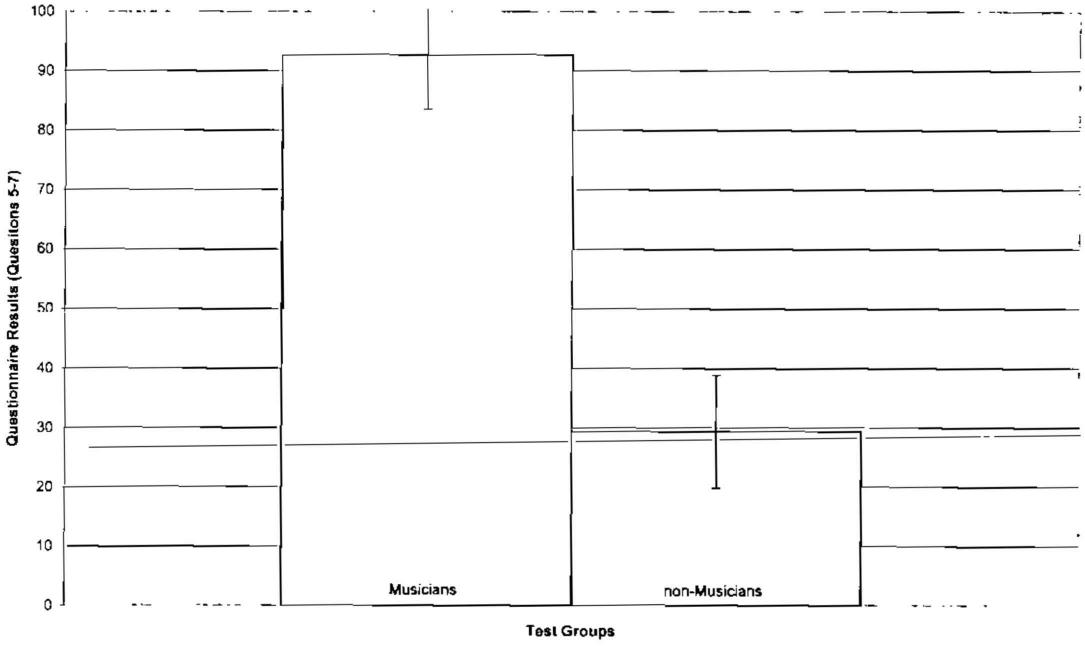


Figure 5.20: Graph showing average percentage results of musical knowledge questionnaire (questions 5-7), showing standard deviations

5.5.7. Training

The observations and experiences of the DNASon testing had shown that training had to be flexible enough for each subject being tested. Where some participants would understand and progress quickly through the schedule, others would require more explanation and time to adjust to the new techniques they were being exposed to. It was hoped that by introducing an audition session prior to the first test session, each subject could move through the process at their own pace (and with greater familiarity) in order to become as familiar with sonification as possible.

As with the DNASon testing, all participants were provided with tutorial material as required (Appendix 5). In the case of the TrioSon testing, the audition session[II] was also used to familiarise participants with both the software operation and the available patterns. The DNASon testing had shown that lack of familiarity was a huge factor during testing- something the listening test was designed to rectify.

All participants were asked to determine which patterns they felt most unique and also explain why. The results for each subject would also allow future tests to be performed more efficiently, with a list of potential choices allowing them to proceed without auditioning patterns each time. The auditioning also showed which participants did or did not understand the concepts of sonification, allowing further explanation to be given if required. By introducing the participants to the principles of sonification before testing began, it was hoped to detect any lack of comprehension at an early stage. The DNASon testing had shown that participants who began testing without fully knowing what they were supposed to be doing had struggled to recover (if at all). This was a situation that the TrioSon test schedule hoped to detect and rectify if at all possible.

Another factor considered while auditioning patterns was the reasons for each user's choices. Informal notes[III] were kept about each user and their particular choices and why they chose them, with a view to using these preferences when amending the pattern framework. It was of interest to ascertain whether the judgments made would change as a result of testing, where a subject may have chosen a pattern only to find it difficult to detect in a sonification. This information would be of benefit when assessing the potential of patterns at the end of the first test sessions.

[II] *As with the chord design auditions (5.3.2), no significant data was collated from this process. Instead auditions were used as a means of providing general feedback about the patterns used to allow further design to take place.*

[III] *Although notes were taken, no significant data was collated. These observations were used as part of the design process described in chapter 6.*

5.6. Results

The test schedule was designed to assess the point estimation and pattern combination performance of participants using the reference patterns. These tests were intended to highlight areas in which performance could be improved, with a view to investigating how such improvements could thus be made. All participants answered a total of 9 questions in each session, with the point estimation and pattern combination sections of each question occurring as required during each test. The point estimation questions sought to define how many values a subject could distinguish (from 2 to 4) and for how many data variables (between 1 and 3). The pattern combination questions sought to assess how effectively participants could determine certain combinations of values found in different variables. Each instrument was also assessed individually to define whether any difference existed between bass, chord and melody pattern matching as required by Hypothesis 4.

5.6.1. Overall Results

The overall test results (Appendix 8) for the reference pattern testing session (Figure 5.21) averaged 53.72%. These results were lower than anticipated, but had to take into account a broad spectrum of performance (21.35% to 76.56%).

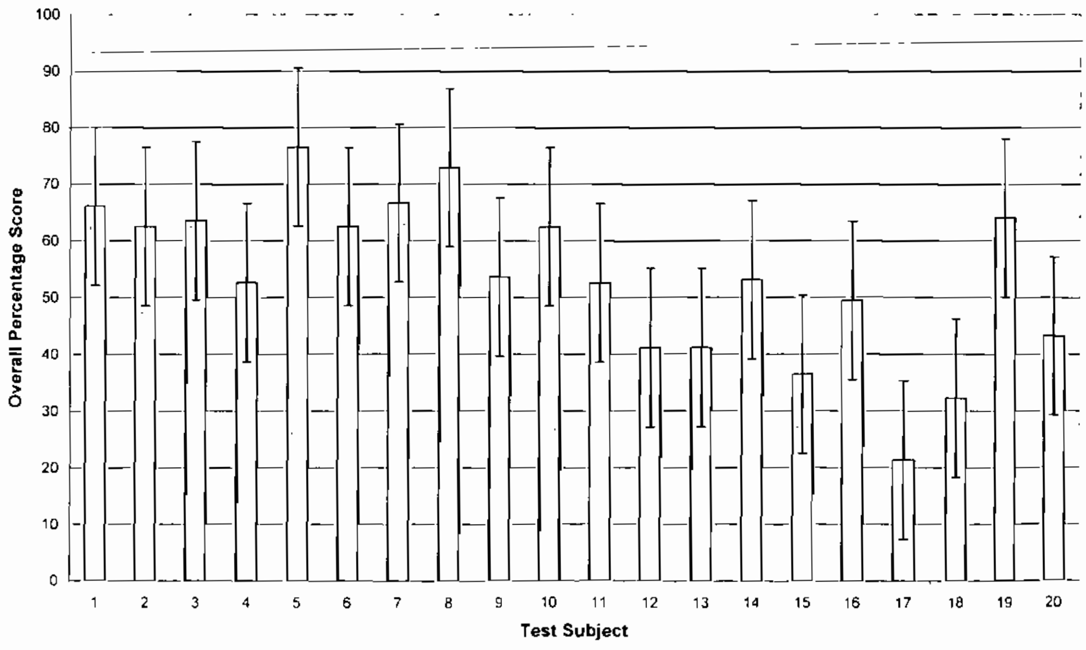


Figure 5.21: Graph showing overall percentage results for reference pattern tests (by subject), showing standard deviations

The overall score was calculated as a combination of both sets of test questions (point estimation and pattern combinations). When the results of these questions were considered individually (Figure 5.22 & Figure 5.23) a more comprehensive understanding of overall performance could be obtained.

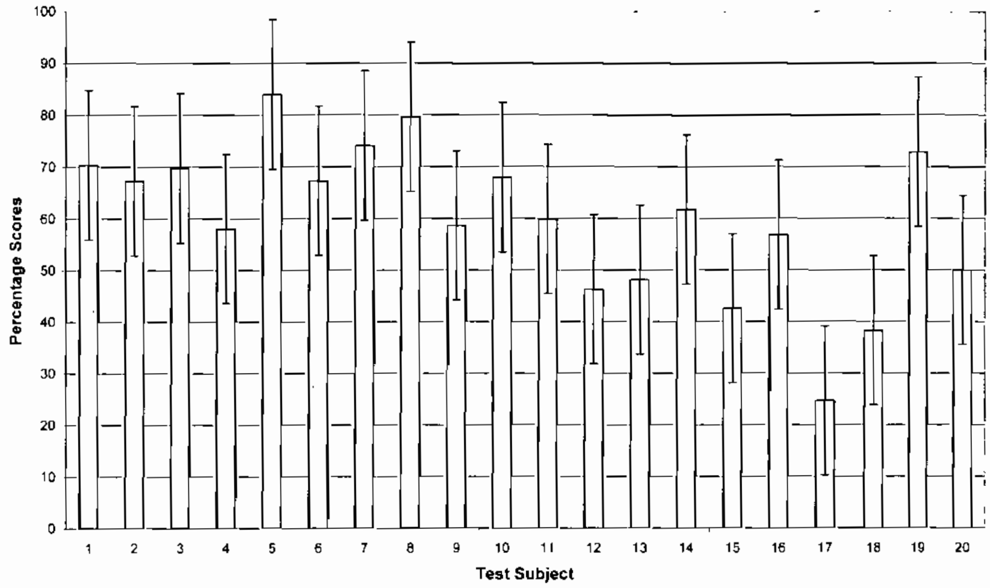


Figure 5.22: Graph showing point estimation percentage results for reference pattern tests (by subject), showing standard deviations

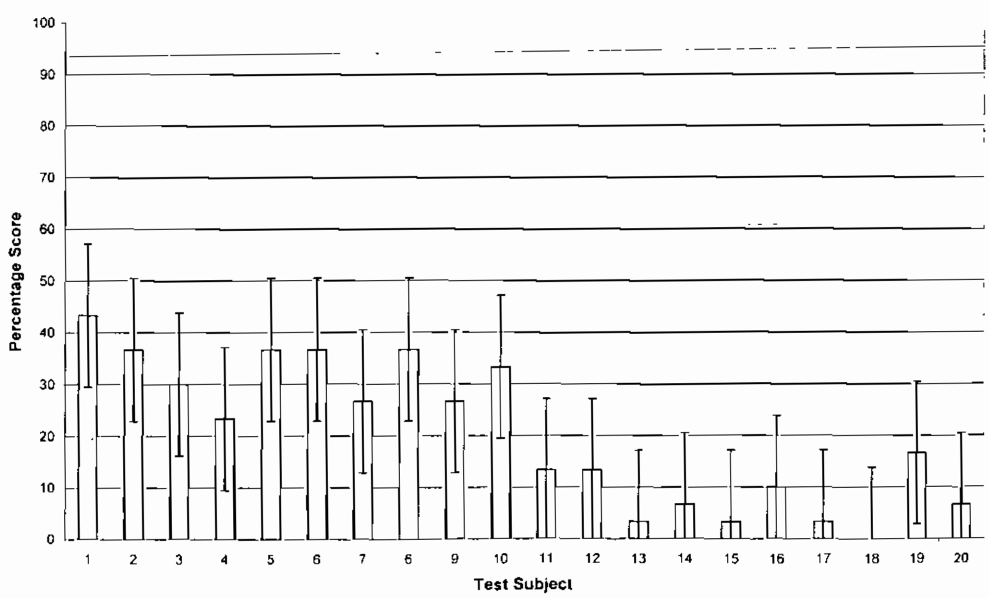


Figure 5.23: Graph showing pattern combination percentage results for reference pattern tests (by subject), showing standard deviations

The point estimation test results averaged 59.91%, which suggested that participants had been able to make distinctions between patterns. Although not as high as desired, the results showed that accurate point estimation was perhaps possible with a more effective method. On the other hand, the pattern combination test results averaged 20.33%, which was a very low score for such an important aspect of the testing. Effective detection of pattern combinations was essential to RQ 3, and so would require improvement in future development.

5.6.2. Effect of Value Count on Results

The number of values present in each variable of a sonification was now considered as a testing factor, to examine how this would affect performance as required by Hypothesis 2. Point estimation tests had been carried out for 2, 3 and 4 value conditions, in each of the 1, 2 and 3 variable tests. The results of these tests were combined, with an overall score for each value now being assessed (Figure 5.24).

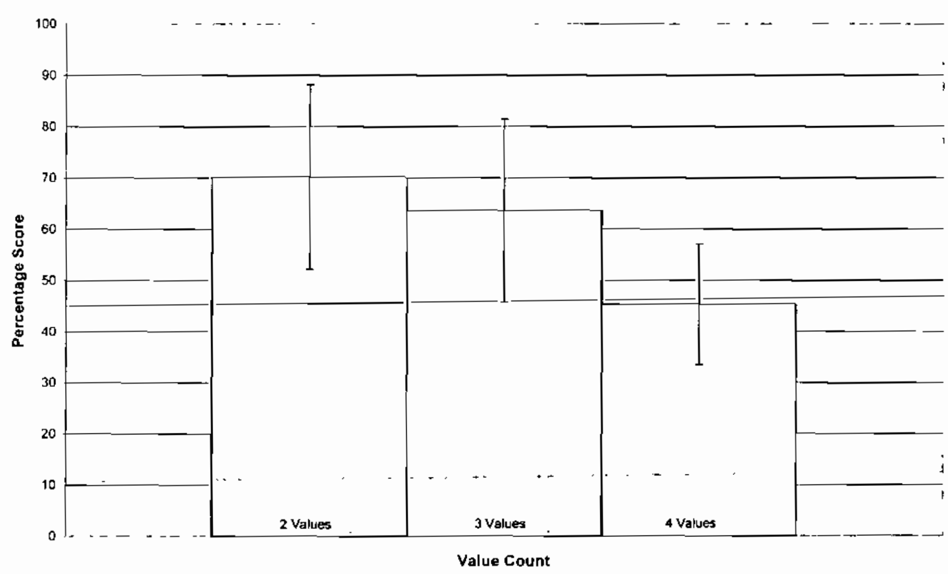


Figure 5.24: Graph showing overall average percentage results (by value), showing standard deviations

The results showed that an average score of 70.15% for 2 values had significantly decreased through 63.61% for 3 values to 45.23% for 4 values. This was confirmed by a between groups Anova [162], which gave a result of $F(1,60) = 17.34$, $p<0.0001$. The Tukey HSD test [163] was used to determine the magnitude of the difference between each value, giving a significant difference between every mean other than 2 and 3 value results (Figure 5.25).

(I) value	(J) value	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
2 value	3 value	6.5463	4.24492	.280	-3.6839	16.7765
	4 value	24.8796	4.24492	.000	14.6494	35.1098
3 value	2 value	-6.5463	4.24492	.280	-16.7765	3.6839
	4 value	18.3333	4.24492	.000	8.1031	28.5635
4 value	2 value	-24.8796	4.24492	.000	-35.1098	-14.6494
	3 value	-18.3333	4.24492	.000	-28.5635	-8.1031

Figure 5.25: Post-Hoc Tukey HSD tests by value count, showing significance to .05 level

These results suggested that the increase in value count to 4 values had significantly reduced the overall performance of participants, and as a result Hypothesis 2 could not be rejected. Future development would therefore have to consider the improvement of 4 value scores, ideally to the extent that overall scores would increase accordingly.

5.6.3. Effect of Variable Count on Results

The amount of variables used in a sonification was now considered as a testing factor, to examine Hypothesis 3 that this would not affect performance as required by RQ 3. As stated, point estimation tests had been carried out for 1, 2 and 3 variable conditions (Figure 5.26). In addition, pattern combination tests had also been performed for 2 and 3 variable conditions (Figure 5.28) and these results were considered separately.

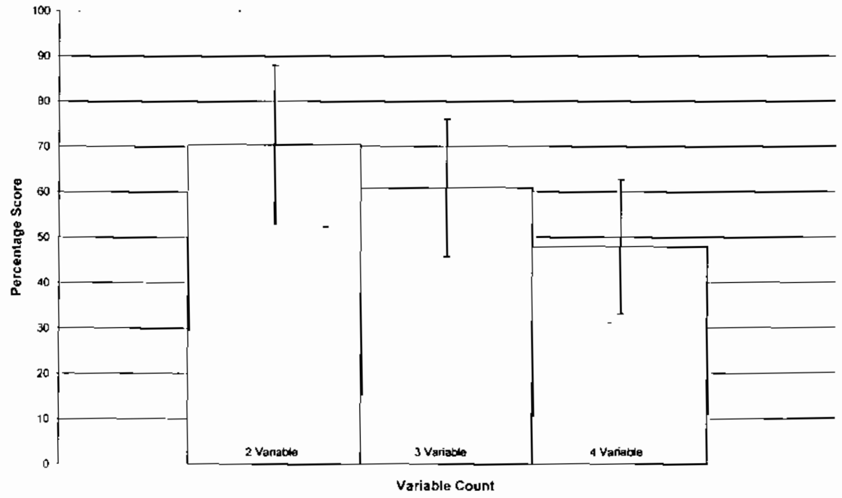


Figure 5.26: Graph showing overall average point estimation results (by variable), showing standard deviations

The results showed that the average of 70.37% for 1 variable tests had fallen through 60.83% for 2 variables to 47.84% for 3 variables conditions. An Anova of the results gave $F(1,60) = 14$, $p<0.0001$, which confirmed that a significant difference existed between groups. A Tukey HSD test gave significant differences for all means other than 1 to 2 variables (Figure 5.27).

(I) variable	(J) variable	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1 variable	2 variable	9.5370	4.23221	.071	-.6625	19.7366
	3 variable	22.5278*	4.23221	.000	12.3282	32.7273
2 variable	1 variable	-9.5370	4.23221	.071	-19.7366	.6625
	3 variable	12.9907*	4.23221	.009	2.7912	23.1903
3 variable	1 variable	-22.5278*	4.23221	.000	-32.7273	-12.3282
	2 variable	-12.9907*	4.23221	.009	-23.1903	-2.7912

Figure 5.27: Post-Hoc Tukey HSD tests by variable count, showing significance to .05 level

As with the value results, it was shown that an increase in data to the 3 variable condition had engendered poor overall performance for point estimation tests. This result was in keeping with work by McGookin [100] which had shown that earcon recognition rate dropped from 70% to 30% for 4 concurrently presented earcons. With this in mind, a similar analysis was performed on the results of the pattern combination tests.

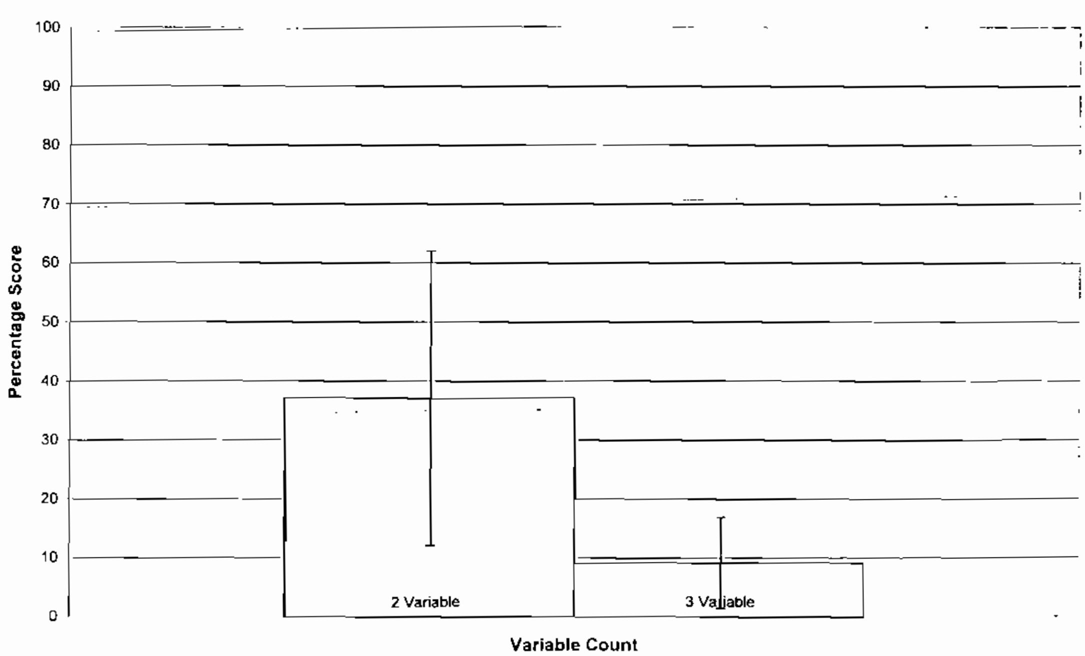


Figure 5.28: Graph showing overall average pattern combination results (by variable), showing standard deviations

Although the pattern combination tests results were very low overall, the average had fallen from 37.08% for 2 variable combinations down to 9.17% for 3 variable combination tests. To confirm this, the results of these questions were analysed in an independent samples t-test [161] to determine whether there was a significant difference between the two groups.The t-test gave a result of $T(10) = 4.66$, $p<0.0001$, which confirmed that a significant decrease had occurred between variable results. Because of this, Hypothesis 3 could not be rejected. As mentioned, the pattern combination results were not of sufficient magnitude to consider individual conditions at this stage. A main focus of improving the performance of the sonification framework would have to be the improved detection of pattern combinations in some manner. Both the point estimation and pattern combination tests had shown the results for 3 variables to be far lower than desired. Improvements would have to be made to the framework to allow for better performance in the triple variable condition, in order that significant amounts of information could be delivered by it.

5.6.4. Effect of Instrument on Pattern Matching

Tests had been performed for single variables using bass, chord and melody patterns on an individual basis. The results of these tests were intended to assess whether different instruments performed better during testing. Participants had been allowed to select their own instrument timbres during testing, but had been guided by the basic groupings defined by Rigas and Alty (2.2.6). It was suggested to all participants that the best distinctions of timbre would be found when choosing timbres from different families. Users were also guided towards instruments with fast attack parameters (such as those produced by mallet or plucked string instruments), so that they would be able to detect the different notes and rhythms in each pattern as clearly as possible.

A common example configuration would use a picked or finger bass for bass, a piano or organ for chords and a flute or oboe for melody. Although other configurations were selected by users, it was found that in most instances a combination of this nature gave best recognition. The results by instrument were considered (Figure 5.29) to investigate any variance during testing.

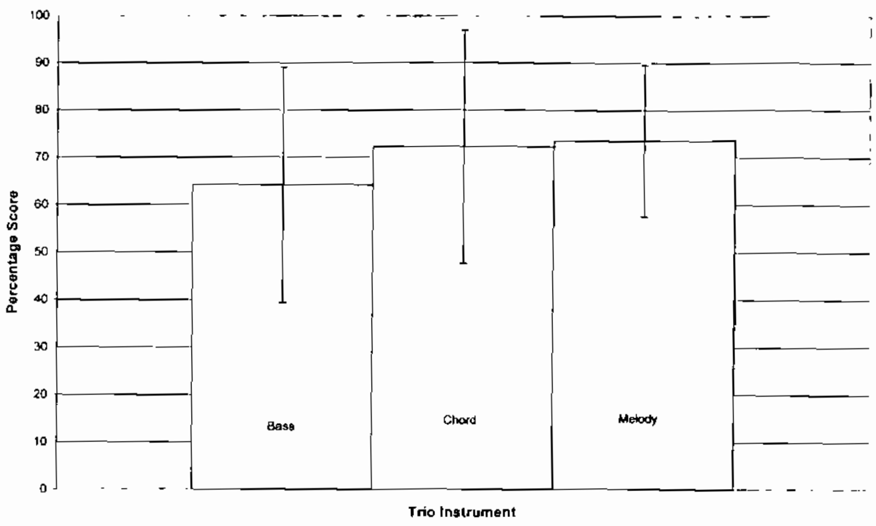


Figure 5.29: Graph showing overall average point estimation results (by instrument), showing standard deviations

An Anova of the results gave F(1,60) = 1, p=0.376 which suggested that no significant variance existed between instrument scores. As a result, Hypothesis 4 could not be rejected. However, it had been noted during testing that many participants were less comfortable with tests involving the bass variable (2.2.1), often listening to 2 or 3 variable tests far more often than with chord or melody tests. This observation was lent further credence by the average results for each instrument, with chord (72.24%) and melody (73.53%) values being fairly close compared to bass (64.15%). Although not statistically significant, the comments of various users had suggested that the bass instrument was the most difficult of the three to work with. It was intended to improve its effectiveness prior to the second set of tests.

5.6.5. Musicianship Test Grouping Results

The test results had indicated much room for improvement, and the test groupings were intended to highlight exactly where this improvement would be best employed. The overall results were examined by musicianship (Figure 5.30) in an endeavour to detect what discrepancies existed.

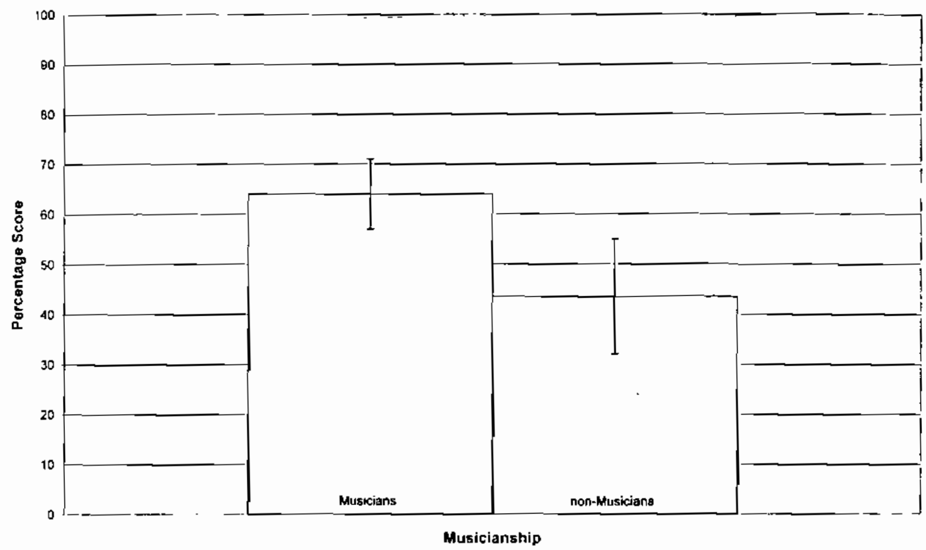


Figure 5.30: Graph showing overall average percentage results (by musicianship), showing standard deviations

The results showed the musicians grouping to have an average score of 63.96% compared to the non-musicians average of 43.5%. An individual samples t-test was performed on the results, giving T(10) = 4.57, p=0.0002. This showed that musicianship had a significant effect on performance in the tests, and so Hypothesis 1 was rejected. Further examination of the individual point estimation and pattern combination results yielded similar data, with the point estimation tests giving T(10)=3.92, p=0.001 compared to the combination test T(10)=9.72, p=<0.0001.

This contrast showed that the musicians group had coped far better with the sonification testing, particularly in the more difficult pattern combination tests where most non-musicians scored very poorly. It had been observed during testing that musicians had scored patterns on the test worksheets as a visual aid to their recognition. This factor had not been considered during the design of the experiment, and future tests would have to ensure that participants were all given equal materials to work with during sonification. It was noted that such visual aids made recognition much easier for musicians (as discussed informally after testing) and so could perhaps be implemented for non-musicians in another manner in future testing.

The results showed that a framework was required which would be far better suited to non-musicians in order to be viable. Analysis of the tests had shown that the initial framework using reference patterns was not easily utilised (or understood) by non-musicians and so had to be simplified and streamlined. Effective musical patterns should not specifically require musical training, and so future testing would focus solely on improving pattern recognition for all participants.

5.6.6. Post Test TLX Results and Testing Observations

At the end of the session, each participant completed a TLX test questionnaire (Appendix 9), to determine how difficult they had found the testing to be. Of particular interest were the individual scores for frustration, mental and temporal demand, although all factors were considered. All results were considered relative to the musicianship groupings, to ascertain whether any particular group felt the testing to be more difficult than others.

The overall TLX results (Figure 5.31) were fairly high, with the average total workload exhibited as 66.193%. Musicians gave an average workload score of 67.8, compared to the non-musicians score of 64.87. A t-test ($T(10) = 0.48$, $p=0.636$) showed that no significant difference existed between workload scores for each group.

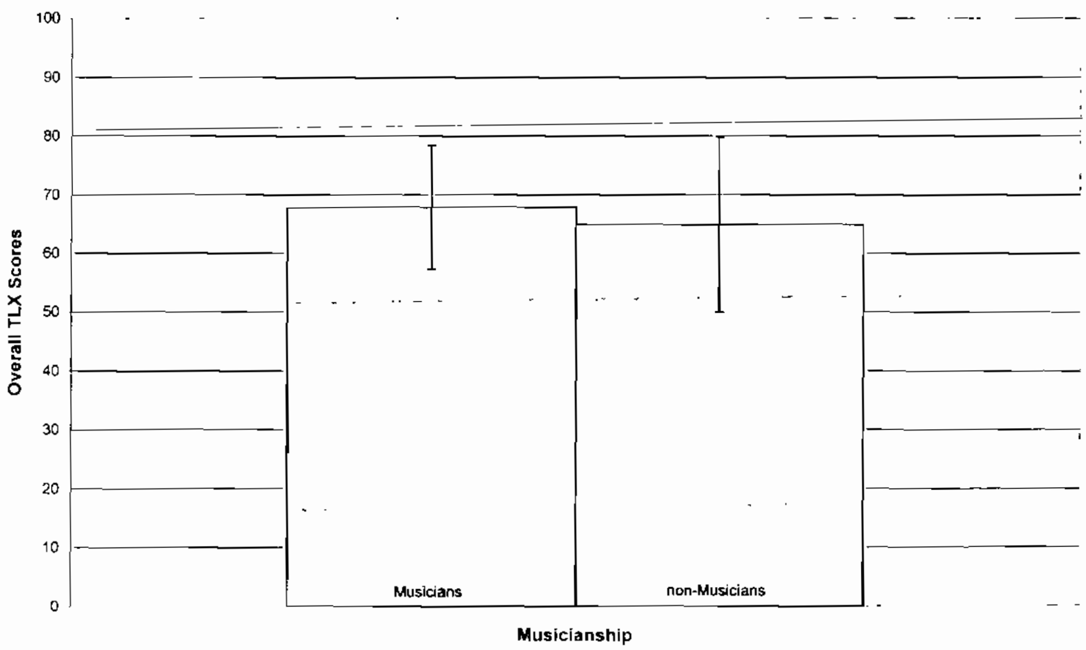


Figure 5.31: Graph showing overall average post-test TLX results (by musicianship), showing standard deviations

These results showed that participants found the tests difficult, with several expressing confusion between patterns over the course of the tests. It was noted that although most participants could distinguish between patterns, they often struggled to remember what each one represented or even which number it was. Future development would have to find a way of more efficiently addressing this problem.

5.7. Discussion

Overall, testing had shown that musicianship made a significant difference to performance. It was also found that performance declined for more than 3 values, or when 3 variable conditions were considered. Although detectable by most participants, the patterns used in testing were not distinctive or memorable enough for efficient user recognition- particularly in multiple variable conditions. It was also realised that participants had been given far too many patterns to work with, requiring a maximum of 4 from 48 patterns for each instrument (or 32 for chords).

The effects of modality were difficult to consider using the TrioSon software, the ability to set the root note of each individual pattern was not useful to non-musicians and too cumbersome for serious musical consideration. It was also found that providing chord families of differing inversions did little to improve performance, with most musicians (and indeed many non-musicians) preferring chord sequences of the same inversion. The requirement to pitch each chord (and the associated musical knowledge required) caused delays in the testing that undoubtedly affected performance. It was felt that a more straightforward sonification framework was needed, ideally reflecting the specifications of the data sets it was intended to represent. Although larger pattern groups gave more scope, if users were unable to adequately define more than three different patterns for one instrument then they were ultimately of little use.

Several areas of development were planned to address the issues raised during testing. The TrioSon application used during testing had proved too complex (and hence confusing) for many participants. Informal discussions after testing suggested that there was too much information on screen, which had served to confuse some of the participants. Instrument configuration settings were a particular source of confusion, and hence a redesign of the application was required to make the process more straightforward. Few participants had altered volume settings, and all had used left, right and centre locations for instrument panning. It had been noted during testing that timbre choices often served to complicate matters for non-musicians who were unsure as to what distinctions they were supposed to make (and whether this was part of testing). Future development would utilise a specific set of predefined timbres (based on the families defined by Rigas and Alty [28]) to remove this ambiguity from the testing process.

Testing had considered the effect of musicianship on sonification performance (5.5.3) and had shown that musicians performed better. This testing condition served to highlight the requirement for more straightforward and understandable musical patterns than those used in the tests. It was also noted that by scoring patterns musicians had a definite advantage during testing and future tests would have to remove this effect. Future pattern design methods would have to contain features that were recognisable (and understandable) to both musicians and non-musicians if an effective method of sonification was to be produced.

The basis for testing had been RQ 2 and RQ 3, to determine what could or could not be achieved using present pattern design guidelines. These results were not intended as a benchmark as much as a guide for future development, with existing research [100] already having been performed on the effectiveness of concurrently presented earcons. The stimulus for testing had been the underlying patterns from which earcons may be created rather than the earcons themselves, and so could not be considered as a comprehensive indicator to their performance. The testing was used to highlight areas in which patterns were ineffective (particularly pattern combinations) with a view to improving them.

As a result of this, RQ 2 could not be answered positively. Although point estimation scores averaged 59.91% they did not perform as well as required. Informal observations during testing had confirmed that participants struggled to remember what a pattern was (or what it represented), even though they could often distinguish that pattern from others without much difficulty. The abstract nature of iconic patterns (3.8.3) makes prior exposure essential to their recognition, in keeping with the notion of familiarity (2.5.1). It is argued that the use of higher level features (such as melodic contour) will improve such recognition and hence aid in making a pattern familiar to the listener.

Pattern combination scores were very low at 20.33%, and so RQ 3 could be rejected under present conditions. No significant determinations could be made about the method of pattern combination used other than it was ineffective. Future development would therefore have to produce a method of determining pattern combinations with a far higher degree of accuracy than those obtained during testing. In doing so, one consideration would have to be the effective interaction of patterns, rather than the design of a single pattern in isolation. This interaction would have to take due consideration of the similarity, good continuation and belongingness of patterns (2.5) in order to be productive.

5.8. Conclusions

The tests carried out in this chapter of the thesis considered the following research questions of this thesis:

> RQ 2. Do present methods of pattern design (notably earcon design guidelines) produce patterns which are not only distinct but also memorable?
> RQ 3. Can present methods of pattern design be used to efficiently render concurrent streams of data?

Both of these conditions were not met during testing, which had showed that both point estimation and pattern combination results were lower than expected using low level pattern design methods. The results of these tests were considered as an impetus for future work, intended to highlight the shortcomings of low level pattern design.

The means by which a pattern can be made both distinct and memorable is central to the work of this thesis, which seeks to investigate the effect of higher level auditory attributes on pattern recognition as defined in RQ 4 and RQ 5. The tests performed in this experiment helped to define what aspects of pattern recognition could be improved, and the consequent work of chapters 6 & 7 seeks to investigate how best to achieve this. Point estimation and pattern combination were now considered as two separate areas of investigation, particularly in light of the poor pattern combination performance during testing. It was realised that the design of memorable patterns would have to take place separately from any investigation into the means of their combination. If a set of memorable patterns could be produced, they would serve as a useful building block for further development in other areas. As a result, the following improvements were intended:

1. *Redesign of Application GUI:* the front end of the test software application (TrioSon) should be more straightforward, with fewer elements on each screen distracting the user's attention. The configuration of instruments should be moved to a separate screen so that it did not confuse the user on start-up.
2. *Streamlining of Pattern choices:* The amount of patterns available to the user was far in excess of what was actually required. Although useful for audition and observation, future tests would use far smaller numbers of patterns to avoid confusing the participants.
3. *Redesign of Patterns:* The patterns used by the current tests were not effective. A new set of patterns were required for each instrument that were more easily recognised by all users, regardless of their musical knowledge. These patterns should ideally be more distinctive and individually recognisable, utilising higher level auditory attributes to do so.
4. *Re-evaluation of chord choices:* The chord allocation aspects of the application proved very difficult to understand, both for musician and non-musician alike. The use of chords would have to be given careful reconsideration with reference to the gestalt grouping categories required of Auditory Scene Analysis (2.5) and the effective combination of patterns (RQ 5 and chapter 7).
5. *Re-evaluation of Volume and Panning specifications*: Participants had not expressed any interest in the volume of different instruments, and all had selected panning locations as far apart as possible (left, centre and right). This suggested that such considerations should be removed from user focus, in order that a more straightforward testing method could be implemented.
6. *Improved Timbre selections:* It was decided that the timbre combinations used in testing should be made more specific, rather than allowing users to make their own (potentially difficult) choices. A set of timbres based on the

guidelines of Rigas and Alty [28] would be used for all future testing in order to reduce their effect on pattern recognition.

The work of the next chapter implements all of the above improvements, particularly the use of higher level musical attributes in the form of contour icons (RQ 4). A full set of tests was performed between the reference patterns used in this chapter and the contour icon pattern set, to demonstrate the improvements in performance that higher level auditory attributes such as contour can make.

6. Contour Icon Pattern Design

6.1. Introduction

The tests performed using low level pattern design methods (chapter 5) had suggested that a detectable pattern may not necessarily be memorable. Further, the tests had shown that neither point estimation nor pattern combination detections were effective using low level patterns. Pattern combination detection was particularly low, and hence would require focus during further development (documented in chapter 7). Several key areas of improvement were specified as a result of testing (5.8), and each of these areas was now considered. In this chapter, the design process by which contour icons were developed (RQ 4) is documented. During this process several ad-hoc auditions of potential patterns were performed, and the outcome of such auditions is mentioned as it relates to the design process (rather than for evaluation). Contour icons seek to utilise melodic contour (2.3.3) as a means of creating more memorable patterns and so were implemented by way of comparison with the low level patterns used in chapter 5. A full set of tests were carried out to assess the effectiveness of contour icon patterns in relation to these low level reference patterns.

The recognition rates of participants (particularly non-musicians) had been lower than desired during reference pattern testing, and it was hoped that changes in implementation would help to rectify this. It was intended to evaluate the pattern design methodology that been employed with reference to the observations and user feedback obtained through testing. Informal notes had been taken during each test and all participants had been canvassed on their thoughts and perceptions during the testing process. The goal of any pattern design method is recognition, and to this end the opinions of participants were vital to improving the method. By assessing the reactions of the participants, it could be decided how best to proceed with re-designing the patterns.

Informal listening tests and auditions were also performed during the redesign process documented in this chapter, with the intention of obtaining as much user feedback about various changes to the patterns as possible. Although not part of a test schedule, the opinions and responses obtained were of invaluable assistance in the design and implementation of the amended framework. These opinions helped to guide the design process rather than evaluate it, and so were not part of any formal assessment.

The reference pattern test schedule (5.5.2) had considered several elements of musical pattern sonification, with point estimation (5.5.4) and pattern combination (5.5.5) tests being carried out during testing. Although this set of tests had indicated many areas of future development, it was felt that a more robust testing method would focus on each aspect of pattern sonification in isolation. For this reason, the implementation of contour icon patterns would be tested in comparison to low level reference patterns (Appendix 10) using point estimation tests. Subsequent to testing, the use of harmonic combination (chapter 7) would also employ pattern combination tests to ascertain the potential for multiple variable sonification. By focussing only on the recognition of patterns, it was hoped to obtain a clearer picture of the effect of melodic contour on musical pattern design as required by RQ 4. The previous set of tests had also suggested several other areas of development, and those relevant to the pattern design process were first considered.

6.2. Redesign of Application GUI

The TrioSon application had been fully tested, with no errors in performance being detected during the first test sessions. However, observations and user feedback obtained during testing had suggested that there were several elements of the GUI operation (and indeed the back end code) that could be improved upon.

6.2.1. Simplification of GUI Display

The GUI was found to be over-complicated by some users, with the instrument configuration panels being the main source of distraction. The volume, panning and instrument assignment controls were moved to a new frame (Figure 6.1) created specifically for the purpose of configuration. Instrumentation, volume and panning settings could now be configured prior to testing, thus avoiding any confusion among participants.

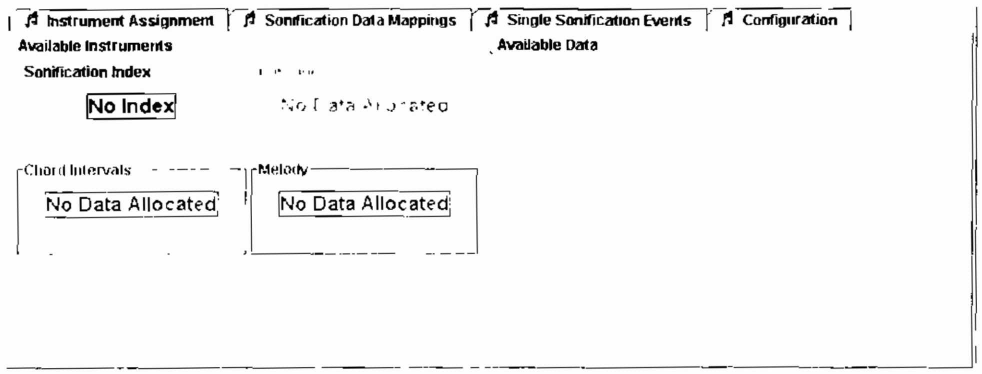


Figure 6.1: Redesigned TrioSon main GUI screen, with configuration settings relocated

All sections referring to a specific instrument were colour coded [176], with bass parameters being signified in blue, chords in green and melody in red. This segregation was intended to further simplify the GUI [187], allowing users to consider each instrument in turn rather than as a larger group.

6.2.2.Simplification of Rhythmic Parsing Options

Rhythmic parsing was one of the main goals of testing (chapter 8), but as with the pattern design section it was realised that over-complication could quickly compromise understanding. In order to test the rhythmic parsing of a sonification as effectively as possible, the rhythm configuration screen (5.4.6) was removed for the purposes of testing. The single events screen was now reconfigured (Figure 6.2), so that their information would now be passed to the model for use in all rhythm aspects of the application.

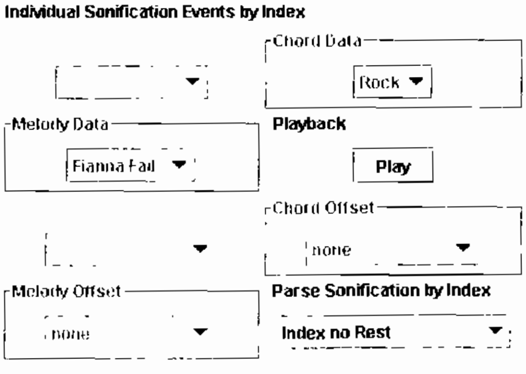


Figure 6.2: Redesigned TrioSon rhythmic parsing section

This simplified version of the rhythm configuration screen was intended to facilitate ease of use for participants. The testing schedule for contour icons did not require any greater level of complexity than could be configured from within this screen. It was intended that participants would not have to devote the same amount of effort to its configuration that had been required by the original TrioSon GUI.

With the GUI reconfigured as required, the patterns used by the sonification framework could now be examined in detail. It was hoped to significantly improve the design of the patterns, in order that a similar improvement may be achieved in test results.

6.3. Improved Pattern Design Considerations

The patterns used in the first test sessions had produced low results, particularly amongst non-musicians. It was found that the recognition rates were low for most patterns, with the associations made between patterns and data being a particular weakness. The first observation gained from testing was the lack of cohesiveness among patterns, largely due to the range of pattern choices available. Informal observations made during testing had shown that musicians did not find enough variety within the major, minor and chromatic groupings to retain their interest (or indeed recognition). Conversely, non-musicians were often highly confused by the definitions of scale and key that the pattern allocation screens afforded. Clearly some form of compromise had to be reached, providing the musicians with richer pattern structures while simplifying their implementation for non-musicians.

6.3.1. Streamlining of Pattern Choices

It was realised during the first test sessions that there were far too many patterns available to the user. Rather than providing greater musical scope, the amount of patterns served only to confuse, inveigle and obfuscate the objectives of sonification. It was decided that with a maximum of 4 values being tested for any instrument, 48 pattern choices was excessive to the point of confusion. As a result, the pattern allocation sections for each instrument were reduced to single groups of 8 patterns (rather than 3 groups of 16).

The use of root note and scale family (major, minor and chromatic) had again proven more difficult than beneficial for most users. It was found that most musicians did not automatically think of a patterns modality (perhaps due to their musical preference) and so were often likely to make abstract key choices (if any). This situation was not improved in the non-musicians case, where it was often proving difficult enough to understand the patterns without the extra complexity of scales and modes. As with the pattern groupings, it was felt that root note and scale choices were confusing rather than comprehensive and so were removed. It was decided that the best course of action would seek to simplify the pattern recognition process as much as possible. To this end, a more robust method of pattern design was required.

6.3.2. Improved Pattern Detection

It had been observed during testing that one of the main differences between the musicianship groups was the ability of the musicians to score representations of patterns prior to listening. By transcribing approximations of the patterns they were about to listen for, some of those in the musicians group often had a useful visual cue for each pattern in front of them during tests. It was realised that this skill allowed them to remove the abstraction that numerical patterns engendered in the tests. This use of transcription had been discovered post-test, when test scripts were returned with musical scorings in the margins. Although this was a factor that would have to be avoided in future testing, it was also felt that the best means of removing its effect was to employ some means of scoring patterns for all participants. By providing more information on a pattern than its numerical name, the musicians who had scored patterns were effectively finding means of making the patterns memorable.

Many non-musicians (and indeed some musicians) had expressed frustration at having to remember that pattern X represented a certain quantity, while also having to remember what pattern X sounded like before counting the frequency of that pattern in a sonification. In this manner, most of the participants were performing several mental processes for each pattern they defined (Figure 6.3).

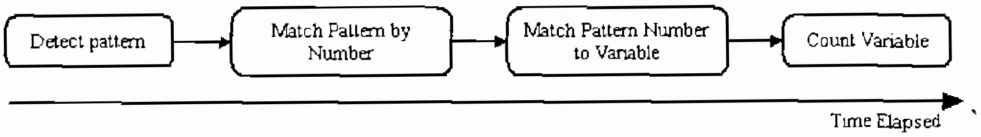


Figure 6.3: High level representation of pattern matching thought process

This concatenated process of detection had proven unworkable at higher data rates (particularly for more than one parameter), and so a better solution had to be found.

The notion of scoring patterns to aid in recognition suggested possibilities: if a method of visually representing patterns could be found that did not require traditional music notation, it would provide the means of detecting patterns in 3 stages rather than at least 4 (Figure 6.4).

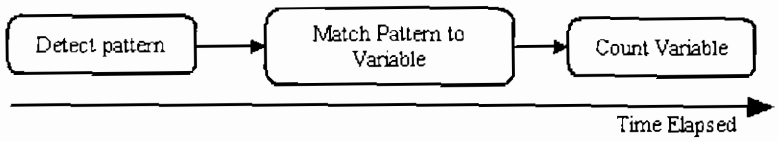


Figure 6.4: High level representation of idealised pattern matching thought process

By defining visual cues for the musical patterns, it would perhaps be possible to use those cues as part of the pattern design process itself. By seeking to provide the participants with a visual template of available patterns (which they would be required to learn), it would also be possible to create patterns which conformed to these same visual cues. In this manner, a more robust framework for pattern design could be considered which would ideally be transparent to all listeners (regardless of musicianship skills).

6.3.3. Improved Pattern Recognition

The patterns used in the first test sessions (chapter 5) were not considered memorable enough by most participants. Many participants found that although the rhythms of the patterns made them initially distinctive, the ability to quantify which pattern it actually was proved more elusive. This was an interesting notion, in that it suggested that potential differences existed between the processes of pattern detection and pattern recognition [46].

This indicated that the rhythmic basis upon which the initial patterns had been designed would serve to make them detectable, though not necessarily memorable. Far more importance would have to be attached to the melodic quality of the patterns, in order that listeners would be able to detect and match a pattern to a quantity as efficiently as possible. With this in mind, a new pattern design methodology was employed.

6.4. Contour Icons

The work of Schoenberg [48] and Adams [49] had shown that high level graphical representations of melodic patterns could be employed in musical description and analysis. Although not singularly defining as a factor, the relational aspects of a visual representation of musical patterns suggested definite advantages- particularly for non-musicians. Bregman [80] suggests that visual representations of audio are of great benefit in description and analysis, with many of the gestalt laws of grouping by proximity being equally applicable to both visual and audio events. Indeed, the gestalt groupings can be considered as a checklist of pattern design (2.5) which is particularly useful for high level patterns. If a pattern can be said to conform to any or all of these categories then it may be fairly considered as being distinctive and memorable. These groupings are also of great benefit when seeking to improve on pattern combination performance (5.7), where patterns must ideally be grouped in some manner while still remaining distinct. In view of this, a contour based design and representation method was embarked upon.

6.4.1. Design Considerations

In considering the possibilities of a set of icons used to represent musical patterns, it was decided that simple shapes describing melodic events would be used as the design template for those patterns. This approach differed from existing work that sought to represent and quantify musical patterns visually, rather than defining patterns visually in advance. In using such techniques, users with no written musical skills can compose musical patterns and sequences of patterns in a purely visual manner. The traditional written score is also a purely visual means of representation, although the syntax precludes its use by those without sufficient training. By providing a basic, shape-based representation to the user it was intended that a high-level, simplified version of the traditional score could be implemented. Although the contour icons would be used to define the patterns they represented, the initial design of those icons was based around common contour shapes. The pattern auditions (5.5.7) carried out prior to the previous test sessions had provided the opportunity to obtain user feedback about the patterns they chose and why.

Many participants (particularly non-musicians) had used visually expressive terms of description such as 'up', 'down' or 'curved' to categorise different patterns when possible. Several participants also used simple diagrams to describe the patterns they chose, and it was subsequently noted during testing that those participants tended to perform better. Although not factored into the test schedule, it was realised that providing a more descriptive set of pattern identifiers (than the existing numerical format) would ideally provide all participants with the same potential advantage.

6.4.2.Initial Contour Icon Pattern Set

Various basic contour shapes were considered, including shapes obtained by analysing some of the most popular and effective patterns (Figure 6.5 and Figure 6.6) used in the first auditions and test sessions. These patterns were not defined statistically as more popular (or indeed effective) but for design purposes were considered a good basis upon which to commence investigation.

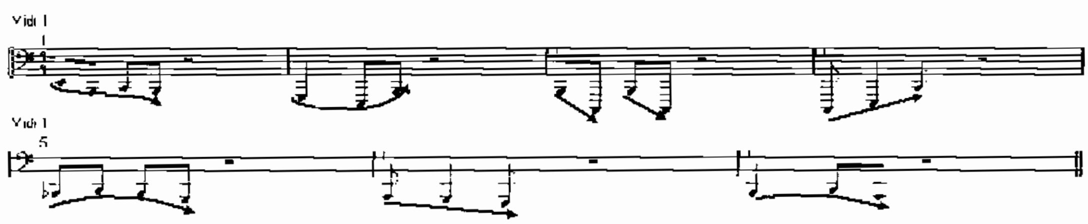


Figure 6.5: Contour graphs of popular bass reference pattern choices (5.3.1)

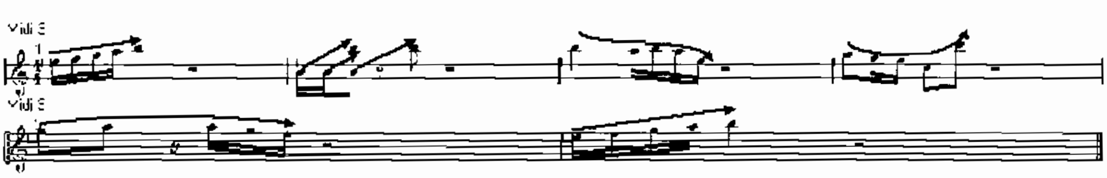


Figure 6.6: Contour graphs of popular melody reference pattern choices (5.3.3)

These simple contours were used to form an initial set of contour icon shapes (Figure 6.7), which were considered for ad-hoc assessment.

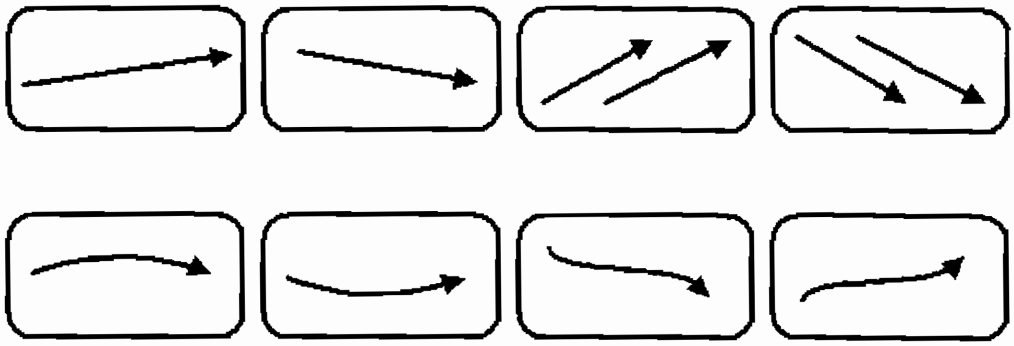


Figure 6.7: Initial contour icon pattern set

A set of auditions of these patterns was performed with several colleagues, where each of the original bass (7 patterns) and melody (6 patterns) patterns used in the design was played to them in turn. Each person was given a sheet with the 8 preliminary icons displayed for every pattern in the sequence (grouped into one set of 7 questions, followed by another of 6). In each case, the person was asked to select the most suitable contour icon from the 8 available and also state how good an approximation it was.

Although not a statistical test (but rather an audition for design purposes), the overall response was favourable. This suggested that contour icons were far more representative than the static numerical relations used in the first sessions. The use of contour icons also suggested a means of conforming to several of the gestalt categories specified for pattern fitness (2.5):

1. *Familiarity*- By using simple shapes, contour icons can take advantage of the previous exposure to visual shapes that are taught from a scholastic level [177]. This familiarity with the visual shape (and hence its' associated melodic contour) can thus be used as a frame of reference for the shape of the melodic pattern of the contour icon.
2. *Good continuation* – Contour icons follow melodic shapes, an attribute considered important in audio pattern recall [46]. The melodic shapes used change in an expected manner, and so exhibit the good continuation required for an audio stream.
3. *Belongingness*- The shape of a contour icon is its melodic definition, and so the melodic pattern used can be said to exhibit belongingness to that shape.

When considered in terms of a group of contour icons, such shapes become part of a set.

These categories showed that a well designed contour icon could potentially provide higher level features which would allow its effective stream segregation. Although no conclusions could be drawn prior to testing, the adherence to several of the gestalt categories was considered a positive step forward in the development. It was now decided to stylise the contour icons further, with a view to subsequently performing a similar amendment to the patterns they represented. In this manner, a new set of patterns could be designed that would be more easily recognisable to the listener.

6.4.3. Amended Contour Icon Pattern Set

The suggested contour icons were redrawn using standard flowchart shapes, based on the initial set of icons used in the first auditions (Figure 6.8). These shapes were now also referred to by descriptive names intended to suggest the contour they represented, rather than by the original numerical methods.

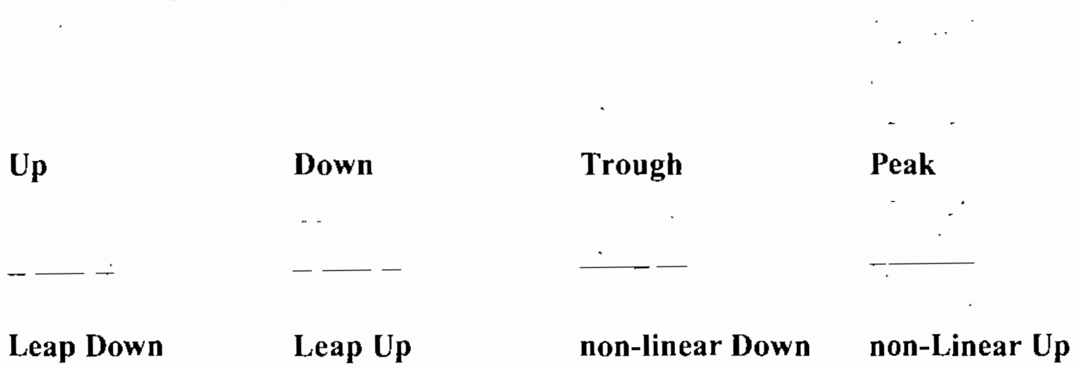


Figure 6.8: Amended contour icon pattern set

The new contour icon pattern set was now put through a further audition with several colleagues (including 2 who had taken part in the first audition). Once again those involved expressed a greater degree of affinity with the patterns than before- and certainly more than the numerical relations. Having said this, the results of the auditions were not 100%, which suggested that the patterns used could at most be described by the contour icons (rather than defined by them).

It was important that the recognition rates for the patterns were as high as possible, and so if the contour icon did not immediately suggest itself to a listener then it could not be considered robust enough for implementation. For this reason, it was then decided to redefine the patterns to better fit the contour icons (6.5.3) that they would be represented by. If a pattern was constructed to suggest the shape of its associated contour icon, then it would ideally help to remove any ambiguities of description found with the previous candidate patterns.

6.5. Contour Icon Pattern Design

The specification of simple visual shapes (6.4.3) as the basis of musical patterns led to the design of the final set of contour icons. The initial low level pattern design guidelines (3.7.5) employed for the reference patterns were used alongside a melodic template defining the overall shape of each contour icon. The design of each pattern was performed in stages, to ensure that gestalt categories of grouping were adhered to without producing confusing patterns. The new pattern set would utilise simple contour shapes as suggested by the auditions, with amendments being considered subsequent to full testing of the principle. Although the potential number of contour shapes was huge, it was decided that the 8 defined by the auditions would form the basis of the contour icon set for testing purposes.

6.5.1. Rhythm Pattern Matrix

Each pattern was designed using an overall rhythm pattern matrix (Table 6.1) which ensured that no two patterns had the same rhythmic signature.

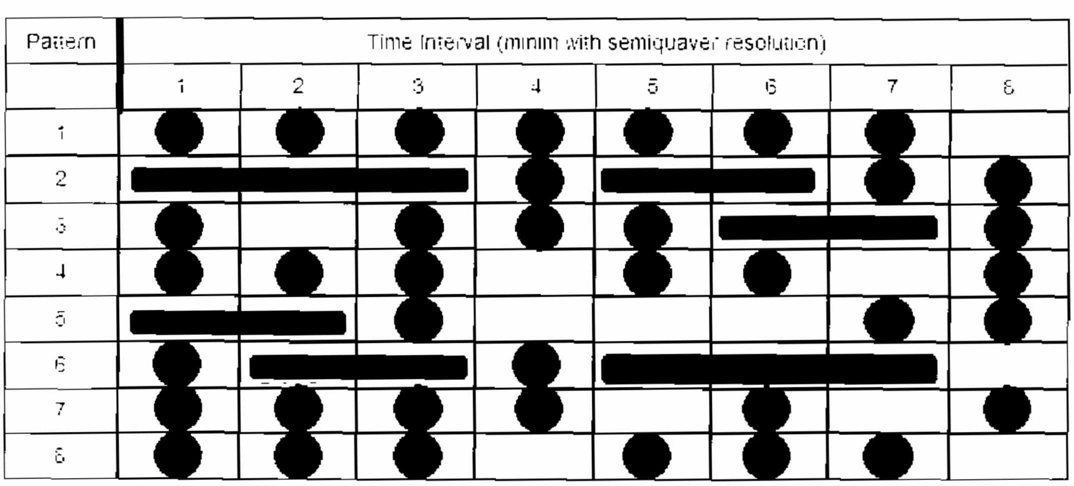


Table 6.1: Rhythm pattern matrix for contour icon pattern design

The aim of the matrix was to provide means of distinguishing the rhythm of each pattern, removing the possibility of two patterns having the same (or similar) rhythm. Patterns 5 and 6 utilised 4 note shapes (leap down and leap up) and so were specified accordingly, with other patterns being defined as a combination of semiquaver, quaver and dotted quaver (patterns 2 and 6) notes.

6.5.2. Boundary Pitches

The 4 boundary pitches used by Adams (2.3.3) in his contour-based classification system were used to give definite anchors to the contour of the overall patterns being analysed. These boundary pitches allowed the shape of the pattern to be accurately specified from point to point- a useful framework for contour design.

This use of boundary pitches also suggested benefits when seeking to create a set of patterns as individual from each other as possible. It had been noticed during the previous tests that participants often struggled to detect patterns that began or ended on the same pitch- perhaps as much a consequence of their proximity as their similarity. As a result, it was considered best practice to use the idea of boundary pitches as part of a design template for the new contour icon set (Figure 6.9).

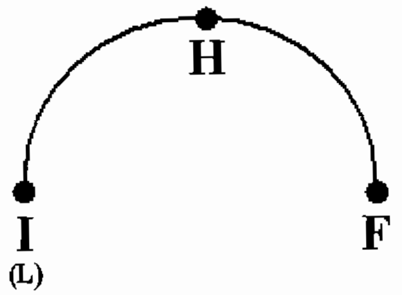


Figure 6.9: Example contour icon defined by boundary pitches

Bass Pattern	Initial (I)	Final (F)	Highest (H)	Lowest (L)
Up	A2	A4	A4	A2
Down	E4	E2	E4	E2
Trough	C4	C4	C4	C3
Peak	F3	F3	Ab4	F3
Leap down	G3	F#2	G3	F#2
Leap up	C#3	Eb4	Eb4	C#3
Non-l down	Ab3	F2	Ab3	G2
Non-l up	Bb2	D4	D4	Bb2

Table 6.2: Boundary pitch table for contour icon pattern set

The boundary pitches used (Table 6.2) would ensure that each pattern differed in overall pitch characteristics from its counterparts- alongside its unique melodic contour. In this manner, it would be less likely that users would struggle to detect the beginning and end of each pattern used in a sonification.

6.5.3. Contour Icon Patterns

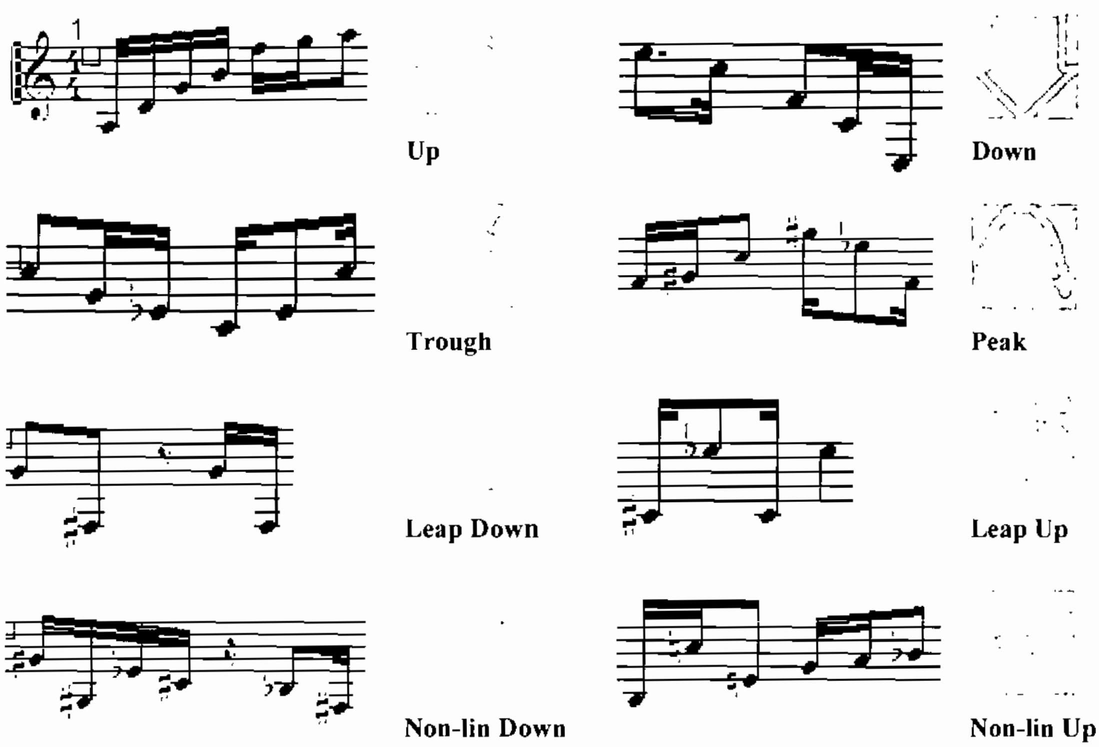


Figure 6.10: Final Contour icon pattern set

The final contour icon pattern set [189] was defined using the low level pattern detection features of rhythm and boundary pitches, alongside the high level recall feature of melodic contour. It was hoped that patterns designed using higher level melodic features would prove easier to recall during testing. With a contour icon pattern set designed, a set of tests was undertaken to assess their effectiveness in relation to the low level reference patterns.

6.6. Contour Icon Testing

Contour icons had been developed in response to RQ 4 of this thesis:

RQ 4: What effect does musical contour have on the recognition (and identification) of musical patterns used in data representation?

The effectiveness of low level reference patterns based on earcon design guidelines [3.7.5] had been considered in chapter 5, with results suggesting that more memorable patterns employing higher level musical attributes were perhaps required. The combination of patterns representing different data variables was also considered, with results again suggesting that more effective methods were required (chapter 7).

The aim of testing was therefore to assess whether contour icons were more memorable than low level musical patterns in data sonification. The 8 contour icon patterns were matched against 8 low level reference patterns (Appendix 10) as used in the tests described in chapter 5. All patterns used conformed to earcon design guidelines (3.7.5), with the contour icon patterns employing the additional high level feature of melodic contour. Testing would show if contour icons improved point estimation scores as defined by RQ 4 of this thesis. By testing point estimation performance in isolation it was hoped to obtain a better understanding of how well patterns were recognised (and remembered during testing). If tests participants could recognise contour icon patterns more easily than the low level reference patterns, then contour icons could be used as a basis for further investigation into pattern combination.

6.6.1. Procedure

20 participants took part in the experiment described in this section which was of a within groups design involving two conditions, the *reference pattern* condition and the *contour icon* condition. All participants used had not taken part in any previous testing during this thesis, nor were they used again during the tests described in chapters 7 and 8. No participants were taken from formal music courses (as had been the case in previous tests), and all participants confirmed they had no formal musical training. Participants were randomly assigned to one of two groups to determine the order in which they would undertake the experiment. Each group contained the same number of participants, and both conditions consisted of training and testing phases (Table 6.3).

	1st Training Session	1st Testing Session	2nd Training Session	2nd Testing Session
Group 1	Reference patterns	Reference patterns	Contour icons	Contour icons
Group 2	Contour icons	Contour icons	Reference patterns	Reference patterns

Table 6.3: Testing procedure for the two groups of participants undertaking the reference pattern vs. contour icon experiment

All tests were performed using survey data held in .csv format files [172], with the number of values identified being the dependent variable. The workload placed on participants by each condition was also of interest, and so NASA TLX questionnaires [164] were filled in by participants after completing each condition.

6.6.2. Training Phase

The training phase was used to familiarise participants with the musical patterns they would be using. Each training phase also contained a tutorial on the sonification method as it was employed during testing (Appendix 5), followed by a brief period in which participants could ask questions about any aspect of the testing procedure they wished. Participants were allowed to audition the 8 patterns used as many times as they required. Once familiar with the patterns a brief listening test was performed, where all 8 available patterns were played to participants once at random. This listening test was used to ensure that all participants could discriminate between every contour icon in the set, to eliminate possible confusions due to ordering effects of patterns in the sonification. If a participant was unable to identify all 8 patterns they were allowed further time to audition them again. After this period a second listening test was performed, and if a participant was still unable to identify all patterns they took no further part in the experiment. In this experiment, all participants identified their pattern choices within 2 attempts as required.

Participants were played an example sonification, accompanied by a visual diagram of the data they were listening to. In the reference pattern condition, participants were shown a list of numerical icons representing each data value in the sonification they were listening to. In the contour icon condition, participants were given an accompanying list of contour icons denoting the patterns they were hearing. After the example sonification, a further brief period was allowed for any other questions participants had about the experiment.

6.6.3. Testing Phase

In the testing phase participants were asked to sonify the contents of 5 survey data files (Appendix 7) of .csv format. The survey files used contained single variable data ranging from 2 to 6 values. This was an increase on the 4 value data sets used in previous tests (5.6.2), allowing a more comprehensive assessment of pattern recognition. If a participant could accurately detect larger pattern sets when used in a data sonification, it would suggest that those patterns were easier to recall.

All sonifications were performed on a Compaq NX6100 laptop, using the onboard ADI AC97 soundcard. Testing in chapter 5 had suggested that timbre choices be constrained (5.8), rather than allowing the participant to make their own timbre choices. For this reason, all tests were carried out using the General MIDI [153] piano sound provided by the ADI AC97 synthesis engine. Participants were asked point estimation questions about the data they had sonified (Appendix 11), to determine how effectively the data had been conveyed. The independent variable in testing was the method of pattern design (low level patterns or contour icons) with the dependent variable being the number of correct point estimation questions answered. The experiment considered the following hypothesis derived from RQ 4:

> Hypothesis 1: Does melodic contour affect musical pattern recognition and identification in data sonification?

All tests were performed with participants being handed writing materials after listening to a sonification, to prevent the scoring of patterns prior to testing (6.3.2). As pattern design was the testing variable, it was crucial that all participants determined the patterns used based only on information provided during testing. Participants were allowed to listen to a data sonification once for each part of a question, ranging from 2 passes through to 6 for the last question of each test. After the 5 test questions were answered, participants were asked to answer post-test TLX questionnaires to determine how difficult they had found the process.

6.7. Results

The aim of testing was to assess the affect on pattern recognition of musical patterns designed with (contour icons) and without (reference patterns) specific melodic contours. The earcon design guidelines (3.7.5) used to create all test patterns were further augmented by basic contour shapes to aid in their recognition. The test schedule assessed point estimation performance for participants using reference patterns and contour icons.

6.7.1. Overall Results

The overall test results (Appendix 12 & Figure 6.11) showed that performance had improved from 44% in the reference pattern condition to 56.87% in the contour icon condition. This was a significant improvement ($T(20) = -3.68$, $p=0.0007$) in point estimation performance between test conditions, suggesting that contour icons were more memorable than low level reference patterns.

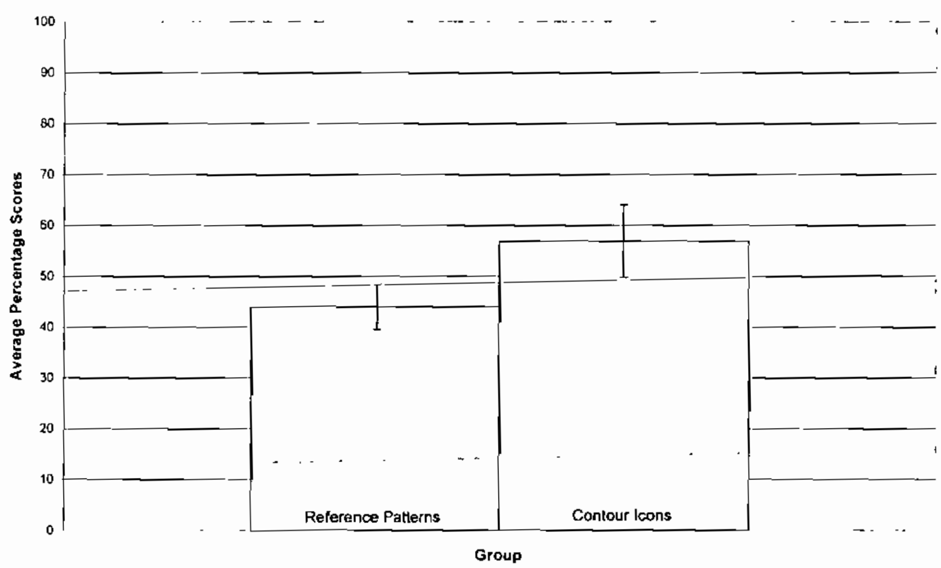


Figure 6.11: Graph showing overall average percentage results (by test condition), showing standard deviations

It was noted that point estimation performance was not as high as the original reference patterns tests (5.6.1), and this could partly have been a consequence of using only non-musicians during testing. The reference pattern tests had also used 4 patterns rather than the maximum 6 in the current tests, and this would also have had a bearing on overall performance. To consider this further, the results for individual value counts were now investigated.

6.7.2. Effect of Value Count on Point Estimation

Point estimation tests had been performed using data files containing 2 through to 6 different values (Figure 6.12), to determine how well participants could recognise the patterns they were asked to detect.

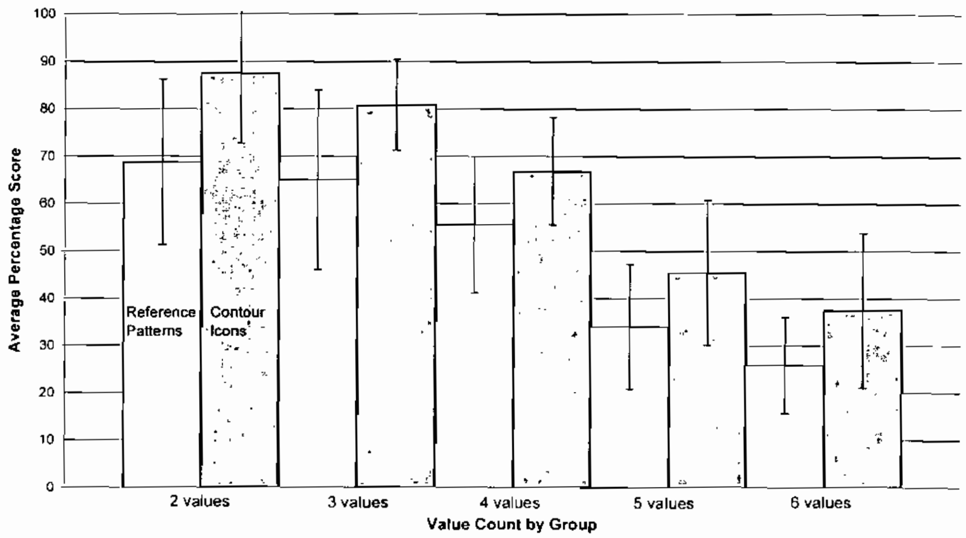


Figure 6.12: Graph showing average percentage results by value count (for each test condition), showing standard deviations

Test results showed that performance in the 2 value condition had reached an average of 87.5% in the contour icon condition (compared to 68.75% for reference patterns), and had decreased through 80.83% (65% reference) to 66.87% for the 4 value test (55.62% reference). This was considered to be a reasonable level of contour icon recognition given that there had been no exposure to them prior to testing. Having said this, performance in the 5 and 6 value conditions dropped from 45.5% (34% reference) to 37.5% (25.83% reference), which was still too low for effective recognition. It had been observed on several occasions during these higher value tests that participants recognised the contour icon they were listening to, but could not recall which value it represented in the data set. This suggested that recognition rates were still reduced by the requirement to map patterns to values (6.3.2), regardless of the effectiveness of the patterns themselves. It was also noted that some participants struggled with the increase in information due to increases in value count, being unsure how many times they had heard a particular contour icon when it did not occur frequently in the sonification.

6.7.3. Post Test TLX Results and Testing Observations

At the end of each session, participants completed a TLX test questionnaire (Appendix 13), to determine what effect contour icons had on workload. The overall TLX results (Figure 6.13) showed a significant reduction (T(20) =4.53, p<0.0001) in overall workload from 50.33 to 36.25 for the contour icon condition.

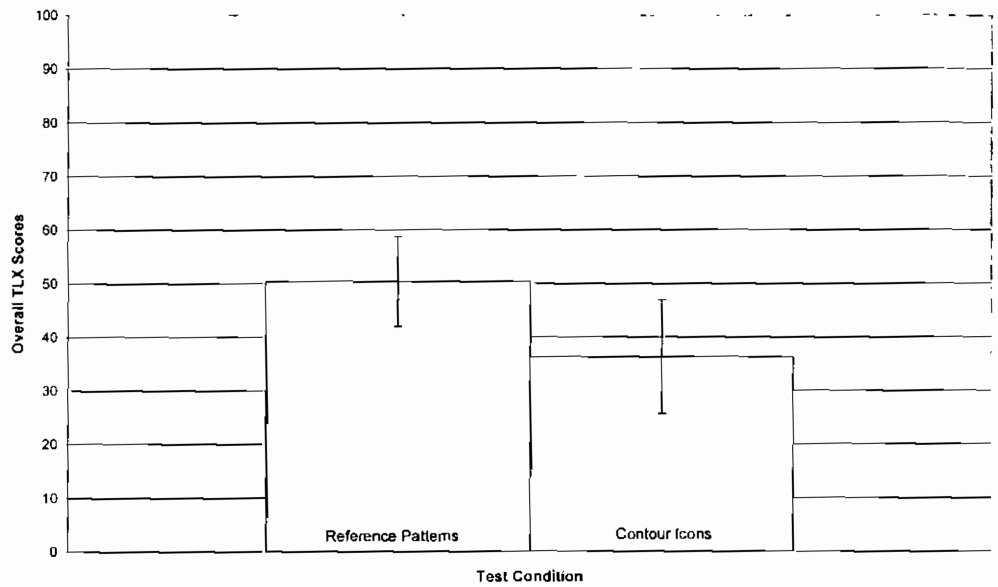


Figure 6.13: Graph showing overall average post-test TLX results (by test condition), showing standard deviations

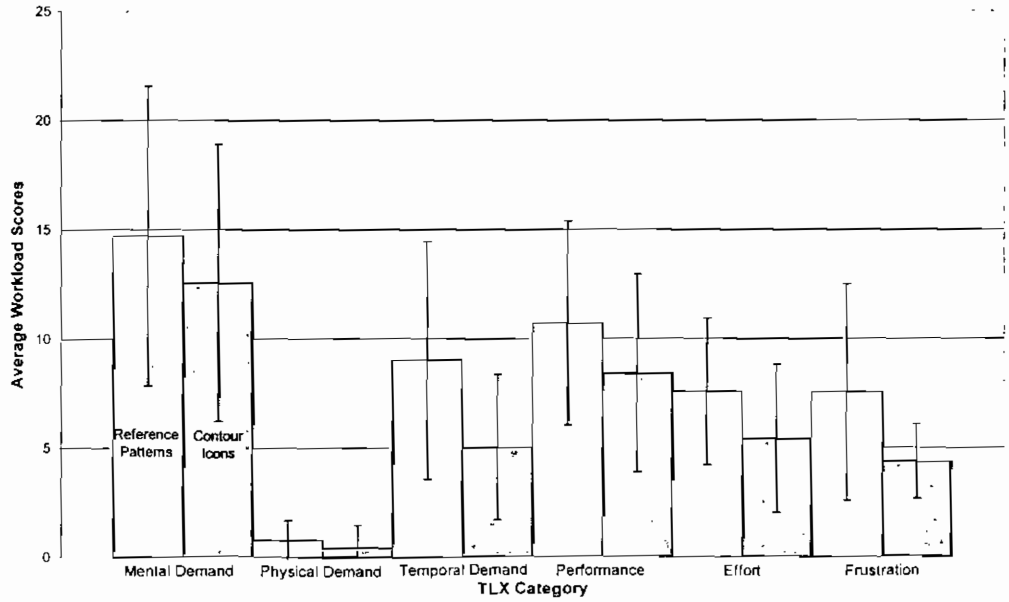


Figure 6.14: Graph showing average post-test TLX results by category (for each test condition), showing standard deviations

Individual workload scores (Figure 6.14) showed that mental demand had been considered the most important aspect of testing, with a reduction in average from 14.72 to 12.57 for the contour icon condition being observed. Though no reduction was significant in any individual category, the scores were lower for the contour icon condition in each case. No problems were encountered during explanation of the test schedule, and participants understood the principle of sonification as it related to the tests.

6.8. Discussion

The contour icon tests had shown that significant improvement could be made when melodic contour was employed as a feature in pattern design, as required by RQ4. Testing had employed non-musicians in a series of point estimation questions, which had shown that contour icons could achieve average recognition rates of 66.87% in 4 value sonifications. Higher value counts had proven less effective, and it was observed on several occasions that participants could determine a particular contour icon but were unable to remember its data mapping. This suggested that the abstract nature of the mapping between value and contour icon was difficult to remember for greater numbers of values, as a contour icon cannot convey any information specific to a data value.

Participants were comfortable with the use of shapes as descriptors of musical patterns, and often suggested other possible shapes during training. This was considered an indicator of the potential of contour icons, in that no musical knowledge or training is required to recognise a melodic shape. Other icon shapes were considered for future testing, but the initial set of 8 used had been recognised and understood by all participants.

It was also noted that some participants found the retention of information more difficult for higher value counts. This aspect of testing had not been fully considered during the design of the experiment, as previous tests had not employed higher value counts. It was realised that some elements of lower point estimation performance were partially attributable to numerical difficulties engendered by the higher value counts involved. These difficulties had manifested themselves as inaccurate point estimations in situations where the participant could not recall how many times a contour icon had occurred, even though they could detect that contour icon. In several other instances, participants had become confused during a sonification and could not recall what they had been listening for during higher value tests. This showed that although contour icons were more effective than the low level reference patterns, they were not yet effective for higher data rates.

Post test TLX questionnaires had shown a significant reduction in overall workload due to contour icons, with all individual categories exhibiting a reduction (although not individually significant). This suggested that contour icons were a more effective method of pattern design than the low level reference patterns, providing participants with a straightforward means of pattern recognition and recall.

6.9. Conclusions

Contour icons had been developed to investigate RQ 4 of this thesis:

RQ 4: What effect does musical contour have on the recognition (and identification) of musical patterns used in data representation?

Low level reference patterns based on earcon design guidelines (3.7.5) had been used for comparison with contour icons in testing, to assess whether contour icons were more memorable in data sonification. Point estimation performance was tested in isolation rather than in conjunction with pattern combination questions (5.5.5) to obtain a better understanding of how well patterns were recognised. Greater numbers of patterns (up to 6) were tested during a single sonification, to observe the effect on performance this would have. Participants in testing were not musically trained, and so assessment of the effectiveness of the patterns used gave better indicators of how such patterns may perform in general.

6.9.1. Testing Conclusions

Contour icons had shown significant improvement in performance during testing, with recognition rates of 87.5%, 80.83% and 66.87% for 2, 3 and 4 value tests respectively. These results showed that musical patterns designed using high level contour features were more memorable than low level patterns employing distinctions of rhythm, register and timbre (3.7.5). Contour icon shapes employed during testing had been effective in conveying the melodic contours they represented, with suggestions for other contour icons being made by participants during training. Contour icons had also produced a significant reduction in workload during testing, again suggesting greater effectiveness than the low level reference patterns.

6.9.2. Limitations of Contour Icons

Although contour icons had performed well in 2 to 4 value tests, this level of recognition had not been observed for higher value counts. As a result, contour icons could not be considered any more effective than low level reference patterns in these cases. This reduction in point estimation performance was considered to be indicative of one of the limitations of contour icon sonification, in that data with high value counts requires a similarly large set of patterns to describe it. By using purely abstract mappings to represent data, the listener is required to make the connection between pattern and value, and so performance is related to the amount of such connections a listener is capable of making.

This level of abstraction is not found in low level patterns such as earcons (3.7), which employ features within the earcon pattern to denote specific information. Although contour icons are not intended for use in the same manner as earcons (or indeed vice versa) the arbitrary mapping of pattern to value can create confusion during a sonification. Further consideration would have to be given to the uses of contour icons (perhaps with small groups of data such as alerts or other graded information), alongside the means by which they may be made less arbitrary as mappings.

6.9.3. Overall Conclusions

Contour icons were developed as a means of employing musical contour in pattern design. Contour icons had performed significantly better during testing than low level patterns which had been designed using earcon design guidelines (3.7.5). Although limited in effectiveness (at present) to small data sets of 4 values, the implementation of contour icons had improved point estimation performance in data sonification. Testing carried out using reference patterns (5.8) had indicated that improved pattern design methods were required, and the introduction of contour icons had fulfilled this requirement as specified by RQ 4. These tests had also indicated that pattern combination was not effective using low level patterns, and so required separate investigation. For this reason, the means by which patterns could be harmonically combined for the purposes of data sonification were next investigated (chapter 7).

7. Harmonic Pattern Combination

7.1. Introduction

The tests performed using contour icon pattern design methods (chapter 6) had shown that musical patterns incorporating higher level attributes such as melodic contour were more effective than those designed using low level attributes. This result was encouraging, and so contour icons were now used in pattern combination development. The reference pattern testing session (5.6.1) had shown pattern combination detection to be the lowest aspect of testing performance, with test participants struggling to determine combinations of patterns in most instances. In this chapter, the means by which multiple patterns relating to different data variables can be effectively combined is investigated by employing harmonic combination of patterns, as defined in RQ 5. A set of tests was performed using contour icon patterns, in both non-harmonic and harmonic combinations. These tests were intended to assess the potential (and limitations) of harmonic combination of patterns, using patterns which had already been demonstrated as more effective (6.7.1) than the low level reference patterns used in pattern combination in chapter 5.

Pattern combination tests performed using low level reference patterns (5.6.1) had proven ineffective. Such low performance suggested that multiple pattern detection was not possible when employing abstract low level reference patterns. Although the design of patterns had been improved (6.4) it was not clear if this was the only factor affecting pattern combination detection. Pattern combinations had not been tested, and so there was no evidence to suggest that contour icon patterns were any more recognisable in combination than the low level reference patterns had been. For this reason, further consideration was given to pattern combination prior to testing.

7.2. Pattern Combination Detection

Results obtained from pattern combination testing (5.6.1) had suggested that combining patterns representing multiple variables prevented listeners from determining more than one pattern at any given time. It was realised that 2 concurrently rendered patterns would not necessarily exhibit any features of similarity or belongingness (2.5), particularly when those patterns were subsequently required to be mapped to data values (6.3.2). This lack of grouping categorisation would not allow listeners to determine which patterns were related to each other, and so pattern combination detection had proven difficult. By utilising purely abstract musical patterns with no specific high level features in common, participants were still required to perform too many operations to detect combinations of patterns (Figure 7.1).

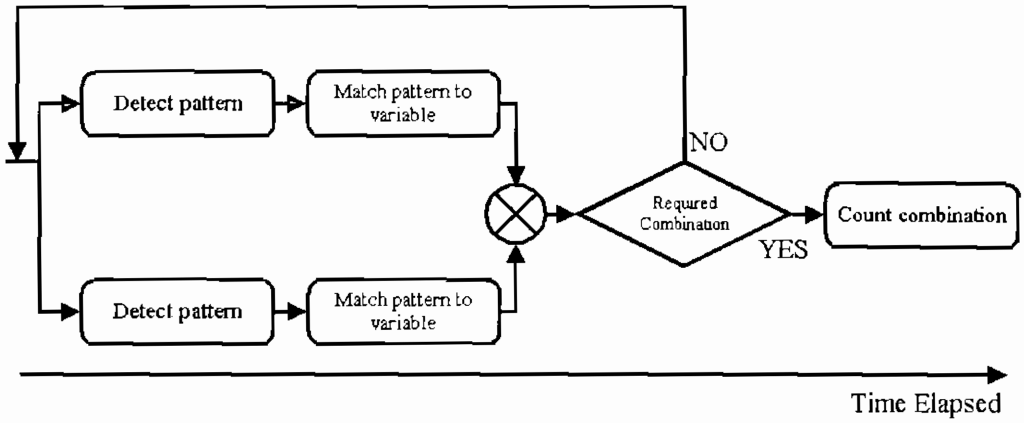


Figure 7.1: High level representation of 2 pattern combination detection thought process

Contour icon testing had shown that listeners performed better when high level melodic features (such as contour) were used as pattern descriptors, and so the means by which such description could be implemented in pattern combinations was now considered.

7.2.1.Streamlined Harmonic Combination Detection Process

A possible improvement to the pattern combination process is the harmonic combination of patterns, requiring the listener to detect a single pattern played by 2 (or more) instruments. By reducing the number of patterns required for combination detection, the process of such detection may be performed more efficiently (Figure 7.2) than with differing patterns.

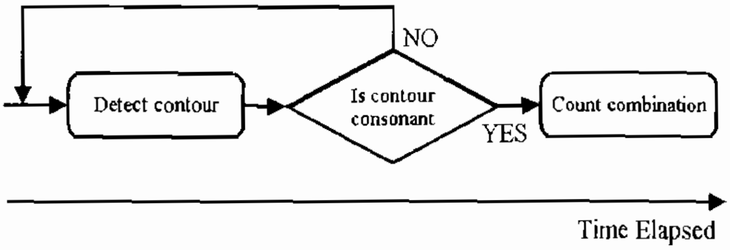


Figure 7.2: High level representation of streamlined 2 pattern combination detection thought process

When specific combinations of patterns are required in multiple variable sonifications, harmony may allow these combinations to be highlighted by their consonance. This use of harmony had been considered in work by Hankinson and Edwards [114], which had investigated the use of harmonic relations between earcon patterns. Related earcons (such as a copy earcon with a file earcon) would sound harmoniously, and thus give the listener hierarchical information about the pattern combination they had heard. This relation was taken as the basis of development in harmonic combination, ideally providing a means of effectively rendering 2 or 3 variable pattern sonifications.

7.3. TrioSon Framework Re-Evaluation

In considering the means by which patterns may be harmonically combined, the existing pattern framework implemented by the TrioSon software (5.3) required alteration. Testing performed on 3 variable combinations in chapter 5 (5.5.1) had used bass and melody patterns alongside chord intervals. It had been noted that chord intervals could not provide the same amount of information as musical patterns (5.8), being devoid of many of the rhythmic and melodic distinctions possible with bass or melody patterns. In combining patterns harmonically, it was essential that only patterns were used.

7.3.1. Chord Interval Re-Evaluation

The use of chord intervals in the reference pattern testing had been implemented as an extension of the basic intervals used in the DNASon case study (4.2.3). These intervals were used as part of a pattern design framework based on the instrumental arrangement of the trio [22], but this format had not produced good results during testing (5.6.1). One of the main areas requiring improvement was that of pattern combination detection, with the interactions between patterns being insufficient for accurate detection. When it had initially been decided to implement a trio framework, one of the reasons for doing so was a desire to capitalise on the effective interplay that can be achieved by several instruments in a performance environment. In using chord intervals as part of this orchestration, the interactions between different patterns in the trio were limited by the static nature of those intervals. For this reason, it was decided to replace the chord interval choices with contour icon patterns in the same register as those chords.

7.3.2. Lack of High Level Audio Attributes

The design process sought to investigate the role of high level audio attributes in pattern recognition (RQ 4 & RQ 5), and it was noted that chord intervals do not possess such attributes as contour. This lack of high level attributes was also considered in the context of work by Hankinson and Edwards [114], and if contour icon patterns could be combined harmonically (RQ 5) then potential would exist for more effective pattern combination detection. This harmonic combination would also be a more robust method of assessing contour icons in isolation, rather than testing them in conjunction with chord intervals (which could serve to confuse results). With this in mind, a new method of trio arrangement was proposed for assessment.

7.4. Harmonic Combination

When 2 musical pitches are sounded together they are defined as an interval (2.2.5), and the relation of these pitches determines the interval as consonant or dissonant [22]. The definition of consonance and dissonance in western music has changed with each period of compositional style [178], but relations of 3rd, 5th and octave [24] have remained sufficiently constant to allow implementation. The most recognisable interval is that of the octave [179], and so this relation was used as an initial basis for development.

7.4.1. Low Level Harmonic Pattern Combination

In combining contour icons from different instruments harmonically, consideration had to be made of the potential violation of several of the current pattern design guidelines. The register of each pattern would be crucial, with the maximum distance between the pitches of each pattern set being a requirement of the earcon design guidelines (3.7.5). In implementing this guideline, it must be noted that its employment is not suggested as sole means of segregation for patterns. For this reason, it can be argued that although register may not be an efficient single discriminator [145] it may also not necessarily serve to confuse patterns that employ other methods of recognition (such as contour).

A similar claim can be made for pattern rhythm, which would not necessarily be violated if each contour icon possessed sufficiently distinct rhythmic structures from one another. In this manner, pattern combinations involving the same contour icon, played on different instruments in unison, would all possess the same rhythmic structure and hence be grouped together in the auditory scene. If significant differences were maintained between pattern rhythms, this grouping by rhythm would not take place between different contour icons.

7.4.2.ASA Factors In Harmonic Combination

Many of the requirements of the gestalt categories could potentially be achieved with effective harmonic pattern combination:

1. *Familiarity-* Harmonic pattern combinations would retain the audio attributes of single contour icons, and hence suggest the same shapes.
2. *Similarity-* By using the same contour icon for each instrument in a specific combination the resulting auditory stream could be grouped due to similarity.
3. *Good continuation-* As with single contour icons, the contour of a harmonic pattern combination would change as expected (by the icon shape) and so exhibit good continuation.
4. *Belongingness-* Harmonic combinations could be considered as belonging to the same auditory stream on grounds of rhythm (6.5.2) and melodic contour.
5. *Articulation-* With only one contour icon being present in a harmonic combination there would be less information for the listener to process. In this manner, a contour icon harmony could be considered articulate.

7.4.3.Potential Issues with Harmonic Combination

The other gestalt category of proximity was considered part of the means of stream segregation, particularly due to temporal onset and spatialisation (5.2.6). Tests performed using reference patterns (5.6) had allowed the user to specify their own panning choices for each instrument used, but this factor would have to be re-evaluated in relation to the gestalt grouping categories. Temporal distinctions had been intended using rhythmic offset (5.4.6) during the rhythmic parsing tests (chapter 8), but this could contradict the stream grouping categories used to define harmonic combination and so would also have to be re-assessed.

Harmonic combination would also determine the amount of value combinations that could be examined, with the use of 3 instruments in different octaves allowing a single distinct combination of values to be specified. By using pattern combinations based on the octave, only one possible combination of 3 values was possible for any contour icon. This was not considered to be a limitation that would prevent testing, which would only assess whether harmonic combination was effective (rather than the extent of its application). Having said this, future work would have to consider the limits of pattern combination (perhaps by considering register gaps other than the octave) so that it may be fully and effectively implemented.

7.5. Contour Icon Re-Definition

Each of the gestalt categories mentioned previously is used as a means of justifying the grouping of a set of patterns harmonically, but these conditions are also used to segregate different audio events into separate streams within the auditory scene. In order that this would not create problems during testing, the design of the contour icons used was now considered in terms of maximising their areas of distinction (rhythm, contour, register, timbre and spatialisation) in order that no contour icon patterns would conflict during testing.

7.5.1. Rhythm

Rhythm is one of the most important features of pattern design, and the rhythm pattern matrix used in the original contour icon design (6.5.1) was similarly maintained for the pattern combination tests. By allocating a distinct rhythm to each contour icon, the segregation of each icon could be performed in a multiple pattern stream.

7.5.2. Contour

The 8 contour icon shapes (6.5.3) used in the chapter 6 tests were retained for the current tests. This led to an important change of implementation, as the chapter 6 tests had allowed participants to allocate any of the 8 contour icons as they wished (6.6.3) during testing. As harmonic combination was to be tested, the non-harmonic condition would require that no control test could utilise the same contour icon more than once (to prevent the occurrence of any harmony). This restriction would allow for a maximum of 4 distinct values in the 2 variables condition (or 2 values for 3 variables) within the set of 8 contour icons used.

Consideration was given to the introduction of more contour icon shapes, but it was noted that point estimation tests using contour icons had not been particularly effective for 5 and 6 value conditions (6.7.2). For this reason, there was no evidence to suggest that any sonification requiring greater than 4 contour icons would be any more effective in combination than had been observed in the individual tests. This condition was offset by the nature of the pattern combinations, which would require a maximum of 3 contour icons to be detected for any one question. By constraining the contour icon choices a participant could make in the control condition, the maximum number of values sonified in the harmonic combination condition would thus be the same. This would be less than the potential number of values that could be sonified, but would allow assessment of harmonic combination in testing.

7.5.3. Register

The register of each pattern set would determine its place within the trio, and hence the data variable represented. Earcon design guidelines (3.7.5) specify that register is a poor source of discrimination in isolation, but if used as part of a design template should ideally utilise gaps of 2 or 3 octaves [188]. The trio format employed in this research could be considered in terms of bass middle and treble patterns (paraphrasing audio terms for frequency ranges [180]), and so the distance between the pitches in each of the bass, middle and treble patterns would be set at 2 octaves (Figure 7.3).

Figure 7.3: Register gap for example contour icon (Up) in all trio instruments (bass, middle and treble)

The bass patterns used were pitched in the range of A0 to A2, with middle patterns from A2 to A4 and treble patterns from A4 to A6. It was noted that a strict gap of 2 octaves did not exist between all patterns, with certain patterns having a greater range of pitch than others (e.g. 2 octaves for Up and Down contour icons). However, this overlap would be countered by the use of boundary pitches, preventing any occurrence of the same pitch at the beginning or end of any pattern (regardless of register).

7.5.4. Timbre

Tests performed in chapter 6 had constrained timbre to a single piano sound. In the harmonic tests, 3 distinct timbres were required that would define bass, middle and treble pattern streams in a sonification. As a result, patterns were chosen based on the different timbre families defined by Rigas and Alty [28]. The bass patterns were allocated the '*picked bass*' sound from the General MIDI soundset [153], with middle patterns being allocated the '*drawbar organ*' and treble patterns allocated the '*flute*' sound. Each pattern was taken from the piano, organ and woodwind categories (2.2.6) defined by Rigas and Alty, due to the poor quality of the wind section timbres and the slow attack of the strings section timbres on the ADI AC97 soundcard used during testing.

7.5.5. Spatialisation

Tests in chapter 5 had allowed participants to choose spatial locations during testing. Testing observations had shown that participants chose standard locations within the azimuth [10] (left, centre and right) and this determination was preserved. In 2 value sonification (involving 2 concurrent pattern streams) the instruments used would be panned left and right, while 3 instruments would be allocated left, centre and right (Figure 7.4). This would allow for the maximum difference in location possible within the stereo field, and so reduce the possibility of proximity effects (2.5.5).

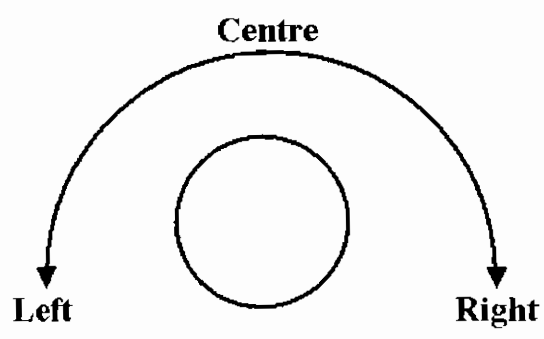


Figure 7.4: Example azimuth locations within the stereo field

Investigation by McGookin [100] showed that the use of spatialisation has a significant effect in concurrent audio presentation. McGookin suggests that the maximum azimuth angle between streams (instruments) be utilised to allow for the most effective pattern recognition, and by using left, right and centre locations in testing this could be achieved.

7.6. Harmonic Combination Testing

The harmonic combination of musical patterns was investigated in response to RQ 5 of this thesis:

RQ 5. What effect during concurrent presentation does harmonic combination have on the identification of features and intersections in data streams?

The combination of patterns representing different data variables had been considered in chapter 5, with results suggesting that more effective means were required. Testing had shown that it was difficult for participants to detect multiple patterns (7.2), and so the combination of a single pattern in 2 or 3 part harmonies was investigated as a possible solution.

The aim of testing was therefore to assess whether harmonic combination was a more effective means of detecting pattern combinations in data sonification. The 8 contour icon patterns developed during the previous set of tests (6.5.3) were now used to assess the effect of harmonic pattern combination. All contour icon patterns used conformed to earcon design guidelines (3.7.5), and were rendered in a maximum of 3 different registers (bass, middle and treble) as required during testing. Testing would show if harmonic pattern combination improved both point estimation and pattern combination test scores as defined by RQ 5 of this thesis.

7.6.1. Procedure

20 participants took part in the experiment described in this section which was of a within groups design involving two conditions, the *non-harmonic combination* condition and the *harmonic combination* condition. All participants used had not taken part in any previous testing during this research, nor were they used again during the tests described in chapter 8. No participants were taken from formal music

courses and all participants confirmed they had no formal musical training. Participants were randomly assigned to one of two groups to determine the order in which they would undertake the experiment. Each group contained the same number of participants, and both conditions consisted of training and testing phases (Table 7.1).

	1st Training Session	**1st Testing Session**	**2nd Training Session**	**2nd Testing Session**
Group 1	Non-harmonic combination	Non-harmonic combination	Harmonic combination	Harmonic combination
Group 2	Harmonic combination	Harmonic combination	Non-harmonic combination	Non-harmonic combination

Table 7.1: Testing procedure for the two groups of participants undertaking the non-harmonic combination vs. harmonic combination experiment

All tests were performed using survey data held in .csv format files [172], with the number of values identified and number of combinations identified being the dependent variables. The workload placed on each participant was assessed by NASA TLX questionnaires [164], which were filled in by participants after completing each condition.

7.6.2. Training Phase

Participants were first introduced to the musical patterns they would be using, followed by a brief period for questions about the testing. The use of contour icons to represent data was explained, alongside the means by which they would be combined harmonically. Each training phase also contained a tutorial on the sonification method as it was employed during testing (Appendix 5). Participants were asked to audition the 8 contour icon patterns used prior to a brief listening test, wherein all 8 patterns were played to the subject once at random. This listening test was used to ensure that all participants could discriminate between every contour icon in the set, to eliminate possible confusions due to ordering effects of patterns in the sonification. If a subject was unable to identify their pattern choices they were allowed further time to audition them again. After this period a second listening test was performed, and if a participant was still unable to identify all patterns they took no further part in the experiment. In this experiment, all participants identified all 8 contour icons within 2 attempts as required.

Participants were then played sample combinations of patterns, involving various contour icons in harmonic and non-harmonic combinations. In each case, a participant was asked to define the number of instruments present, what contour icon(s) they heard and whether all instruments played the same contour icon. If a participant could not accurately detect the presence of multiple instruments they took no further part in testing. If a participant could not determine a consonant or dissonant contour icon pattern for multiple instruments they took no further part in testing. In this experiment, all participants identified the number of instruments and their harmonic combination correctly.

All participants were played an example sonification, with an accompanying visual listing of the contour icon patterns used in that sonification. In the non-harmonic combination condition, participants were informed they were required to detect combinations of differing contour icons in 2 and 3 variable conditions. In the harmonic combination condition, participants were told they would be asked to detect a single contour icon played in harmony by 2 or 3 instruments. After the example sonification, a further brief period was allowed for any other questions participants had about the experiment.

7.6.3. Testing Phase

In the testing phase, participants were asked to sonify the contents of 5 survey data files of .csv format (Appendix 7). The survey files used contained multiple variable data ranging from 2 to 4 values. Testing sought to assess how well participants could detect point estimation and pattern combinations for 2 and 3 variables. The test format contained three 2 variable tests ranging from 2 to 4 values, followed by two 3 variable tests for 2 value data sets.

All sonifications were performed on a Compaq NX6100 laptop, using the onboard ADI AC97 soundcard. Participants were asked point estimation and pattern combination questions about the data they had sonified, to determine how effectively the data had been conveyed. Point estimation questions were used to determine whether participants could effectively detect a single pattern accurately in a multiple stream sonification. It was possible that harmonically combining patterns could affect perception of individual patterns in a sonification, and so point estimation questions would show whether participants had any difficulties with this condition. Pattern combination questions were intended to show the effectiveness of harmonic combination in a multiple stream sonification. The independent variable in testing was the harmonic combination of patterns, with the dependent variables being the number of correct point estimation and pattern combination questions answered. The experiment considered the following hypotheses derived from RQ 5:

Hypothesis 1: Does harmonic combination affect the identification of individual features in a data stream during concurrent presentation?

Hypothesis 2: Does harmonic combination affect the identification of intersections in data streams during concurrent presentation?

All tests were performed with participants being handed writing materials after listening to a sonification. A participant was allowed to listen to a sonification once for each question they were required to answer. Once testing had been completed, each participant was asked to answer a TLX questionnaire on their performance.

7.7. Results

The aim of testing was to assess the affect of harmonic combination on point estimation and pattern combination detection within a multiple stream sonification. The test conditions used non-harmonic and harmonic combination respectively, to assess which case (if either) was more effective. The test schedule assessed point estimation and pattern combination performance for participants in both conditions.

7.7.1. Overall Results

The overall test results (Appendix 15 & Figure 7.5) showed that performance had improved from 58.25% in the non-harmonic combination condition to 75% in the harmonic combination condition. This showed significant improvement ($T(20) = -3.02$, $p=0.0043$) in performance between test conditions, suggesting that harmonic combination was more effective in multiple stream sonification.

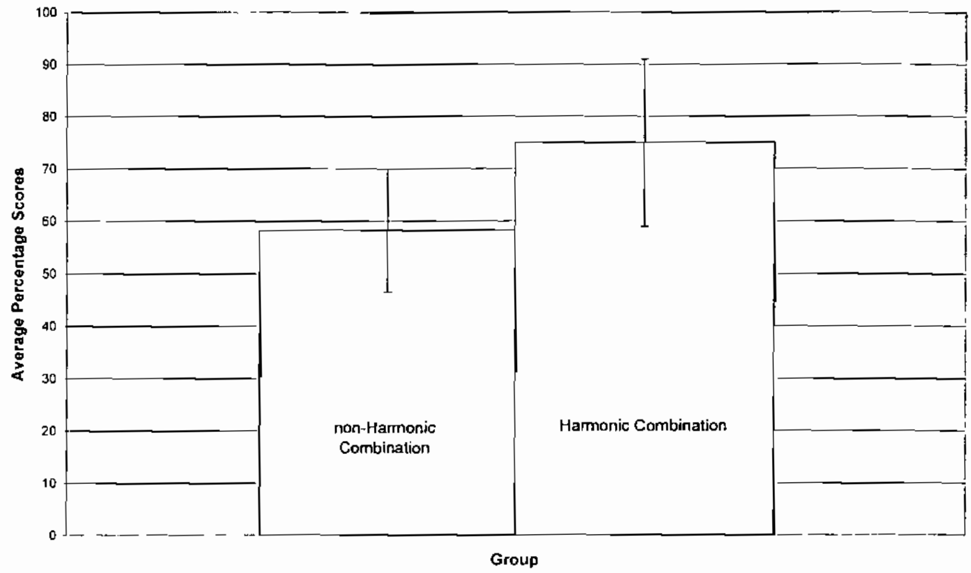


Figure 7.5: Graph showing overall average percentage results (by test condition), showing standard deviations

To consider this improvement further, the individual results for point estimation and pattern combination questions were next considered.

7.7.2. Effect of Harmonic Combination on Point Estimation

Point estimation questions had been asked to determine whether harmonic combination had any effect on individual pattern detection performance (Figure 7.6).

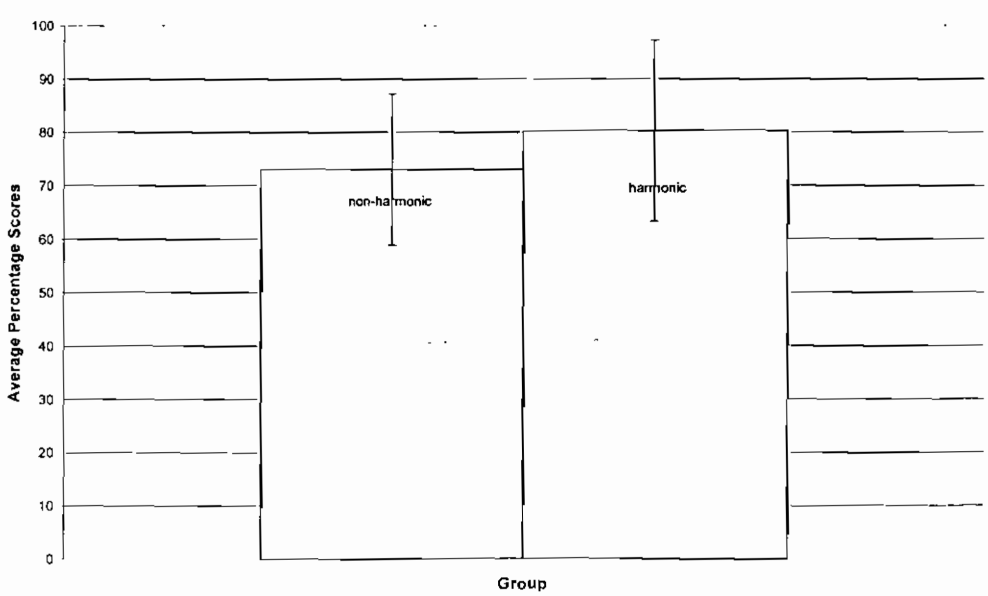


Figure 7.6: Graph showing average point estimation percentage results (for each test condition), showing standard deviations

Results showed that point estimation performance in the non-harmonic condition had improved from 73% to 80.25% in the harmonic condition. Although not significant (T(20) = -1.43, p=0.161), there had been no reduction in performance due to the use of harmonically combined patterns (indeed an increase had been observed). This result showed that harmonic combination would not affect the point estimation of individual patterns in a multiple stream sonification, as required by testing hypothesis 1.

7.7.3. Effect of Harmonic Combination on Pattern Combination

The main aim of harmonic combination was the improvement of pattern combination detection during multiple stream sonification, which had been the lowest aspect of testing performance during the original reference pattern tests (5.6.3). Although overall results had improved due to harmonic combination, the specific effect on pattern combination performance was now considered.

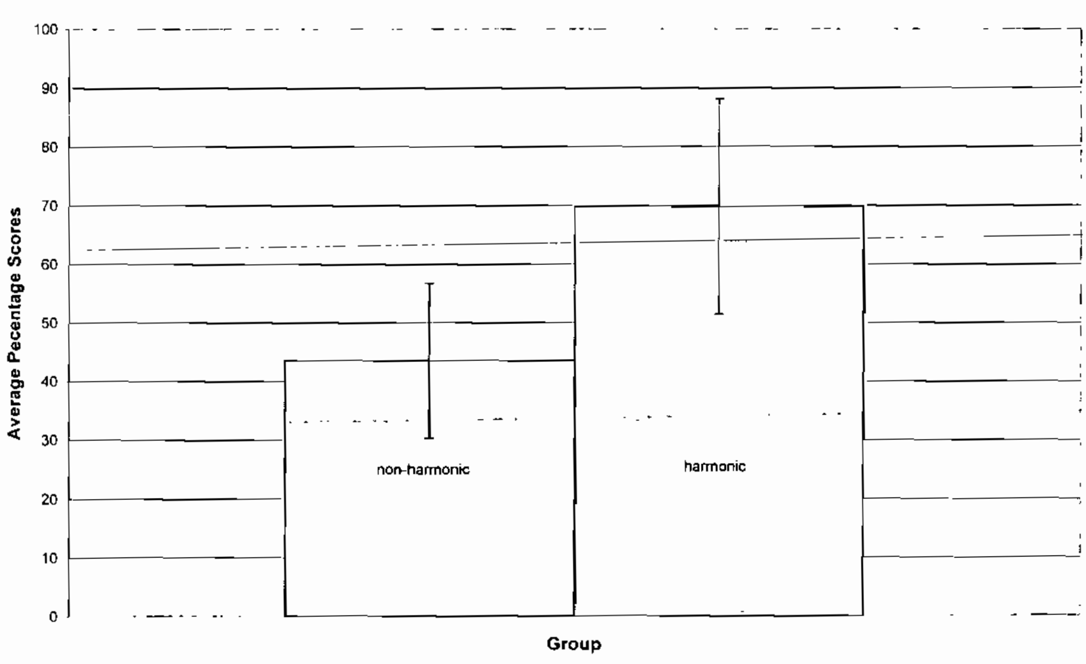


Figure 7.7: Graph showing average pattern combination percentage results (for each test condition), showing standard deviations

Results for the pattern combination test questions (Figure 7.7) showed significant improvement from 43.5% for the non-harmonic condition to 69.75% in the harmonic condition (T(20) = -5.06, p<0.0001). This result was encouraging, as the pattern combination scores were higher in both cases than had been observed during reference pattern testing (5.6.3). Harmonically combined patterns had been significantly easier to detect, and so the results for 2 and 3 pattern combinations were now considered individually (Figure 7.8).

Scores for 2 variable pattern combination questions showed a significant increase from 50.42% for the non-harmonic condition to 79.17% for the harmonic condition ($T(20) = -4.36$, $p<0.0001$). A similarly significant increase was observed in the 3 variable pattern condition ($T(20) = -3.52$, $p=0.001$), with an average non-harmonic combination score of 33.12% rising to 55.62% in the harmonic combination condition.

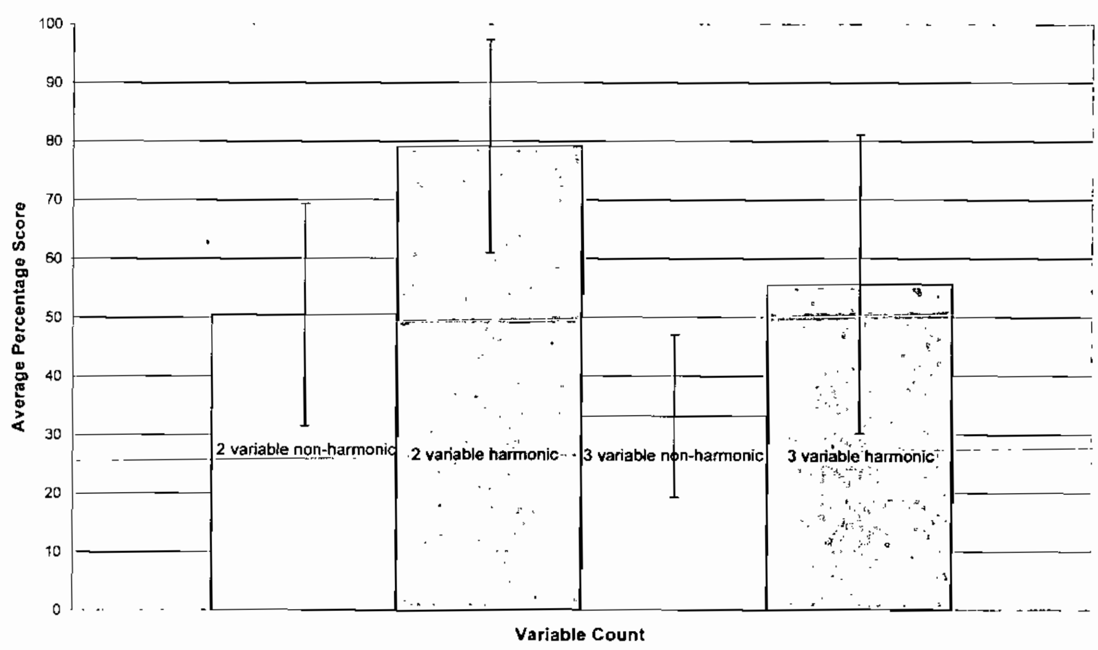


Figure 7.8: Graph showing average 2 and 3 variable pattern combination percentage results (for each test condition), showing standard deviations

However, it was noted that performance in the 3 variable condition was not as effective as had been hoped, with some participants detecting false positive values in conditions where 2 instruments were in harmony (rather than the required 3). Future work would have to consider how harmonies of 2 instruments in 3 variable combinations could be made more dissonant, to highlight the presence of a conflicting value in the third instrument present.

7.7.4. Post Test TLX Results and Testing Observations

After each test session, all participants completed TLX questionnaires on the testing process (Appendix 16), to determine what effect harmonic combination had on test workload. Overall TLX results (Figure 7.9) showed a significant reduction (T(20) =6.18, p<0.0001) in workload from 54.95 to 38.9 in the harmonic combination condition.

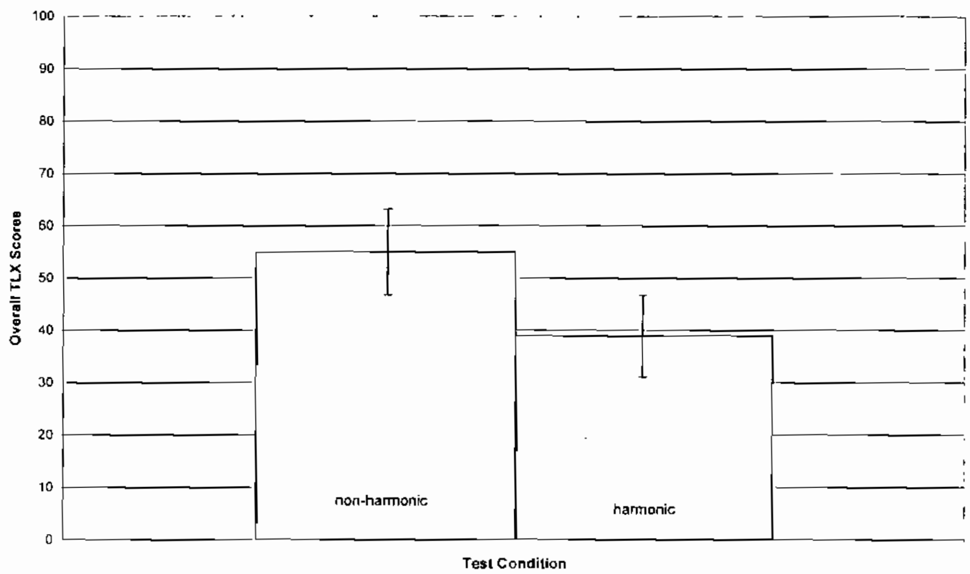


Figure 7.9: Graph showing overall average post-test TLX results (by test condition), showing standard deviations

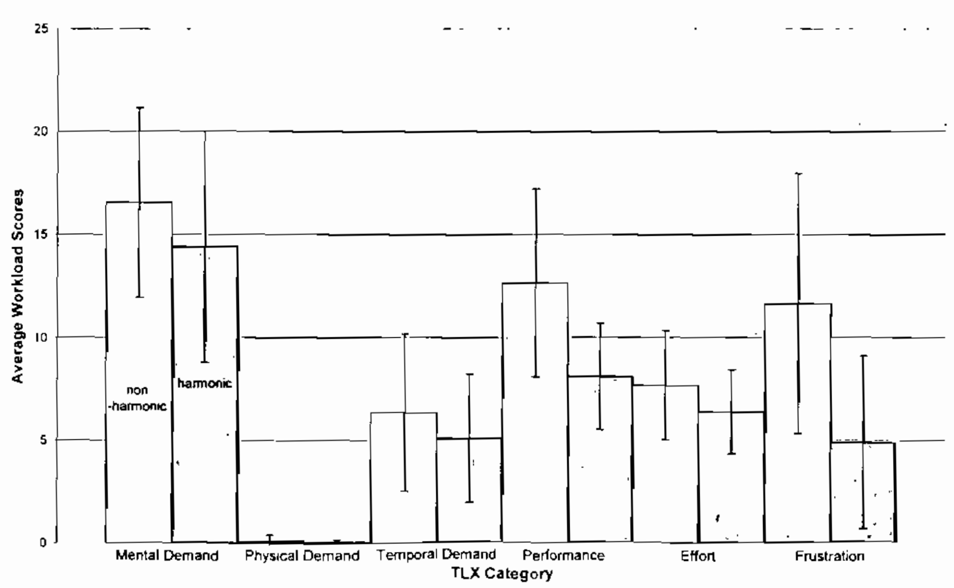


Figure 7.10: Graph showing average post-test TLX results by category (for each test condition), showing standard deviations

Workload scores for each test category were examined individually (Figure 7.10), with mental demand scoring highest in both conditions (16.55 and 14.4 respectively). A significant reduction was observed in the performance workload score from 12.63 to 8.1 ($T(20) = 3.77$, $p<0.001$), suggesting that participants felt they had performed better when patterns were combined harmonically. This improvement was accompanied by a similar reduction in frustration from 11.63 to 4.88 ($T(20) = 3.87$, $p<0.001$), which suggested that participants were more comfortable with harmonically combined patterns. No problems were encountered during explanation of the test schedule, and participants understood the principles of sonification, contour icons and harmonic combination as they related to the tests.

7.8. Discussion

The test schedule had been carried out to investigate the effect of harmonic combination on pattern combination detection, as defined by RQ 5. Non-musicians had taken part in a series of point estimation and pattern combination tests, and results had shown that harmonic combination significantly improved overall performance from 58.25% to 75%. Point estimation performance had not been affected by harmonic combination (as considered by testing hypothesis 1), and had improved from 77.5% to 82.5% in the harmonic condition. Although this improvement was not significant, testing had been concerned with false positives being detected due to the presence of a required contour icon in one or more other registers and this had been discounted.

Overall pattern combination results had significantly improved from 43.5% to 69.75% in the harmonic condition, with 2 variable pattern conditions exhibiting a significant increase in performance from 50.42% to 79.17%. A significant increase was also observed in the 3 variable condition (from 33.12% to 55.62%), but it was noted that some participants detected false positives when 2 patterns were in combination (rather than the required 3). This perception of a false positive had not been adequately considered during the design of the test schedule, and so no relevant information was obtained to determine whether certain combinations of instruments or contour icons generated false positives. This was a factor which would require further consideration, to determine whether participants were more strongly influenced by certain instrument combinations in the presence of a third dissonant pattern. Similarly, further investigation into the combination of differing contour icons would be required in order to discount the possibility of a contour icon being masked by the presence of another in 2 registers.

Post test TLX questionnaires had shown a significant reduction in overall workload due to harmonic combination, with significant reductions also being observed for performance and frustration scores. Several participants had commented that harmonic combination was much more straightforward to understand, and improvements in performance observed during testing suggested that harmonic combinations were also easier to detect.

7.9. Conclusions

Harmonic pattern combination was tested to answer RQ 5 of this thesis:

RQ 5: What effect during concurrent presentation does harmonic combination have on the identification of features and intersections in data streams?

Contour icon patterns were used in both harmonic and non-harmonic combination, to observe whether patterns played in harmony were easier to detect and understand. Participants were comfortable with the use of contour icons to represent data values in a sonification, and understood the use of harmonic combination to define intersections within the data. Several participants from testing group 2 (who performed the harmonic combination tests first) were confused by the multiple pattern combinations in the non-harmonic tests, and expressed frustration with this method in post-test discussions. Significant improvement in pattern combination detection was observed using harmonic combination, and this had been the main aim of testing. No significant effect had been observed on point estimation due to harmonic combination (other than a slight improvement), and this had discounted the possibility of false positives being detected due to the presence of a contour icon in another register (or register). This was not the case for 3 variable pattern combinations however, where several false positives were detected when only 2 instruments rendered a pattern in harmony. This suggested that greater dissonance was required between patterns, to overcome the strength of the 2 pattern grouping.

7.9.1. Limitations of Harmonic Combination

Although harmonic combination had significantly improved testing performance, there were still aspects of the method that required further investigation. The method of harmonic combination employed during testing would only provide for a single combination involving any one value used in the sonification. Thus, the intersection of a specific value from variable A with another single value from another variable B could be determined, but no further definition was possible for other intersections between this value and any other value from variable B. This can be considered as a major drawback for efficient data analysis, where the intersection of one value with others in a set is rarely limited to a single combination. Future work would have to consider means by which other values could be defined in multiple combinations based on a single value from a certain variable. Possible solutions may involve the use of other common harmonic intervals within the octave (such as the 3^{rd}, 5^{th} and 7^{th}), and further investigation would be required to assess the potential of such combination.

The detection of false positives in 3 variable conditions due to the presence of a 2 variable harmony had also not been considered prior to testing, and so could not be adequately addressed. It was possible that certain instrument combinations would suggest a 3 part harmony even when the other pattern was dissonant, and this had not been accounted for in the method. It was also possible that certain contour icons were not sufficiently dissonant from others to highlight their presence in a 2 part harmony. This was another aspect of harmonic combination that had not been considered prior to testing, where it had been assumed that contour icons which had been shown as distinct in previous tests (6.7.2) would be similarly distinct in the presence of a stronger 2 part harmony grouping. Further work would have to consider this more fully, to determine what changes are required to either contour icon design or methods of harmonic combination (or both).

7.9.2. Overall Conclusions

Harmonic combination had sought to provide a more effective means of highlighting intersections between values in a multiple variable sonification, as defined by RQ 5 of this thesis. Significant improvement had been observed with harmonically combined patterns during testing, and this had confirmed the streamlined pattern detection method (7.2.1) that had been intended. Limitations were observed due to combination restrictions (one to one mappings) and also due to the detection of false positives in 3 variable conditions, but overall performance had shown the method to have potential. Testing had been performed using contour icon patterns, but such patterns were not essential to application of harmonic combination. Testing of low level reference patterns (5.6.3) had shown that pattern combination was difficult, and harmonic combination was developed as a possible improvement. When used in conjunction with contour icons, an effective means of detecting point estimations and pattern combinations in multiple variable data sonification could be achieved, as stipulated by the research questions of this thesis. Testing performed during the DNASon case study (4.5) had considered the potential of rhythmic parsing, and the next chapter of this thesis would give full consideration to its application in a sonification.

8. Rhythmic Parsing in Data Sonification

8.1. Introduction

Harmonic pattern combination testing (chapter 7) had demonstrated significant improvements in pattern combination performance. These tests had been performed during the development of a framework for pattern sonification, which included the implementation of contour icons (chapter 6) to produce detectable and memorable musical patterns based on simple melodic contour shapes. Although improvements had been demonstrated in both point estimation and pattern combination test performance, testing had not considered the organisation and grouping of information temporally. This method of grouping data was intended for further investigation subsequent to the development of a more effective method of pattern sonification, as detailed in chapters 5, 6 and 7. The use of rhythmic parsing in a sonification had been considered during the DNASon case study (4.2.4), and further work was required to determine its potential. In this chapter, the use of rhythmic parsing to group data in a sonification is investigated. A set of tests was carried out investigating the effect of rhythmic parsing on data sonification, using harmonically combined contour icons to convey features and intersections in the data concerned. These tests consider the possibilities of rhythmic parsing with contour icons, but are intended to demonstrate a technique that could potentially be applied to other methods of data sonification.

Previous work carried out in this thesis (4.2.4) considered the potential of rhythmic parsing as a means of grouping and segregating events within a sonification. In the DNASon case study, rhythm was used to group nucleotide bases into codon groups for the purposes of analysis during testing. Both 3/4 and 4/4 rhythmic parsing templates were used, to highlight the occurrence of different amino acids and their subsequent combinations. Although no significant improvement due to rhythmic parsing was observed during testing, there was no indication of why this had not occurred (or how it differed between rhythmic templates). For this reason, further investigation into the effect of rhythm parsing in sonification was required.

8.2. Rhythm in Existing Data sonification

Many existing methods of sonification [100, 121, 144] have employed some form of rhythm as a means of organising events. Earcon research conducted by the likes of Brewster [144] and McGookin [100] often utilises static time intervals of around 100-300ms to separate concurrently presented earcons, and this allows for segregation of each event when no definite hierarchy or prioritisation exists within the earcons used. In fact, in such situations the use of rhythmic groupings can actually create an unwanted prioritisation of the data [174] and so is avoided. Earcons are usually considered in physical time increments [145], with note lengths of 0.0825 seconds being suggested in patterns containing 6 notes within 1 second. Although smaller note lengths are acceptable, no structure is defined for the relation between differing notes (or the tempo at which they should be rendered).

In cases such as earcons, the use of rhythmic parsing is confined to the application of a static delimiter between notes. Rhythm within earcons is of vital importance to the detection process, but the segregation of individual earcons using rhythm is given less focus (mainly due to the equal importance of each earcon). Although this configuration is sufficient for such patterns, in other types of data sonification the use of rhythm could be employed to far greater effect. A data set is often hierarchical, in that sub-groups can be found at different levels within the overall raw data. In such cases, the use of rhythm as a delimiter is essential.

Research conducted by Smith and Walker [121] into the use of axes, tick marks and labels in data sonification implemented audio tick marks to denote the x axis of a data set (3.3.3). Although significant results were not obtained during testing of the method, the principle of grouping each event temporally in a specific manner has great potential. If a listener can determine where they are within a data sonification, then they are similarly capable of determining differing levels of grouping and structure within that data. An analogy can be drawn with the visual graph, wherein groups within a data set can be more easily defined when significant location information (such as labelling) is supplied.

Although other examples of rhythmic implementation have been suggested [181, 182, 183], no specific consideration has been given to the use of musical rhythmic structures in the grouping of data in a sonification. By employing existing compositional means of rhythmic parsing and organisation within the context of such data sonification, it is suggested that information can be conveyed more efficiently as a result.

8.3. Rhythm and Musical Structure

8.3.1. Tempo

Musical rhythms consist of structures that define the relation between the relative time of events (2.4.3), and these relations serve as a template that is independent of the tempo at which the events are performed at (within the physical limits of the performers concerned). By using a structure unrelated to a physical tempo, differing physical time intervals will occur relative to the note lengths used. In this manner, different events can be grouped together by consequence of their relative occurrence over time- rather than as a single physical definition. This allows for events to be rendered at differing tempos (as preferred by the listener) without loss of information or structure, a function not always possible with physical time definitions.

8.3.2. Structure

Musical composition is hierarchical in structure, with many levels of grouping occurring within each piece of music. In classical music composition, short melodic phrases known as motifs [24] are developed within sections that comprise a single movement [75] in a piece. A full symphony can be comprised of several such movements, wherein different motifs (and variations thereof) are developed in many ways in each movement. In this manner, a composer can convey a great number of ideas within a piece based around motifs and their variations. The listener can grasp the differing levels of musical structure in the symphony because of the arrangement of these motifs, with each section and movement being highlighted musically during the piece.

Figure 8.1: Excerpt from Beethoven's 5th symphony, 1st movement, adapted from Austin [184]

In the above example (Figure 8.1), 2 sections from the 1st movement of Beethoven's 5th symphony are punctuated by a gap of 1 bar (bar 57) followed by a variation on the motif from the 1st section indicating that a new section is beginning (bars 59-62). This variation could be considered equivalent to a label, indicating to the listener that a new section within the same overall movement is beginning. The use of a breve rest (bar 57) serves to punctuate the 2 sections, again indicating to the listener that a new section is about to begin. This use of rhythm to separate 2 sections within a movement allows the hierarchical grouping of musical to be performed effectively. In the above example, the variation on the motif from section 1 (bars 59-62) employs previously rendered information in a new context- a context that is defined by the breve rest of bar 57.

This grouping of musical events in various levels of hierarchy forms the basis of western composition, and allows several often unrelated motifs to be organised in such a manner as to become part of a greater whole. Similarly in sonification, the data involved may contain structures of events which could be conveyed using rhythmic parsing. By grouping musical events in a sonification using rhythm, differing levels of information could then be conveyed within that sonification.

8.4. Rhythmic Parsing of Data for Analysis

Grouping events in a sonification has potential for more efficient data analysis, particularly in situations where larger data sets are used. In many cases, large data sets will contain subsets of grouped information that is pertinent to the understanding of the entire set as a whole. In considering how best to group a data set, it is first important to determine how this grouping can effectively be conveyed to the listener.

8.4.1. Justification of Rhythmic Parsing

Musical composition employs features such as rest notes, modulations and variations on melodic motifs to denote transition and grouping within a piece. Although existing work [121] has considered the use of tick marks and labels in sonification, no study has been undertaken into the use of higher levels of rhythmic parsing in a data sonification. In this research, the use of rhythmic parsing as a means of grouping events is investigated as a research question:

RQ 1: What effect does rhythmic parsing have on the understanding of structures within a data set?

In considering this effect, a data set must be used which contains sub-groups that relate to the overall whole in such a manner that listeners can determine their presence in a data set. By employing rhythmic parsing to highlight these sub-groups, it is intended to show that the perception of such features can be performed more efficiently.

8.4.2. Choice of Data for Rhythmic Parsing Sonification

To allow testing of a rhythmic parsing method, a suitable data set containing an appropriate level of structure was required. In keeping with previous tests, the nature of the data sonified was required to be as simple and familiar to listeners as possible so that it would not unduly affect test performance. Data sets of survey information were considered (where different groups could be asked a set of questions and the responses collated sequentially), but the reasoning behind comparing groups was not felt brief enough for tutorial explanation. Instead, data sets of exam results (Table 8.1) were considered as a familiar means of conveying grouping of data within an overall set.

Student Number	Course	Exam 1	Exam 2	Exam 3
1	1	A	C	C
2	1	A	C	B
3	1	B	A	C
4	1	C	C	A
5	1	C	C	C
6	2	B	A	B
7	2	C	C	B
8	2	B	A	A
9	2	C	B	A
10	2	A	A	A
11	3	B	A	C
12	3	B	B	C
13	3	A	A	C
14	3	A	B	B
15	3	A	C	A
16	4	A	C	B
17	4	A	A	A
18	4	A	A	A
19	4	C	B	C
20	4	B	A	A

Table 8.1: Example data set of fictitious examination results

In the above table, 4 groups of students from different courses have sat exams in 3 different subjects. The results of these exams are listed sequentially, but also grouped by the course number of each student. If these results were to be sonified, the 20 events would specify the result (or results) for each student of each course in order of course number (Figure 8.2).

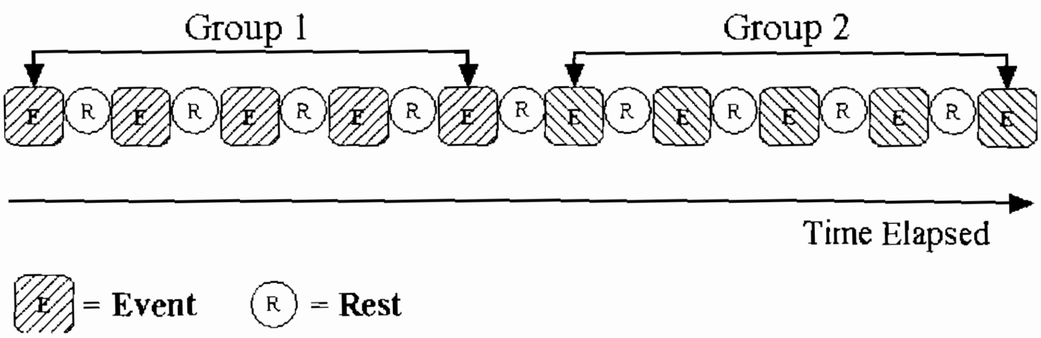


Figure 8.2: Example grouping of Table 8.1 examination results

A listener would have to be informed of the size of each group prior to sonification, and thus be required to maintain a count of events (to determine which course was currently being sonified) alongside remembering the results for a specific student or course.

If rhythmic parsing was employed in such a sonification, the course grouping could be denoted by a longer rest note between events in different groups (Figure 8.3).

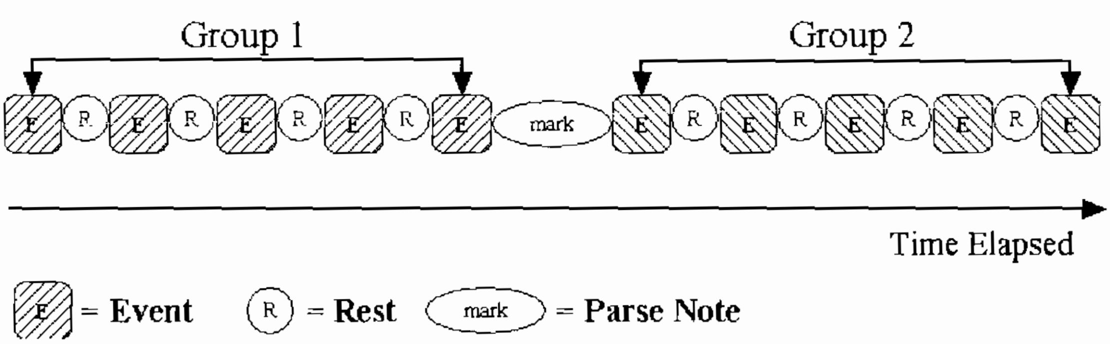


Figure 8.3: Example grouping of Table 8.1 examination results using rhythmic parsing

By adding a longer rest (equivalent to a breve) between groups of results, the listener would not be required to group the events themselves (and thus not to maintain a count of sonification events). In this manner, the amount of information a listener would be required to process during a sonification would be less than in the non-rhythmic parsing condition.

This basic implementation of grouping using rhythmic parsing was scheduled for testing, to demonstrate the potential of the method as a means of indicating structure within a data sonification. Although far more complex levels of structure could be created in this manner (alongside the means by which they could be indicated), it was decided that testing should concern the viability of the method rather than the extent of its potential implementation.

8.5. Rhythmic Parsing Testing

The rhythmic parsing of events in a data sonification was investigated in response to RQ 1 of this thesis. The aim of testing was to assess whether a rhythmically parsed data sonification was more effective in conveying structures and groupings within a data set. All tests were performed using harmonically combined contour icons, which had proven an effective means (7.7.1) of conveying features and intersections within a data set. The 8 contour icon shapes (6.5.3) used in the chapter 6 and chapter 7 tests were retained for the current tests. Although contour icons were used, the principle of rhythmic parsing does not require any specific musical patterns. As a result, future development could consider patterns such as earcons (or indeed other musical patterns) for further investigation.

8.5.1. Procedure

20 participants took part in the experiment described in this section which was of a within groups design involving two conditions, the *non-rhythmic parsing* condition and the *rhythmic parsing* condition. No participants had taken part in any previous tests, and all participants confirmed they had no formal musical training. Participants were randomly assigned to one of two groups to determine the order in which they would undertake the experiment. Each group contained the same number of participants, and both conditions consisted of training and testing phases (Table 8.2).

	1st Training Session	**1st Testing Session**	**2nd Training Session**	**2nd Testing Session**
Group 1	Non-rhythmic parsing	Non-rhythmic parsing	Rhythmic parsing	Rhythmic parsing
Group 2	Rhythmic parsing	Rhythmic parsing	Non-rhythmic parsing	Non-rhythmic parsing

Table 8.2: Testing procedure for the two groups of participants undertaking the non-rhythmic parsing vs. rhythmic parsing experiment

All tests were performed using fictitious examination results stored in .csv format files [172], with the number of values identified and number of combinations identified being the dependent variables. The workload placed on each participant was assessed by NASA TLX questionnaires [164] and (Appendix 19), which were filled in by participants after completing each condition.

8.5.2. Training Phase

Participants were played each of the 8 contour icon patterns (6.5.3), and the use of contour icons to represent data was explained. Harmonic combination was explained as a means of representing intersections in the data, and a tutorial was given on the sonification method used during testing (Appendix 5). Participants were first asked to audition all contour icons used, before undertaking a listening test where each contour icon was played once at random. This listening test was used to ensure that all participants could discriminate between every contour icon in the set, to eliminate possible confusions due to ordering effects of patterns in the sonification. If a participant could not correctly identify all 8 contour icons they were given further time to audition the patterns, prior to a second listening test. If a participant still could not identify all 8 contour icons they took no further part in the experiment. In this experiment, all participants identified all 8 contour icons within 2 attempts.

Participants were then played various contour icons in harmonic and non-harmonic combinations, and asked to define the number of instruments present, what contour icon(s) they heard and whether all instruments played the same contour icon. If a participant could not accurately detect the presence of multiple instruments they took no further part in testing. If a participant could not determine a consonant or dissonant contour icon pattern for multiple instruments they took no further part in testing. In this experiment, all participants identified the number of instruments and their harmonic combination correctly.

Participants were informed they would be asked questions on sonifications of fictitious examination results. Each sonification would contain 20 results, and participants were told each sonification contained 4 distinct course groups (with 5 members each) in sequential order. Participants were given an example data sonification with an accompanying visual diagram, to demonstrate what they were required to detect. In the non-rhythmic parsing condition, participants were told they would have to keep track numerically of each group and its location in the data (by counting) while also comparing group results. In the non-rhythmic parsing condition, the example sonification contained 20 sequential events without grouping. In the rhythmic parsing condition, participants were informed that each group would be parsed by a rest note and so they were required to remember the count for each group for comparison of their results. In the rhythmic parsing condition, the example sonification demonstrated rhythmic parsing of 20 events into 4 groups of 5 members. After the example sonification was played, participants were given a final brief period for any other questions about the tests.

8.5.3. Testing Phase

In the testing phase participants were asked to sonify the contents of 5 data files of .csv format (Appendix 7). The files each contained 20 fictitious examination results in 4 sequential groups of 5 students. The results for each student ranged from 2 values (pass or fail), 3 values (A, B and C) through to 4 values (A, B, C and fail). Students were listed for 2 and 3 variables, where each variable defined a specific examination. Testing sought to assess how well participants could detect point estimation, pattern combinations and determine group comparisons (8.5.4) for 2 and 3 variable data sets. The test format contained three 2 variable tests ranging from 2 to 4 values, followed by two 3 variable tests for 2 value data sets.

8.5.4. Group Comparison Questions

Group comparison questions were used as a means of determining how effectively participants could analyse the groups contained within the data they were listening to. By asking point estimation and pattern combination questions based on individual group data, the use of rhythmic parsing as a means of grouping data could be assessed. Typical questions would compare the results for a certain exam(s) between 2 different groups of students who had sat that exam, or consider which group had achieved the highest number of a certain grade of pass (or fail). All group comparison questions required a group name (or number) as an answer. In this manner, the effect of rhythmic parsing on participants understanding of the data could be shown.

All sonifications were performed on a Compaq NX6100 laptop, using the onboard ADI AC97 soundcard. All instrument timbres were taken from the general MIDI soundest, with bass patterns allocated the '*picked bass*' sound, middle patterns allocated the '*drawbar organ*' and treble patterns allocated the '*flute*' sound. Point estimation questions concerning the overall data (without grouping) were used to assess the effect of rhythmic parsing on analysis of the entire data set. It was important that the introduction of a parse note did not affect the representation of the overall data set as a whole. The independent variable in testing was the rhythmic parsing of patterns, with the dependent variables being the number of correct point estimation and pattern combination questions answered. The experiment considered the following hypotheses derived from RQ 1:

Hypothesis 1: Does rhythmic parsing affect the identification of individual features in a data stream during concurrent presentation?

Hypothesis 2: Does rhythmic parsing affect the detection of grouping of individual features (and their subsequent identification) for comparison in a data stream during concurrent presentation?

Hypothesis 3: Does rhythmic parsing affect the detection of grouping of pattern combinations (and their subsequent identification) for comparison in data streams during concurrent presentation?

All tests were performed with participants being handed writing materials after listening to a sonification. A participant was allowed to listen to a sonification once for each question they were required to answer. Once testing had been completed, each participant was asked to answer a TLX questionnaire on their performance.

8.6. Results

The aim of testing was to assess the effect of rhythmic parsing on group comparisons involving point estimation and pattern combination detection within a multiple stream sonification. Testing also considered the effect of rhythmic parsing on overall point estimation, to ensure that this did not inhibit performance in non-group analysis. The test conditions used non-rhythmic parsing and rhythmic parsing respectively, to determine the effectiveness of both conditions relative to each other.

8.6.1. Overall Results

The overall test results (Appendix 17 & Figure 8.4) had showed performance improved to 75.3% in the rhythmic parsing condition from 67.6% in the non-rhythmic parsing condition. This improvement was significant (T(20) = -2.79, p=0.008), suggesting that rhythmic parsing had a positive effect on performance in multiple stream sonification.

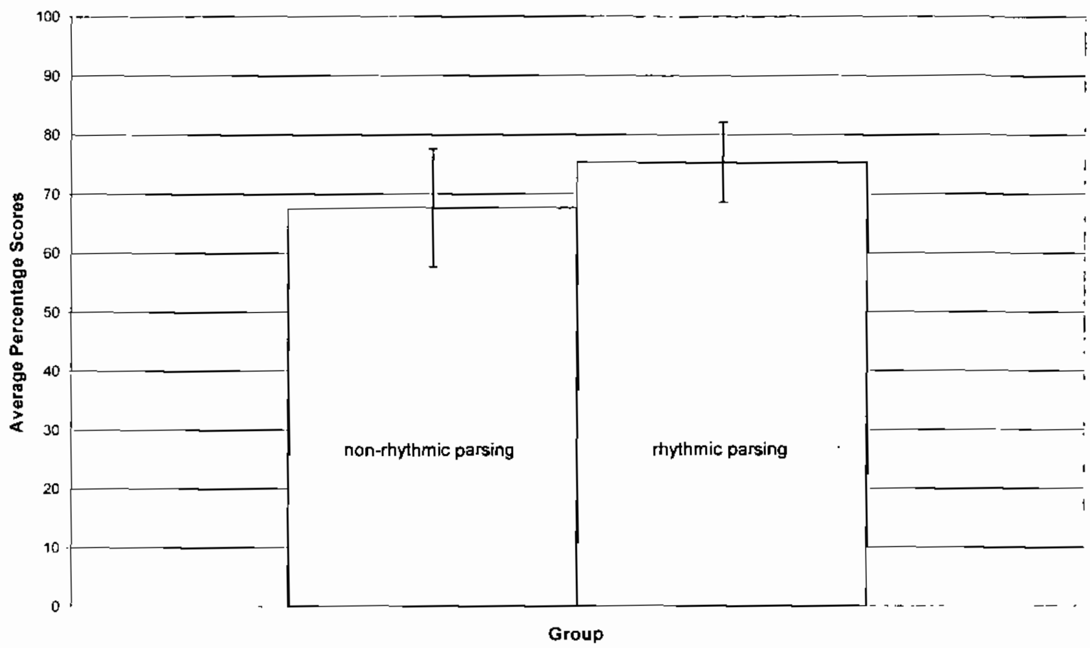


Figure 8.4: Graph showing overall average percentage results (by test condition), showing standard deviations

The testing hypotheses (8.5.4) considered the effect of rhythmic parsing on both non-group and group conditions, and so each was analysed in turn as required.

8.6.2. Effect of Rhythmic Parsing on Overall Point Estimation

Overall point estimation questions had been asked to ensure that rhythmic parsing did not impede accurate point estimation in non-group analysis. Results (Figure 8.5) showed that overall point estimation had improved from 75% in the non-rhythmic parsing condition to 81.25% in the rhythmic parsing condition. Although not a significant improvement (T(20) = -1.807, p=0.079), this result indicated that rhythmic parsing did not unduly affect the analysis of overall trends in the data.

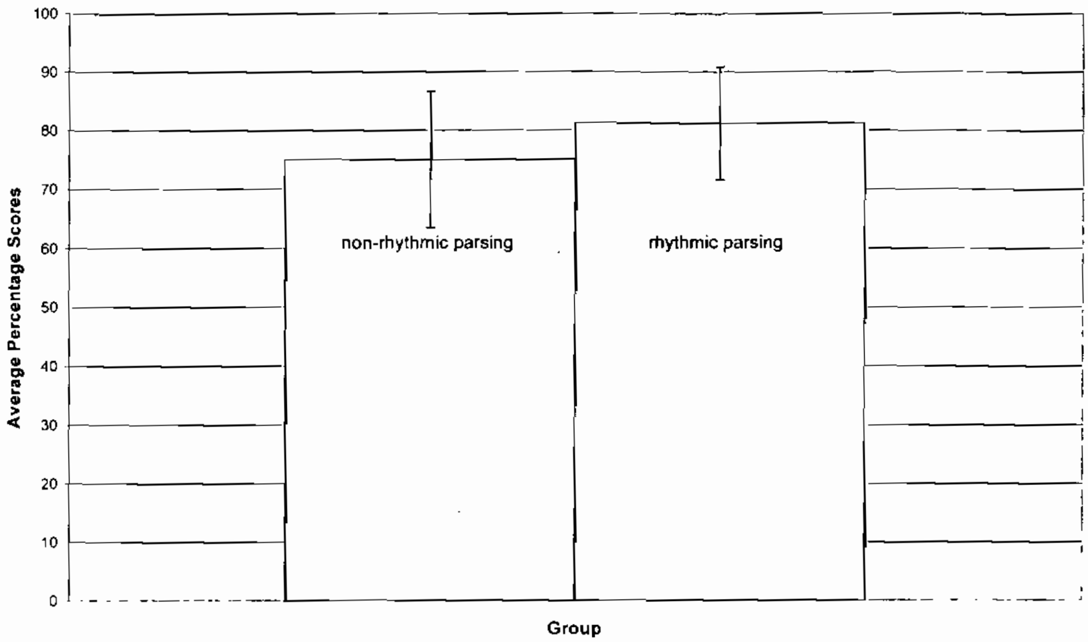


Figure 8.5: Graph showing overall average point estimation percentage results (for each test condition), showing standard deviations

This was an important aspect of testing (as defined by hypothesis 1), as any use of rhythmic parsing to group data would not be effective if it introduced confusion in the analysis of the overall data set as a whole. The observed improvement in score was confirmed by informal feedback from several participants, who found it easier to retain a count when gaps in the sonification were present.

8.6.3.Group Comparison by Point Estimation

Rhythmic parsing is intended as a means of defining sub-groups within an overall data set, and so comparison of data between such groups was one of the aims of testing. Results of group comparison point estimation questions (Figure 8.6) indicated a significant improvement ($T(20) = -2.220$, $p=0.032$) in accurate point estimation comparison from 58.5% in the non-rhythmic parsing condition to 68.5% with rhythmic parsing.

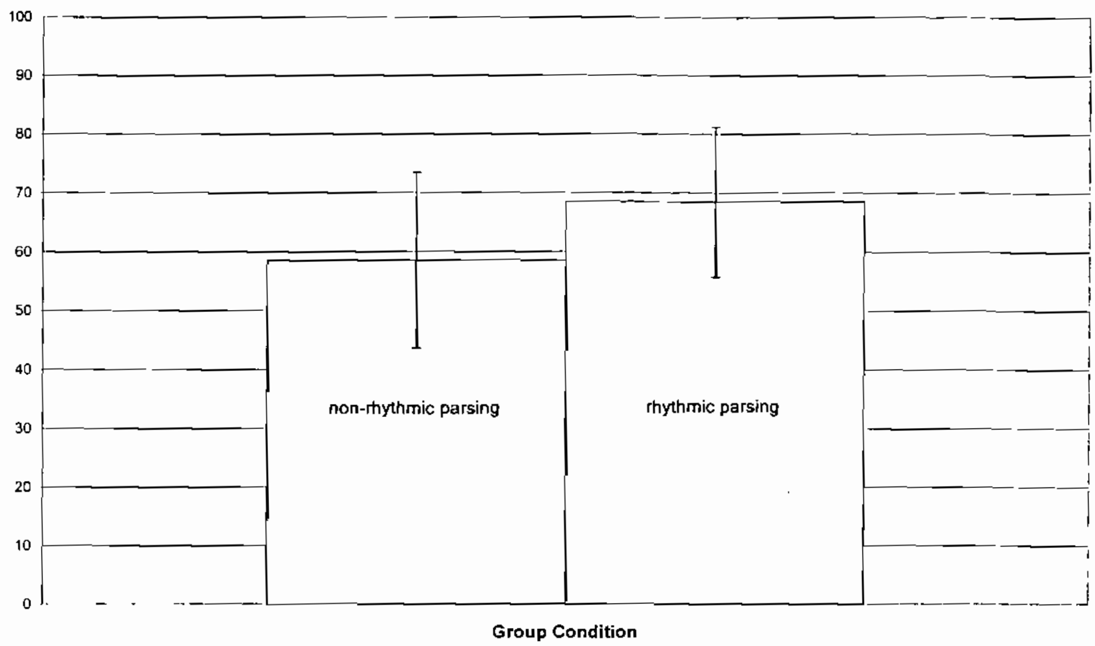


Figure 8.6: Graph showing average point estimation percentage results for group comparison questions (for each test condition), showing standard deviations

This result confirmed testing hypothesis 2, which sought to assess whether rhythmic parsing had any effect on between groups comparison by point estimation. Several participants from testing group 1 (8.5.1) commented that rhythmic parsing gave them more time to retain and compare results between groups, without having to consider the current location in the sonification. Conversely, participants from testing group 2 found the extra counting requirement needed to group results to be more demanding (8.6.5) and considered the rhythmically parsed condition to be easier to understand.

8.6.4. Group Comparison by Pattern Combination

Testing hypothesis 3 considered the effect of rhythmic parsing on between groups comparison by pattern combination. Harmonically combined contour icons (7.5) were used to define the relevant pattern combinations during testing. Results of group comparison pattern combination questions (Figure 8.7) showed an increase from 72% to 77% in the rhythmically parsed condition.

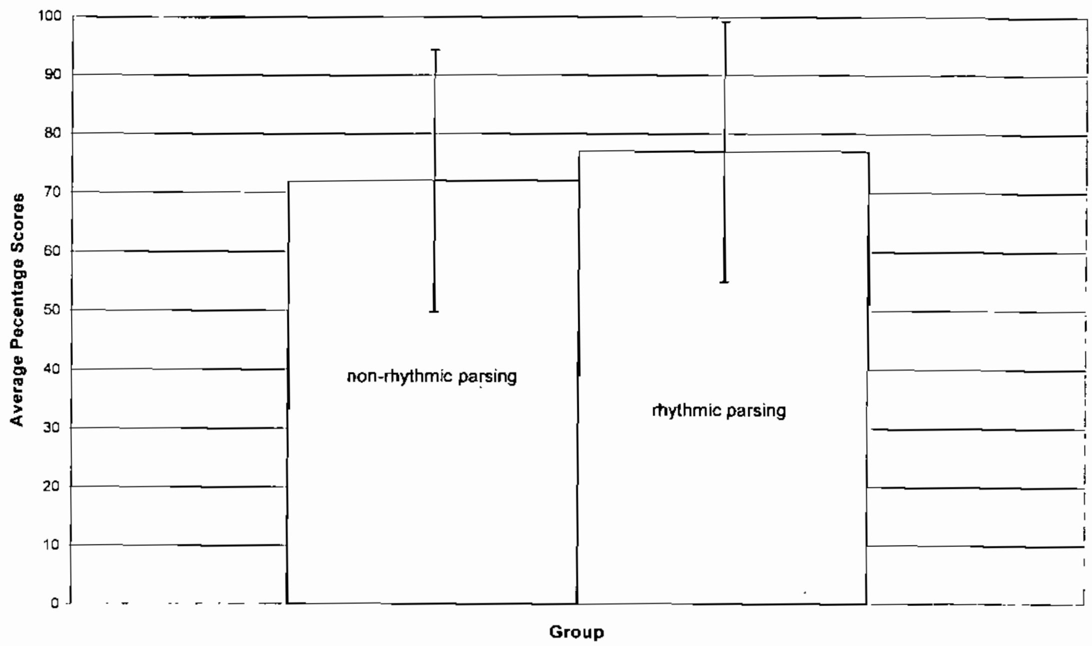


Figure 8.7: Graph showing average pattern combination percentage results for group comparison questions (for each test condition), showing standard deviations

Although this increase was not significant (T(20) = -0.694, p=0.492), pattern combination performance had improved due to rhythmic parsing. It was noted during informal post test discussions with several participants that the lower counts involved with pattern combinations had made it easier to compare groups in both test conditions. The test schedule had not fully considered the effect of lower value counts between point estimation and pattern combination in group comparison questions, and so a more accurate assessment could not be made. For this reason, testing hypothesis 3 would have to be rejected.

8.6.5. Post Test TLX Results and Testing Observations

At the end of every test session, all participants completed TLX questionnaires (Appendix 19) to assess the effect of rhythmic parsing on test workload. Results (Figure 8.8) showed that overall workload had dropped from 60.75 to 41.33 in the rhythmic parsing condition.

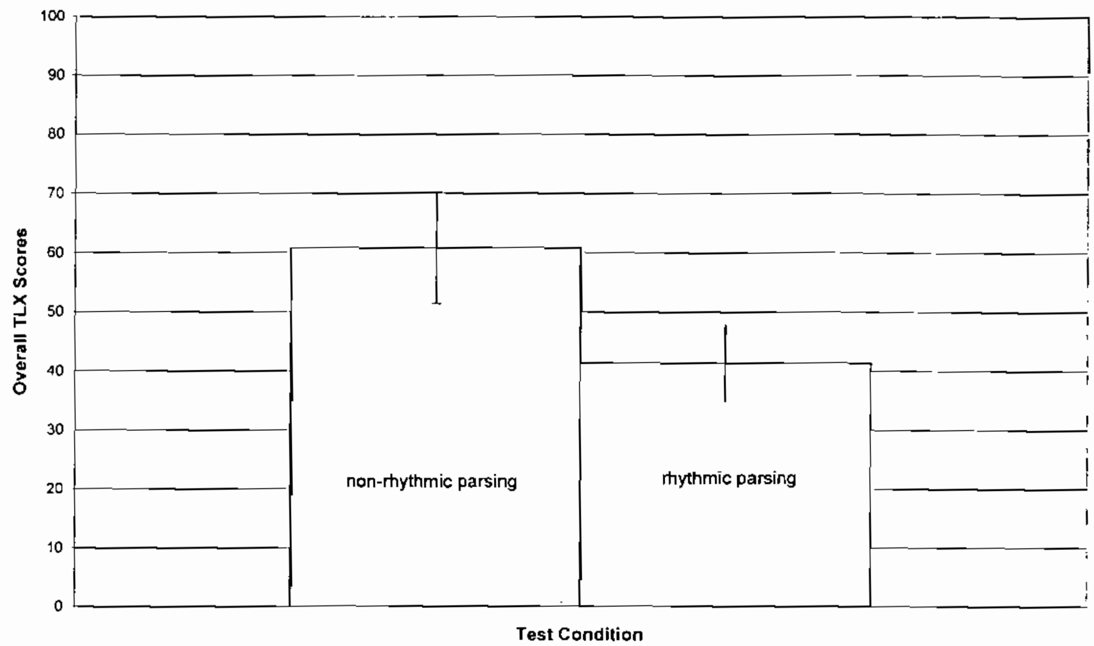


Figure 8.8: Graph showing overall average post-test TLX results (by test condition), showing standard deviations

This was a significant reduction (T(20) =7.45, p<0.001), and so individual workload categories were examined (Figure 8.9) to determine the exact nature of the improvement.

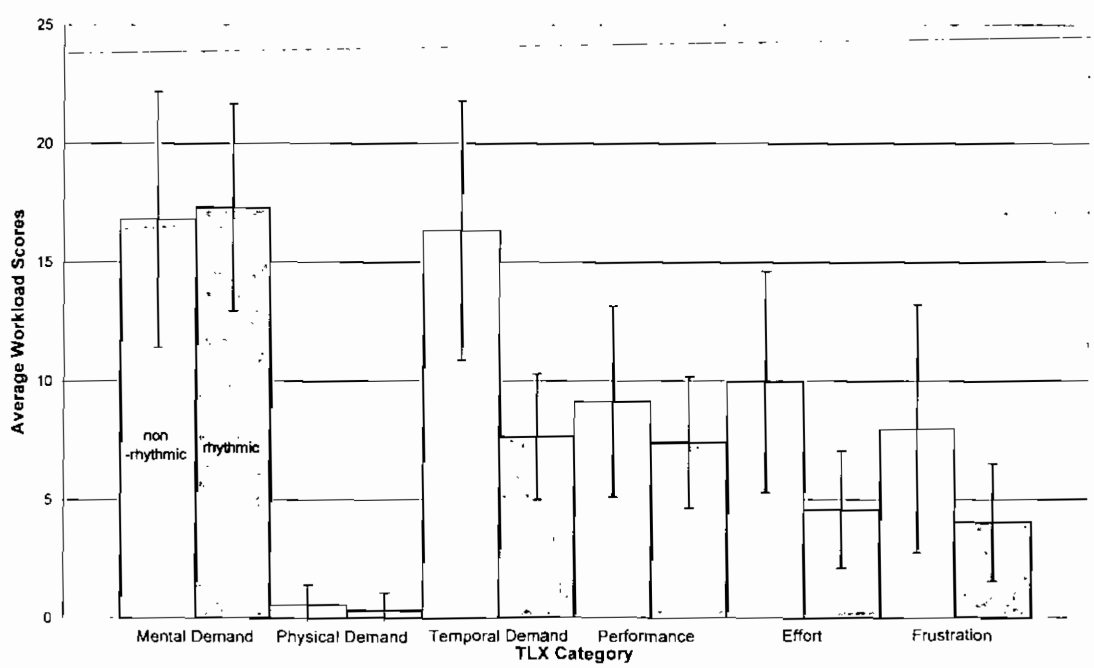


Figure 8.9: Graph showing average post-test TLX results by category (for each test condition), showing standard deviations

Mental demand was the highest workload factor, and the overall score increased in the rhythmic parsing condition to 17.32 from 16.8 (in the non-rhythmic tests). Although this increase was not significant ($T(20) = -0.325$, $p = 0.747$), it did suggest that participants had not found rhythmic parsing to be any less mentally demanding than the non-rhythmic tests.

A significant reduction was observed in the temporal demand score from 16.33 to 7.65 ($T(20) = 6.236$, $p < 0.001$), and this reduction in temporal workload was an important factor in post test analysis. By expressing less temporal demand in the rhythmically parsed condition, participants indicated that they had more time to analyse the data and hence perform better. A similar reduction was also observed in effort from 9.95 to 4.583 ($T(20) = 4.435$, $p < 0.001$), and in frustration from 7.983 to 4.05 ($T(20) = 2.966$, $p = 0.005$). These results suggested that participants had found the rhythmic parsing condition a more effective method of representing sub-groups in a data sonification, and this was an encouraging indication of the potential of the method. No problems were encountered during explanation of the test schedule, and participants understood the principles of sonification, contour icons, harmonic combination and rhythmic parsing as they related to the tests.

8.7. Discussion

The test schedule sought to investigate the use of rhythmic parsing to define groups within a data sonification, as required by RQ 1. Non-musicians had undertaken a series of group comparison tests involving point estimation and pattern combination questions, alongside overall point estimation questions. Testing had shown that the use of rhythmic parsing significantly improved overall performance from 67.6% to 75.3% in the rhythmic parsing condition. Overall point estimation (in non-group questions) performance had improved from 75% to 81.25% due to the use of rhythmic parsing, although this improvement was not statistically significant. The overall point estimation questions had been used with regard to testing hypothesis 1 to ensure that rhythmic parsing did not negatively affect overall performance, and so it had been shown that rhythmic parsing did not hinder overall analysis of a data sonification.

Group comparison questions sought to determine whether rhythmic parsing was an effective means of highlighting sub-groups within a data sonification, and both point estimation and pattern combination questions were used. Performance in group comparison using point estimation had significantly improved from 58.5% to 68.5% in the rhythmic parsing condition, suggesting that rhythmic parsing was an effective method of defining sub-groups in a data sonification as required by testing hypothesis 2. Pattern combination performance had also improved (from 72% to 77%) but not significantly so, and this was partly attributed to the low pattern counts employed in the test schedule. Because smaller numbers of pattern combinations were used, it was often possible that participants could count them effectively in both conditions. Future work would have to consider larger data sets (with higher pattern combination counts) to better assess the effect of rhythmic parsing on pattern combinations as required by testing hypothesis 3.

Post test TLX questionnaires had shown a significant reduction in overall workload due to rhythmic parsing, with significant individual reductions being observed for temporal demand, effort and frustration scores. This was in keeping with informal feedback obtained from participants after testing, which suggested that rhythmic parsing had made group comparison much more straightforward. Participants from testing group 2 (8.5.1) had also expressed greater difficulty in the non-rhythmic parsing tests, where the requirement to retain greater amounts of information affected overall performance. Having said this, participants found the rhythmic parsing tests to be more mentally demanding than their non-rhythmic counterparts, and so future work would have to consider how the entire sonification process could be further simplified.

8.8. Conclusions

Rhythmic parsing of a data sonification was investigated as required by RQ 1 of this thesis:

RQ 1: What effect does rhythmic parsing have on the understanding of structures within a data set?

Harmonically combined contour icon patterns were used to represent fictitious examination results for multiple course groups undertaking multiple exams. Test participants were asked various group comparison questions about sonifications of these results, with rhythmic parsing being used to define each sub-group within the data. Participants performed better using rhythmic parsing, with significant improvement in test results being observed in the rhythmic parsing condition. Participants were also asked overall point estimation questions, to ensure that rhythmic parsing did not adversely affect the analysis of the entire data set as a whole. In this case, improvement in point estimation was again observed in the rhythmic parsing condition (although not to a statistically significant level). Participants also found group comparison much less demanding in terms of workload, when required to determine the occurrence of each group within the sonification in the rhythmic parsing condition. These results suggest that rhythmic parsing has potential as a means of grouping and segregating data within a sonification.

8.8.1. Limitations of Rhythmic Parsing

The test schedule had sought to determine the effect of rhythmic parsing as a means of grouping data into hierarchical structures within an overall set. Although this had proven effective, the full application of such a technique would require further work. The test schedule was only concerned with the comparison of non-rhythmic and rhythmic parsing conditions, and so did not take into account the most effective means of grouping data (or how best to define it). Existing work [121] using axes, tick marks and labels has considered how to convey context within a data sonification, and the tests performed in this chapter did not employ such features. Rather, the use of a parse note served to indicate a change in the current context within the sonification.

It is suggested that a more effective method of rhythmic parsing would thus employ such features as markers and labels, rather than a simple rest note (or combinations thereof). By combining such methods, far more verbose information could be conveyed to the listener about their present location within the data they are listening to. The data used in testing could have been indexed by a marker to indicate specific group information to the listener (rather than merely the presence of a new group). Data sonification employing this method would not require the listener to possess any information about data structure prior to sonification, a factor which was unavoidable in testing due to the comparison with the non-rhythmic condition. Future work could consider the best methods of employing such markers alongside rhythmic parsing to more efficiently convey data in a sonification.

As stated, the test schedule sought to assess the effect of rhythmic parsing on data sonification, rather than determine its most effective implementation. Future work would also have to consider the levels of structure that could be conveyed using rhythmic parsing without making the sonification overcomplicated. A single parse note would not be sufficient in most practical circumstances (other than to allow the listener more time for mental arithmetic) and so further consideration would have to be given to the possible structures that could be employed in effective rhythmic parsing. In this manner, a more comprehensive investigation into the application of rhythmic parsing could be performed, rather than consideration of its potential as in this chapter.

8.8.2. Overall Conclusions

Rhythmic parsing had first been investigated during the DNASon case study (chapter 4), as a means of highlighting amino acids (and their associated nucleotide bases) within a DNA or RNA sequence. Development had next focused on pattern design and interaction (chapters 5-7), in order that an effective method could be tested with rhythmic parsing. In this chapter, a set of tests was carried out using hierarchical data in the form of fictitious examination results (8.4.2) which were arranged in 4 sequential groups of 5 students. Testing investigated whether the use of rhythmic parsing to highlight each group was more effective than a linear rendering of the data in a sonification.

Test results showed that rhythmic parsing was a more effective means of denoting groups in a data sonification than a sequential rendering (where the grouping must be done by the listener). Group comparison questions were asked involving point estimation and pattern combinations, with significant improvement being observed in point estimation (although improvement was present for pattern combinations). Overall point estimation questions were used to assess the effect of rhythmic parsing on the data set as a whole, with improvement (though again not statistically significant) being observed in the rhythmic parsing condition. Testing workload was also reduced as a result of rhythmic parsing, and thus RQ 1 was answered as required. Further work is needed to fully assess the extent of this potential however, notably in possible combination with some form of labelling [121] as a more effective means of conveying group context rather than merely the presence of a grouping.

9. Conclusions

9.1. Summary of Work

This thesis documents an investigation into the sonic representation of mathematical data using musical pattern sonification. A review of sound and perception was first undertaken (chapter 2), investigating the human hearing mechanism (2.2), fundamentals of music (2.2.5, 2.2.6 and 2.4.3) and the higher level cognitive processes associated with audio cognition (2.3 and 2.5). The role of melodic contour in musical pattern memory (2.3.3) was considered, and also the implementation of gestalt grouping categories (2.5) in musical pattern design. The role of rhythm in speech, audio and music (2.4) was also considered, as a means of synchronisation and grouping within the auditory scene. This chapter of the review suggested that the processes by which detection and recognition of a melody take place are distinct [46], and thus require different audio features for effective implementation. This chapter also considered the use of rhythm to organise musical events in a sonification (2.6), and determined that the role of melodic contour and rhythm in sonification would be investigated.

The next chapter of the review documented existing work in the field of sonification [90] and auditory display [100]. Different methods of rendering data using audio and music were considered, with particular focus being given to the sonification of DNA and RNA nucleotide sequence data (3.4). Methods of organising events in a sonification were investigated (3.3.3), alongside existing methods of audio and musical pattern design. Earcons (3.7) were given particular focus, notably in the guidelines for their design (3.7.5). Although this research does not employ earcons, the method by which a pattern may be made distinct is of great importance. As a result of this review several areas of research were considered, leading to a statement of the research questions which defined the scope of work for this thesis:

RQ 1: What effect does rhythmic parsing have on the understanding of structures within a data set?

RQ 2: Do present methods of pattern design (notably earcon design guidelines) produce patterns which are not only distinct but also memorable?

RQ 3: Can present methods of pattern design be used to efficiently render concurrent streams of data?

RQ 4: What effect does musical contour have on the recognition (and identification) of musical patterns used in data representation?

RQ 5: What effect during concurrent presentation does harmonic combination have on the identification of features and intersections in data streams?

An initial case study of DNA and RNA sequence sonification was first undertaken (chapter 4). This case study sought to improve upon existing methods [128] of DNA and RNA sequence sonification so that different levels of structure within that sequence could be rendered. Results of testing (4.5) showed that single note or interval mappings were difficult to understand (particularly for non-musicians), and so more musically descriptive mappings were required. Testing showed that complex data sets such as DNA and RNA nucleotide base sequences were difficult to understand without extensive training (4.6.1), and thus could only be considered for testing once a robust framework for sonification (4.7) had been developed.

Existing methods of musical pattern design were evaluated (chapter 5) in accordance with RQ 2 and RQ 3, notably in the use of earcon design guidelines to create distinct musical patterns. Although earcons were not used at any point during development or testing, existing work suggested that earcon design guidelines would produce distinct patterns as required by testing. A set of tests were performed to investigate the effectiveness of these low level patterns, with results (5.6.1) suggesting that a distinct pattern may not perhaps be memorable to the listener. Concurrent patterns had also been tested, and results (5.6.3) showed that it was difficult to detect multiple patterns in combination using low level musical patterns. Musicianship had also been considered as a testing factor (5.6.5), and observations made during testing had shown that a musician's ability to score patterns prior to listening gave them an advantage in pattern recognition.

Amendments to the sonification method were suggested (5.8), and 2 areas of development were suggested. The first area (chapter 6) would consider means by which a musical pattern could be made distinct and memorable using high level design features (such as melodic contour), while the second (chapter 7) would investigate more effective means of combining patterns during concurrent presentation (using harmonic combination).

The development of memorable musical patterns was considered in chapter 6, with particular focus being given to the use of musical contour as stated in RQ 4. Testing in chapter 5 had shown that musicians made use of visual representations during testing (5.6.5), and so visual methods of representing patterns were considered as a means of aiding the recognition process. This investigation led to the development of contour icons (6.5.3), which utilise musical patterns based on simple iconic shapes. By designing musical patterns based on visual shape, a method of effectively scoring patterns in a high level manner understandable to non-musicians was found. A set of tests was carried out comparing contour icons to low level patterns design using earcon guidelines (though not earcons themselves). Results (6.7.1) showed that contour icons significantly improved point estimation performance in sonification, as required by RQ 4. The inclusion of high level features (in this case contour) in pattern design had produced patterns which were both distinct and memorable, while also fulfilling gestalt design considerations (2.5).

Pattern combination testing in chapter 5 (5.6.3) had proven ineffective, and so more efficient means of combining patterns was considered in chapter 7. Existing work [114] had considered the use of harmony in concurrent presentation, and so means of harmonically combining patterns was investigated as stated in RQ 5. Harmonic combination was considered with reference to both earcon design guidelines (3.7.5) and gestalt grouping categories (2.5), and a set of contour icons based on these guidelines was developed (7.5) in 3 registers (allowing 3 variable combination). A set of tests was performed using contour icons in non-harmonic and harmonic combination, with results (7.7.1) which showed significant improvement in the detection of pattern combinations in the harmonic condition. Point estimation performance had not been affected due to harmonic combination (and had indeed been slightly improved), but it was noted during testing that several participants had detected false positive combinations (7.9.1) in the 3 variable condition when 2 instruments played in harmony with the other dissonant. No provision had been made for this in the experimental design, and so no proper assessment of this effect could be made. It was noted that future work would have to consider means by which such false positives could be avoided, alongside more extensive combination using higher variable counts.

Rhythmic parsing had been investigated during the DNASon case study (4.4.3), and had been scheduled for further work when a more robust sonification framework had been developed. Work carried out in chapter 8 considers the potential of rhythmic parsing as a means of highlighting groupings within a data set, as required by RQ 1. This thesis contends that musical rhythm and arrangement provides great scope for organising events hierarchically in a data sonification, and a set of tests (8.5) into the effect of rhythmic parsing were performed to investigate this. Results (8.6.1) showed that rhythmic parsing significantly improved group comparison in a sonification, and improved was also observed (though not statistically significant) in overall point estimation (8.6.2). Rhythmic parsing made sonification much less demanding (8.6.5), and suggests great potential for future implementation alongside other techniques such as data labelling (3.3.3).

9.2. Contributions of the Thesis

This thesis has presented several original contributions to data sonification, which made significant improvement to sonification performance during testing:

1) *Contour Icons*- contour icons were developed to investigate the effect of melodic contour in musical pattern design. Testing showed that contour icons were easier to detect in a data sonification, by utilising high level visual representations of their musical shape to aid in the recognition process.
2) *Harmonic Combination*- harmonic combination was proposed as a means of improving pattern combination detection during concurrent presentation. Testing showed that harmonic combination was a more effective means of highlighting specific combinations of values in a data sonification, by streamlining the pattern recognition process from 3 distinct patterns to a single pattern in harmony.
3) *Rhythmic Parsing*- rhythmic parsing was investigated as a means of conveying grouping and structure within a data sonification. Tests showed that sub-

groups within a data set were easier to analyse when rhythmically parsed, by highlighting the presence of groups to the listener using musical rest notes between events and groups of events.

This thesis has considered the means by which memorable musical patterns may be used to represent information in a concurrent data sonification. It has also investigated means by which data may be grouped and structured for more effective analysis. In addition to the original contributions of this thesis, further work is required to fully develop the techniques presented here.

9.3. Future Work

Work carried out in this thesis has produced significant improvement in the areas of musical pattern design, pattern combination and structuring of information within a data sonification. Three major areas of investigation were undertaken, and each is now considered in turn to determine how development may best proceed.

9.3.1. Contour Icons

The development of contour icons suggests means by which musical patterns may be made both distinct and memorable by including high level cognitive features, and further work is required to determine what other additions could be made. Musical contour was chosen as an effective high level descriptor of a pattern, and the shapes used for contour icons during this thesis are by no means comprehensive (or indeed conclusive). Future work will investigate the use of shape more thoroughly, to consider:

1) *What shapes are possible?*- basic shapes such as up and down arrows proved effective, but many other shapes are possible. Further work could approach this from 2 directions: the analysis of existing popular melodies to determine which shapes are most common (in a manner similar to Adams [49]), and the design of contour icons based on recognisable visual shapes. By examining results of such analysis, a more comprehensive set of contour icons could be produced, ideally taking full advantage of the higher level cognitive features they employ.
2) *How distinct can contour icons be made from one other?*- although development produced a set of contour icon shapes, no study was undertaken

to assess how distinct or similar those icons were from each other. Further work could consider how to maximise the distinction between icons, utilising features such as boundary pitches and perhaps timbre to create the most disparity between each icon in a set.

3) *Can contour icons be concatenated to create more complex shapes?*- earcons are modular in design, with more complex patterns containing greater information being constructed from smaller musical units. The same approach could be considered with contour icons, investigating whether contour icons can be concatenated to form more verbose patterns. Similarly, an overall shape (such as up or down) could be used as the basis of a family of icons, where changes in other pattern features would denote a new icon within a larger sub-group.

Contour icons proved effective in testing, but further work is needed to determine the extent of this effect. Until a set of icons is produced which can generate high recognition rates for larger variable counts (than observed in testing), contour icons cannot be considered as a fully effective method of data representation in sonification.

9.3.2. Harmonic Combination

Harmonic combination was developed to improve pattern combination detection during concurrent representation. Although results showed significant improvement, further work is required to develop it implementation fully:

1) *How many patterns can be combined effectively?*- although 3 variable combinations were tested in this thesis, higher counts may be possible if intervals within the octave are employed. Further work could consider whether such intervals allow for greater levels of combination, and if a limit of recognition exists (when proximity becomes a grouping factor).

2) *How can several patterns be combined distinctively?*- the detection of false positives during testing suggests that further investigation is need into the role of consonance and dissonance in harmonic combination. Effects of instrument (timbre) and register must be considered, alongside means by which different contour icons can be made more dissonant during combination.

3) *How can one pattern be combined with more than one other in another given variable?*- testing had considered single combinations, wherein a value from one variable could be matched with one other from each subsequent variable. Although sufficient for assessment of the method, such a limited means of combination is not applicable in practice. Further work would have to consider how to combine a pattern with several others in other registers, again observing gestalt grouping factors such a belongingness and similarity.

Harmonic combination suggests great potential as a means of rendering musical patterns concurrently in data sonification. Having said this, limitations in the current implementation preclude its effective use in real data analysis until further work increases the number of combinations that can be produced.

9.3.3. Rhythmic Parsing

Rhythmic parsing was developed to investigate the use of musical rhythm and structure in data sonification. Testing showed that groups within a data set can be effectively highlighted using rhythmic parsing, but further work is required to investigate its extent:

1) *What levels of grouping can be achieved effectively?*- in testing, a single level of grouping was performed within the data set used (fictitious examination results). Future work would have to consider how greater levels of structure could be implemented using rhythmic parsing, particularly the limit at which groups are no longer effectively detectable.

2) *What considerations must be made for specific data sets?*- initial work using rhythmic parsing had used fictitious examination results, with groupings that had been chosen to allow effective implementation during testing. Future work would have to consider how rhythmic parsing can be used with real data, and how different grouping structures and levels of grouping could be highlighted by the listener as required. Testing had sought to show the potential of the method, but practical use would require far greater investigation.

3) *Can rhythmic parsing be combined with markers and labels?*- the use of markers and labels to convey context in a sonification is an important aspect of

defining data structure, with analogies to the visual graph and bar chart being applicable. Further work could consider how labels could be used with rhythmic parsing to deliver information about the grouping structures present (rather than merely indicating their presence). It is suggested that a far more powerful means of structuring data could be achieved using a combination of both methods.

Rhythmic parsing was introduced to punctuate and highlight events in a sonification, employing the existing techniques of musical arrangement to create hierarchical structures in a data sonification. Future work must consider the extensive possibilities of such parsing more fully, to determine how effectively it can be applied to real data.

9.3.4. Applications of Contributions

The use of contour icons in a suitable application will be the focus of future work subsequent to this thesis. Although contour icons have yet to demonstrate recognition rates of 100% (6.7.1) a smaller set of icons comprised of up and down shapes could conceivably be used in the design of intelligent ringtones and alerts for mobile devices. The possibilities of longer training and exposure times afforded by implementing contour icons on a mobile device given to a participant for a long-term trial lasting several days or even weeks would allow better assessment to be made of their potential in conveying information. The use of prolonged exposure in a live environment as a form of training would allow contour icons to be assessed in an ecological context.

This method of exposure would also allow for a set of tests to be conducted between low level patterns (Appendix 10) and contour icons in a practical context. By giving one group ringtones based on reference patterns and another based on contour icons, recognition rates could be tested at regular intervals to assess the effects of continous exposure. It would be of interest to determine how quickly a set of contour icon shapes could be remembered in comparison to low level patterns, again helping to indicate the benefits of musical patterns based on higher level cognitive features.

Harmonic combination of such icons could also be investigated using mobile devices, allowing greater amounts of information to be conveyed to the user in a single pass. The use of consonant or dissonant harmonic combinations could help to signal differing forms of alerts (such as unanswered calls or texts) or indeed the priority of that alert (1 instrument for low priority alerts, 3 instruments for high priority alerts). In this manner, the use of harmonic combination could be extended outside of contour icons to include common ringtone and alert melodies which could be harmonically combined to convey additional information. Such combinations could be tested in a similar manner to contour icons, taking advantage of the longer exposure times possible with a mobile device allocated to a specific participant for a given test duration of days or even weeks.

Rhythmic parsing seeks to exploit the use of hierarchical musical rhythm structures to structure data within a sonification. In this regard, it is possible that lower level musical patterns such as those used in the audio abacus (3.3.2) or earcons (3.7) could be better employed to convey information relating to groups of data within an overall set. The complexity of structures that can be created using musical rhythms has not been fully investigated by this thesis, rather the technique itself. For this reason, applications involving weather records [133], stockmarket [135] or network monitoring [136] data may prove useful sources for rhythmic parsing. The fluctuations in specific aspects of such data over time are of great interest for analysis, and thus means of suitably structuring the data in a sonification using rhythmic parsing could prove to be a beneficial application of the technique.

9.3.5. Other Development

This research initially investigated the sonification of DNA and RNA nucleotide base sequences, and in doing so discovered that data of such complexity could not be rendered effectively using existing sonification methods. Subsequent work sought to develop better methods of representing information, but at time of writing no method has been developed that could yet be applied to data such as DNA or RNA sequences in a fully effective manner. Future work is intended to develop such a framework, having realised that the scope of such work is far greater than had originally been realised. It is also intended to investigate the use of methods such as harmonically combined contour icons to deliver smaller amounts of information using mobile devices. Future work will consider how simple melodic shapes can be used to convey information or alerts to a listener, in a similar manner to current ringtones and alerts used on such devices. It is hoped that a more structured approach can be used to design ringtones and alerts to convey information in a functional manner, potentially reducing the conflicts that more aesthetically defined patterns can often engender. Mobile devices have the potential to provide longer testing periods for contour icons and harmonic combination.

9.4. Experimental Design

In all experiments carried out during this thesis, limitations due to the practicalities of testing were encountered. Although the results published in this thesis (chapters 5-8) demonstrate the potential of the significant contributions made, future work will aim to minimise extraneous factors that could affect the results of testing. Experimental design must always acknowledge the presence of unwanted noise in the data and due care must be taken to reduce these effects.

9.4.1. Training conditions

The use of training sessions in the experiments undertaken during this thesis were intended to ensure that all participants were capable of performing the tasks involved in those tests. As such, the training sessions were employed as much to vet potential candidates as they were for the introduction of materials pertinent to the tests themselves. In all tests, comprehensive tutorial material was provided (Appendix 5), but the length of time spent on training could ideally have been increased to afford of the benefits of longer term exposure. More expansive training could feasibly be included in an ecological application of contour icons as alerts on mobile devices (9.3.4), to better assess their potential in a live environment. Such training could introduce contour icon shapes over longer periods of time (such as one contour icon per day) to assess how quickly groups of contour icons can be learned for the purposes of everyday recognition.

9.4.2. Sample size

All experiments undertaken in this thesis utilised participant groups of 20, with the DNASon (4.4.7) and reference pattern tests (5.5.6) further grouping the participants into 2 groups of 10 based on musicianship. Although results of testing related to the contributions of this thesis- contour icons (chapter 6), harmonic combination (chapter 7) and rhythmic parsing (chapter 8)- indicated significant improvement in all cases, further work is needed to better assess the extent of those contributions in a wider context. No standard value exists for sample size definition [161], but recognised guidelines state that: the greater the sample size taken, the lower the margin of error in that sample [163]. For this reason, future tests would ideally involve larger groups of participants- around 55 to 68 for an alpha level of 0.05 and 0.01 respectively [191]. By using larger sample groups, a more reliable indicator of performance could be obtained. Having said this, larger sample groups would also place greater demands on both equipment and resources than with smaller tests, and thus recommendations also include provision for improvements in testing equipment and facilities (9.4.4 and 9.4.5).

9.4.3. Musical ability

The effects of musical ability on the detection and recognition of musical patterns is another aspect of testing that was considered during some experiments in this thesis (chapters 4 and 5), but later tests sought to minimise this factor by testing non-musicians who had no formal musical training. In spite of this, it is conceivable that a participant may have answered questions relating to musical ability incorrectly, or may also have had significantly more exposure to music (i.e. as an avid listener) than others tested. For this reason, a more robust method of determining musical ability will be employed in future experiments, to ensure that this factor does not unduly influence the outcome of testing. Techniques such as the SAMATS test [114] have considered how best to ascertain the musical ability of test participants, but no comprehensive method has yet been developed. For this reason, it can be considered a part of the future work of this thesis to investigate the development of a suitable test of musical ability and training.

9.4.4. Testing Environment

The testing environment used in the tests carried out during this thesis consisted of a number of acoustically treated rooms, with equipment (9.4.5) being kept as portable as possible for mobiity. Future tests would ideally avail of more suitable and permanent resources (such as sound isolation booths) to provide a better environment for testing. The physical comfort of participants was an aspect of the testing environment that was not given enough due consideration during this thesis, with the use of furniture being determined by availability rather than suitability. For this reason, it is argued that participants may conceivably have exhibited a shorter attention span in some instances- due in part to some level of discomfort engendered by poor seating over long periods of time. Future experiments would ideally employ more comfortable furniture in a more permanent environment to help relax participants, so that their performance during testing would not be unduly affected.

The use of sound isolation booths would also provide an opportunity to create a more ideal acoustic environment for listening tests, notably in the potential to reduce the effect of unwanted noise from external sources. Although sonification is a field of research with practical application, it is argued that cohesive testing in a controlled environment can be used as a benchmark for further ecological applications of methods and techniques developed in the field.

9.4.5. Testing Equipment

The equipment used during testing was a Compaq NX6100 laptop, using the onboard ADI AC97 soundcard. Although instrumental timbres were not the focus of work in this thesis, it is conceivable that the use of a best case scenario for equipment would be beneficial to testing performance. The aims of the tests carried out in this thesis were the effectiveness of musical patterns in the conveyance of information, but the conveyance of any musical content is to some extent reliant on the quality of the medium. For this reason, future work will employ higher quality audio equipment capable of a more extensive range of timbres. By widening the available palette of sounds (2.2.6), it is hoped that listeners will be capable of making more efficient distinctions on patterns made within that palette.

9.4.6. Future Experiments

Further work carried out susbsequent to this thesis will seek to further investigate the significant contributions presented; contour icons, harmonic combination and rhythmic parsing. For each of these contributions, testing will be focussed on the directions for future work (9.3). Future tests will employ larger groups of participants in smaller test schedules- perhaps using mobile devices (9.3.4)- to assess how well different contour icon patterns perform in an ecological context. The harmonic combination of contour icons could also be tested using mobile device equipment, to convey different types of alert or levels of alert status within a single icon combination. Such experiments would ideally indicate the potential of applications for the sonification methods presented in this thesis. Other tests could be performed on the construction of new contour icons using sound isolation booths (9.4.4) with high quality audio equipment (9.4.5) to deliver contour icons of various types in a highly controlled environment. In this manner, participants would be better able to focus solely on the contour icons used and thus assess their validity without the influence of a practical application. Such tests would help to indicate the true extent of musical contour as a pattern design feature, thus building on the significant results submitted in this thesis.

9.5. Overall Conclusions

9.5.1. Thesis Statement

This thesis was undertaken in relation to the following statement:

Conveying complex data or information using sonification is difficult, particularly during concurrent presentation of multiple variable data. Existing methods of musical pattern design define patterns which are distinct for the purposes of detection, but do not adequately consider the means by which such patterns may be made memorable. Rhythm in sonification is often constrained to a single discrete time interval between events, and so is not capable of conveying structures or sub-groupings within multiple variable data sets.

This statement was defended by answering the following research questions:

RQ 1: *What effect does rhythmic parsing have on the understanding of structures within a data set?*- Rhythmic parsing was investigated during the DNASon case study, and subsequently in a full set of tests using harmonically combined contour icons detailed in chapter 8. Rhythmic parsing highlights sections and grouping within a data set using musical structures based on rhythm. Results of the chapter 8 tests showed that rhythmic parsing significantly improved group comparison performance in a data sonification.

RQ 2: *Do present methods of pattern design (notably earcon design guidelines) produce patterns which are not only distinct but also memorable?*- This question was considered in conjunction with RQ3 during the testing of low level patterns in chapter 5. Results showed that while a pattern may be made distinct, it may not necessarily be memorable. This conclusion formed the basis of the development of contour icons (as detailed in chapter 6) in response to RQ4.

RQ 3: *Can present methods of pattern design be used to efficiently render concurrent streams of data?*- As with RQ2, tests in chapter 5 showed that combining patterns in multiple streams was difficult for listeners to analyse. These results led to the investigation of harmonic combination (during chapter 7) as defined in RQ5.

RQ 4: *What effect does musical contour have on the recognition (and identification) of musical patterns used in data representation?*- This question was considered subsequent to RQ2, during the contour icon design detailed in chapter 6. Contour icons are a high level method of representing musical patterns, based around visual shapes that convey the patterns musical contour. Testing showed that contour icons significantly improved pattern recognition when compared to low level reference patterns (as used in chapter 5).

RQ 5: *What effect during concurrent presentation does harmonic combination have on the identification of features and intersections in data streams?*- This question was investigated as a result of RQ3 in the harmonic combination tests of chapter 7. Harmonic combination allows intersections within a data set to be highlighted as a single pattern harmony during a data sonification. Results showed that harmonic combination significantly improved pattern combination performance when tested against low level patterns (chapter 5) in concurrent representation.

This research has considered musical pattern design, concurrent representation and the grouping and structuring of information in data sonification. Significant improvements were produced during testing of contour icons, harmonic combination and rhythmic parsing- the main contributions of this thesis. Although further work is required in all of these areas (9.3), the contributions of this thesis have gone some way towards a fully effective method of data sonification.

Appendix 1.DNASon Test Questions

DNASon Testing Schedule Session 1

Thank you for your time in taking part in this three part test schedule. You will be asked several questions about test RNA sequences (see attached tutorial) to determine what information can be obtained through sonification of those sequences. Please remember there are no wrong answers and you are not being tested- rather it is the software used and the principles it defines that is the focus of the study.

You may ask questions of the test observer at any time, but no opinion may be canvassed on the answers themselves.

Session 1: (non Rhythmic Parsing) Control Tests

Frequency Test

Please use **section1freq.fasta** for the Sequence sonification.

By judicious selection of intervals, please define the following:

1. Does the Amino Acid Tyrosine occur? If so, how often?

   ....

2. Does the Amino Acid Proline occur? If so, how often?

   ....

3. Does the Amino Acid Alanine occur? If so, how often?

   ....

4. Does the Amino Acid Glycine occur? If so, how often?

....

5. Does the Amino Acid Proline occur? If so, is it always expressed by the same codon pattern?

....

6. Does the Amino Acid Tyrosine occur? If so, is it always expressed by the same codon pattern?

....

Combination Test 1

Please use **section1combi1.fasta** for the Sequence sonification.

Consider the following amino acid combinations and thus determine if and how often they occur:

1. Does the combination of Proline and Valine amino acids occur? If so, how often?

....

2. Does the combination of Glycine and Arganine amino acids occur? If so, how often?

....

3. Does the combination of Serine and Valine amino acids occur? If so, how often?

....

Combination Test 2

Please use **section1combi2.fasta** for the Sequence sonification.

Consider the following amino acid combinations and thus determine if and how often they occur:

1. Does the combination of Valine, Alanine and Glycine amino acids occur? If so, how often?

   ....

2. Does the combination of Valine, Alanine and Aspartic Acid amino acids occur? If so, how often?

   ....

3. Does the combination of Histidine, Arganine and Serine amino acids occur? If so, how often?

   ....

Thank you for taking part in this test. Please hand your workbook to the test observer.

DNASon Testing Schedule Session 2

Thank you again for your time in taking part in this second test. You will again be asked several questions about test RNA sequences (see attached tutorial) to determine what information can be obtained through sonification of those sequences. Once again, please remember there are no wrong answers and you are not being tested- rather it is the software used and the principles it defines that is the focus of the study.

You may ask questions of the test observer at any time, but no opinion may be canvassed on the answers themselves.

Session 2: 3/4 Time Signature Tests

Frequency Test

Please use **section2freq.fasta** for the Sequence sonification.

By judicious selection of intervals, please define the following:

1. Does the Amino Acid Asparagine occur? If so, how often?

   ....

2. Does the Amino Acid Valine occur? If so, how often?

   ....

3. Does the Amino Acid Tryptophan occur? If so, how often?

   ....

4. Does the Amino Acid Isoleucine occur? If so, how often?

   ....

5. Does the Amino Acid Valine occur? If so, is it always expressed by the same codon pattern?

   ……………………………………………………

6. Does the Amino Acid Asparagine occur? If so, is it always expressed by the same codon pattern?

   ……………………………………………………

Combination Test 1

Please use **section2combi2.fasta** for the Sequence sonification.

Consider the following amino acid combinations and thus determine if and how often they occur:

1. Does the combination of Glutamic Acid and Glycine amino acids occur? If so, how often?

   ……………………………………………………

2. Does the combination of Asparagine and Tryptophan amino acids occur? If so, how often?

   ……………………………………………………

3. Does the combination of Tryptophan and Isoleucine amino acids occur? IF so, how often?

   ……………………………………………………

Combination Test 2

Please use **section1combi2.fasta** for the Sequence sonification.

Consider the following amino acid combinations and thus determine if and how often they occur:

1. Does the combination of Asparagine, Cysteine and Asparagine amino acids occur? If so, how often?

   ....

2. Does the combination of Glutamic Acid, Isoleucine and Valine amino acids occur? If so, how often?

   ....

3. Does the combination of Asparagine, Valine and Asparagine Acid amino acids occur? If so, how often?

   ....

Thank you once again for taking part in this test. Please hand your workbook to the test observer.

DNASon Testing Schedule Session 3

Thank you for your time in taking part in this final test. Again you will be asked several questions about test RNA sequences (see attached tutorial) to determine what information can be obtained through sonification of those sequences. As always, please remember there are no wrong answers and you are not being tested- rather it is the software used and the principles it defines that is the focus of the study.

You may ask questions of the test observer at any time, but no opinion may be canvassed on the answers themselves.

Session 3: 4/4 Time Signature Tests

Frequency Test

Please use **section3freq.fasta** for the Sequence sonification.

By judicious selection of intervals, please define the following:

1. Does the Amino Acid Histidine occur? If so, how often?

   ....

2. Does the Amino Acid Valine occur? If so, how often?

   ....

3. Does the Amino Acid Leucine occur? If so, how often?

   ....

4. Does the Amino Acid Alanine occur? If so, how often?

   ....

5. Does the Amino Acid Alanine occur? If so, is it always expressed by the same codon pattern?

   ....

6. Does the Amino Acid Leucine occur? If so, is it always expressed by the same codon pattern?

   ....

Combination Test 1

Please use **section3combi1.fasta** for the Sequence sonification.

Consider the following amino acid combinations and thus determine if and how often they occur:

1. Does the combination of Glutamine and Alanine amino acids occur? If so, how often?

   ....

2 Does the combination of Threonine and Arganine amino acids occur? If so, how often?

   ....

3 Does the combination of Lysine and Leucine amino acids occur? If so, how often?

   ....

Combination Test 2

Please use **section3combi2.fasta** for the Sequence sonification.

Consider the following amino acid combinations and thus determine if and how often they occur:

1 Does the combination of Threonine, Glutamine and Arganine amino acids occur? If so, how often?

....

2 Does the combination of Threonine, Glutamine and Arganine amino acids occur? If so, how often?

....

3 Does thc combination of Tryptophan, Lysine and Valine amino acids occur? If so, how often?

....

Thank you very much for your time and effort in taking part in all three sections of this test. Please hand your workbook to the test observer.

Appendix 2.DNASon RNA Sequence Files

Below are listings of sequence files used during the DNASon case study tests. All files are in FASTA format.

session1freq.fasta
> Section 1 Frequency Test fasta sequence augucuuaucaaccugucgccgacggccaccgagcaguucccucauaugauggcgcaguaccguag

session1combi1.fasta
> Section 1 Combination Test 1 fasta sequence augucucccguagauggucgacauuaccagccuccggugggccgaucagucggaagacccuag

session1combi2.fasta
> Section 1 Combination Test 2 fasta sequence augucuccagauguagccggugaucacagguccccguagcuggccacgucccagauuacgucgcccaucaau cuccugauuaucguuag

session2freq.fasta
> Section 2 Frequency Test fasta sequence augugcuuuaauauuguggccgaaggcugguaugugaaugucaucgccgaaugugguuuuuag

session2combi1.fasta
> Section 2 Combination Test 1 fasta sequence augugugccauugagggcguuuuuaauuggauuuucgucuacgaagggaauuggguugcuuag

session2combi2.fasta
> Section 2 Combination Test 2 fasta sequence augggcgcuauugaaguuaauuguaacguagcagguuauguugcugaaauugucuuuuguuuuauugccaau uguaacgaaauugucuag

session3freq.fasta
> Section 3 Frequency Test fasta sequence

augucuaaacuucgucaugucuggacuaagcuuagggccacccguuggcugcaugcuacuuag

session3combi1.fasta
> Section 3 Combination Test 1 fasta sequence augacuaggguucauaaacuccaggcaaggcucaagucacaagccacccggaaaguauuguag

session3combi2.fasta
> Section 3 Combination Test 2 fasta sequence auguggcggacugcccagucucacaagguccucuggaaaguaacucaacgacuuaaaucucaaacucaacgauc ucuucauaaaguuuag

Appendix 3.DNASon Questionnaire and Results

This is a copy of the test questionnaire given to all participants prior to the first session tests (for both the DNASon and reference pattern test schedules).This questionnaire was used to determine the musicianship and music technology skills of each participant. The results of both questionnaires are listed sequentially.

Please fill out the following brief questionnaire below. Please remember there are no wrong answers and you are not being tested- rather it is the software used and the principles it defines that is the focus of the study.

1. Do you have any Computer Experience (please circle one item):

- None
- Home use
- Academic/Business use
- Frequent use
- Expert user

2. Do you have an Interest in Computers and Technology:

- None
- Casual
- Fair
- Very Interested
- Professional

3. Types of Software Application Used (please select all that apply):

- Email and Office Applications (such as Hotmail or MSOffice)

- Desktop Publishing and Web Design Applications (such as Quark or Dreamweaver)
- Sound Editing and Recording Applications (such as Wavelab or ProTools)
- Sequencing and Sound Processing Applications (such as Cubase or Reason)
- Music Notation and Arrangement Applications (such as Sibelius)

4. Do you have exposure to Computer Programming Languages:

- C++
- Pascal
- Visual Basic
- Java
- Unix

5. Do you have an Interest in Music:

- No Interest
- Casual Music Interest
- Keen Music Listener
- Musician (as a hobby)
- Professional Musician

6. Do you have any Musical Qualifications:

- None
- Up to Grade 2
- Up to Grade 4
- Up to Grade 6
- Up to Grade 8

7. Please define the following in Standard Notation:

- A bass clef in the key of A major

- An Interval of G(Root) with a 5^{th}

- An Interval of C(Root) with a 3^{rd}

- A 2 quaver, 1 crotchet rest Rhythm Pattern

- A 2 crotchet, 1 semiquaver rest Rhythm Pattern

8. Do you have an interest in Audio Technology:

- None
- Hi-Fi Enthusiast
- Home Recording/production
- Sound Engineer
- Recording Engineer/ Producer

9. Do you compose music using any of the following:

- Sequencer
- Synthesiser
- CSound
- Algorhythmic Synthesis Software

- Sampler

10. Do you use any of the following equipment in your music:

- Soft Sampler
- Effects Plugins
- Soft Synthesiser
- MIDI Controller
- HD recording System

DNASon Results (by test grouping)

	Question	1	2	3	4	5	6	7	8	9	10	Overall Results	Questions 5-7 (%)
	marks	5	5	5	5	5	5	5	5	5	5	50	
	Musicians												
1		1	2	1	0	5	5	5	2	1	1	23	100.00
2		3	3	2	0	5	4	4	0	1	1	23	83.33
3		3	2	2	0	4	4	4	1	2	1	23	75.00
4		2	1	1	0	5	4	5	0	1	1	20	91.67
5		2	2	2	0	5	5	4	2	2	1	25	91.67
6		2	0	1	0	4	4	5	1	1	1	19	83.33
7		3	3	3	1	5	5	5	2	1	1	29	100.00
8		1	3	2	0	4	4	4	2	2	1	23	75.00
9		0	3	2	0	5	5	4	0	1	1	21	91.67
10		3	2	1	0	5	5	5	1	2	1	25	100.00
													Average=91.33
	non-Musicians												
1		4	4	4	3	4	3	3	3	4	4	36	58.33
2		4	3	2	1	4	3	2	0	2	2	23	50.00
3		2	2	2	1	3	2	1	0	2	2	17	25.00

4		4	3	4	0	3	1	2	2	2	3	24	25.00
5		3	2	2	0	2	0	0	0	2	2	13	8.33
6		1	2	3	0	2	2	2	0	1	1	14	25.00
7		1	1	1	0	3	0	0	0	0	0	6	16.67
8		3	3	2	1	3	0	2	2	2	1	19	25.00
9		2	1	1	0	3	2	0	1	1	1	12	25.00
10		3	3	3	2	3	3	0	0	3	2	22	33.33
													Average=38.67

Reference Pattern Results (by test grouping)

	Question	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Overall Results**	**Questions 5-7 (%)**
	marks	5	5	5	5	5	5	5	5	5	5	50	
	Musicians												
1		3	2	2	0	5	5	5	3	0	0	25	100.00
2		4	5	4	1	5	3	4	5	3	5	39	80.00
3		2	2	1	0	5	5	5	1	0	0	21	100.00
4		4	4	4	1	5	5	5	3	1	1	33	100.00
5		2	3	4	0	5	5	5	2	0	0	26	100.00
6		4	2	2	0	5	5	5	1	0	0	24	100.00
7		5	5	5	3	5	3	4	5	3	5	43	80.00
8		3	3	5	1	5	5	5	3	3	2	35	100.00
9		4	4	3	0	4	4	5	3	1	4	32	86.67
10		5	5	5	4	5	3	4	5	3	5	44	80.00
													Average=92.67
	non-Musicians												
1		2	2	1	0	4	1	0	3	0	1	14	33.33
2		2	2	1	0	2	1	0	1	0	0	9	20.00
3		2	1	1	0	3	1	0	1	0	0	9	26.67
4		3	3	2	1	3	1	0	1	0	0	14	26.67
5		2	2	1	0	3	1	0	1	0	0	10	26.67

6		4	4	2	2	3	1	0	2	0	0	18	26.67
7		2	1	1	0	2	1	0	1	0	0	8	20.00
8		1	1	1	0	2	1	0	1	0	0	7	20.00
9		5	4	5	3	4	2	1	3	2	5	34	46.67
10		4	5	3	0	5	2	0	5	3	4	31	46.67
													Average=29.33

Appendix 4. DNASon Test Results

All test results are listed below by session. Each session comprised of frequency and combination tests, with overall results for all sessions also listed.

Session 1

	Frequency Test											
Questions	1a	1b	2a	2b	3a	3b	4a	4b	5a	5b	6a	6b
Marks awarded	2	2	2	2	2	2	2	2	2	1	2	1
Correct Answer	Y	2	Y	3	Y	3	Y	2	Y	N	Y	Y
Musicians												
1	Y	1	Y	1	Y	1	N	0	Y	N	N	N
2	Y	1	Y	3	Y	2	N	0	Y	Y	N	N
3	Y	1	Y	1	Y	3	N	0	N	N	Y	N
4	Y	1	Y	2	Y	2	N	0	Y	Y	N	N
5	Y	1	Y	1	Y	2	Y	2	N	N	N	N
6	Y	1	Y	1	Y	1	N	0	Y	Y	Y	N
7	Y	2	Y	1	Y	1	N	0	Y	N	N	N
8	N	0	Y	2	Y	2	Y	1	N	N	Y	Y
9	Y	2	Y	2	Y	2	N	0	Y	Y	N	N
10	Y	1	Y	2	Y	2	N	0	Y	N	N	N
Non- Musicians												
1	Y	2	Y	1	Y	1	N	0	Y	N	N	N
2	Y	2	N	0	Y	1	N	0	Y	N	N	N
3	Y	1	Y	1	Y	1	Y	1	N	N	N	N
4	Y	1	Y	1	Y	2	Y	1	Y	Y	N	N
5	Y	2	Y	1	Y	1	N	0	N	N	N	N
6	Y	1	N	0	Y	1	Y	1	N	N	Y	N
7	Y	2	N	0	Y	2	Y	1	N	N	Y	N
8	Y	1	Y	1	N	0	Y	1	Y	Y	N	N
9	N	0	Y	1	N	0	Y	2	N	N	Y	Y
10	Y	1	N	0	Y	2	Y	3	Y	Y	N	N
	Combination Test 1						**Combination Test 2**					
Questions	1a	1b	2a	2b	3a	3b	1a	1b	2a	2b	3a	3b
Marks awarded	2	2	2	2	2	2	2	2	2	2	2	2
Correct Answer	Y	2	Y	3	Y	1	Y	2	Y	2	Y	1

Musicians												
1	Y	1	Y	1	Y	1	Y	1	Y	1	N	0
2	Y	1	Y	2	N	0	Y	2	N	0	Y	2
3	Y	1	Y	2	Y	1	N	0	Y	1	Y	1
4	Y	1	Y	1	Y	2	N	0	N	0	Y	1
5	Y	2	Y	2	N	0	Y	2	Y	1	N	0
6	Y	1	Y	1	N	0	Y	1	Y	1	Y	1
7	Y	1	Y	1	Y	1	Y	2	Y	1	Y	2
8	Y	1	Y	2	Y	1	Y	1	Y	1	N	0
9	Y	1	Y	1	N	0	N	0	N	0	N	0
10	Y	1	Y	1	Y	1	Y	1	N	0	Y	1
Non- Musicians												
1	Y	1	Y	2	Y	1	Y	2	Y	1	Y	1
2	Y	1	Y	1	N	0	Y	1	N	0	N	0
3	Y	1	Y	1	Y	2	Y	1	Y	1	Y	2
4	Y	2	Y	2	Y	2	Y	1	Y	1	Y	1
5	N	0	Y	1	N	0	N	0	Y	1	N	0
6	Y	1	Y	1	N	0	Y	1	Y	1	N	0
7	Y	1	Y	1	N	0	N	0	N	0	Y	2
8	Y	1	Y	1	Y	1	N	0	Y	1	Y	1
9	Y	2	Y	2	N	0	Y	1	Y	1	N	0
10	Y	3	Y	1	Y	1	N	0	N	0	Y	1

Session 2

	Frequency Test											
Questions	1a	1b	2a	2b	3a	3b	4a	4b	5a	5b	6a	6b
Marks awarded	2	2	2	2	2	2	2	2	2	1	2	1
Correct Answer	Y	2	Y	3	Y	1	Y	2	Y	N	Y	Y
Musicians												
1	Y	1	Y	1	Y	2	Y	1	Y	Y	Y	N
2	Y	2	Y	1	N	0	Y	1	Y	N	N	N
3	Y	1	N	0	Y	2	Y	1	Y	N	N	N
4	Y	1	Y	1	N	0	Y	1	Y	N	N	N
5	Y	3	Y	1	Y	2	Y	1	N	N	Y	Y
6	N	0	Y	1	Y	1	Y	2	Y	N	N	N
7	Y	2	Y	2	Y	2	Y	1	Y	N	Y	Y
8	Y	1	Y	1	N	0	Y	1	Y	N	N	N
9	Y	1	Y	3	N	0	Y	1	Y	Y	Y	N

10	Y	1	Y	1	N	0	Y	1	N	N	Y	Y
Non- Musicians												
1	Y	1	Y	2	Y	2	Y	1	Y	N	Y	N
2	N	0	N	0	Y	1	Y	1	Y	N	Y	N
3	Y	1	Y	1	Y	1	Y	1	N	N	N	N
4	Y	1	Y	3	Y	2	N	0	Y	Y	N	N
5	N	0	N	0	Y	1	Y	1	Y	N	N	N
6	Y	2	Y	1	Y	2	Y	1	Y	N	N	N
7	Y	1	Y	2	Y	1	N	0	Y	N	N	N
8	N	0	Y	2	N	0	Y	2	N	N	Y	N
9	Y	1	Y	1	Y	1	Y	2	N	N	Y	N
10	N	0	Y	2	Y	1	Y	2	N	N	Y	N
	Combination Test 1						**Combination Test 2**					
Questions	1a	1b	2a	2b	3a	3b	1a	1b	2a	2b	3a	3b
Marks awarded	2	2	2	2	2	2	2	2	2	2	2	2
Correct Answer	Y	2	Y	2	Y	1	Y	2	Y	2	N	0
Musicians												
1	Y	1	Y	1	N	0	Y	1	N	0	N	0
2	Y	2	N	0	N	0	Y	1	Y	1	Y	1
3	Y	2	Y	2	N	0	Y	1	N	0	N	0
4	N	0	Y	1	Y	2	Y	1	Y	2	Y	1
5	Y	1	Y	1	Y	2	Y	1	N	0	Y	2
6	Y	1	Y	2	Y	1	Y	2	Y	1	N	0
7	Y	2	N	0	Y	1	Y	1	Y	2	Y	1
8	Y	2	N	0	N	0	Y	1	Y	1	Y	1
9	Y	1	Y	1	Y	1	Y	2	Y	1	N	0
10	Y	1	N	0	N	0	N	0	N	0	N	0
Non- Musicians												
1	Y	1	Y	1	Y	1	Y	1	Y	1	N	0
2	Y	2	N	0	N	0	N	0	N	0	N	0
3	Y	1	Y	1	N	0	Y	1	N	0	N	0
4	Y	1	N	0	N	0	N	0	Y	2	N	0
5	Y	1	Y	2	N	0	N	0	Y	1	Y	1
6	Y	2	Y	1	Y	2	Y	1	N	0	N	0
7	Y	1	Y	1	N	0	Y	1	N	0	Y	1
8	N	0	N	0	N	0	N	0	Y	1	N	0
9	Y	1	Y	1	Y	2	N	0	N	0	N	0
10	Y	1	Y	1	N	0	Y	1	Y	1	Y	1

Session 3

	Frequency Test											
Questions	1a	1b	2a	2b	3a	3b	4a	4b	5a	5b	6a	6b
Marks awarded	2	2	2	2	2	2	2	2	2	1	2	1
Correct Answer	Y	1	Y	1	Y	3	Y	2	Y	N	Y	N
Musicians												
1	N	0	Y	1	Y	2	Y	2	Y	N	N	N
2	Y	1	Y	1	Y	1	N	0	N	N	N	N
3	Y	1	Y	2	Y	1	Y	1	Y	Y	Y	N
4	N	0	N	0	Y	3	Y	2	N	N	Y	N
5	Y	2	Y	1	Y	1	N	0	Y	N	Y	N
6	N	0	N	0	Y	2	Y	2	Y	Y	Y	N
7	N	0	Y	1	Y	3	Y	1	Y	N	Y	Y
8	Y	1	N	0	Y	1	Y	1	Y	N	N	N
9	Y	1	Y	2	Y	1	Y	2	Y	Y	N	N
10	Y	1	N	0	Y	2	Y	1	N	N	Y	Y
Non- Musicians												
1	N	0	Y	1	Y	4	Y	1	Y	Y	N	N
2	Y	1	Y	1	Y	3	Y	2	Y	Y	N	N
3	Y	2	N	0	Y	2	Y	1	Y	Y	Y	Y
4	N	0	Y	1	Y	1	Y	1	Y	N	Y	Y
5	Y	2	Y	1	Y	2	Y	2	N	N	N	N
6	N	0	Y	1	0	0	Y	1	N	N	N	N
7	Y	1	N	0	Y	1	Y	1	Y	Y	N	N
8	Y	2	Y	2	Y	1	Y	3	N	N	Y	N
9	N	0	Y	2	Y	1	N	0	Y	N	Y	N
10	Y	1	Y	2	Y	2	N	0	Y	N	N	N
	Combination Test 1						**Combination Test 2**					
Questions	1a	1b	2a	2b	3a	3b	1a	1b	2a	2b	3a	3b
Marks awarded	2	2	2	2	2	2	2	2	2	2	2	2
Correct Answer	Y	2	Y	1	Y	1	Y	2	Y	2	Y	1
Musicians												
1	Y	1	Y	1	Y	1	Y	1	N	0	N	0
2	N	0	Y	1	Y	1	Y	1	N	0	Y	1
3	Y	1	Y	1	Y	2	Y	1	N	0	Y	1
4	Y	1	Y	2	N	0	N	0	Y	1	N	0
5	Y	1	Y	1	N	0	Y	1	Y	2	N	0

6	Y	2	N	0	N	0	Y	1	N	0	Y	1
7	Y	1	Y	1	Y	1	Y	1	N	0	Y	2
8	Y	1	N	0	N	0	Y	1	N	0	N	0
9	Y	1	N	0	Y	1	Y	1	N	0	Y	1
10	Y	1	N	0	Y	1	Y	2	N	0	Y	1
Non- Musicians												
1	N	0	N	0	Y	1	Y	1	N	0	Y	1
2	Y	2	Y	1	Y	1	Y	1	Y	1	N	0
3	Y	1	N	0	Y	1	Y	2	Y	1	Y	1
4	N	0	N	0	Y	1	Y	1	N	0	Y	2
5	Y	2	Y	2	N	0	Y	1	N	0	Y	1
6	N	0	N	0	Y	2	N	0	N	0	N	0
7	Y	1	N	0	N	0	Y	1	N	0	N	0
8	Y	1	Y	1	Y	1	Y	1	Y	1	N	0
9	Y	2	N	0	N	0	Y	1	N	0	N	0
10	N	0	Y	1	Y	1	Y	1	N	0	Y	1

Overall results (by session)

	Frequency			**Combinations**			**Overall**		
Marks awarded	22			24			46		
Session	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Musicians									
1	10	15	14	15	13	14	25	28	28
2	12	12	10	13	10	15	25	22	25
3	11	11	16	17	15	17	28	26	33
4	11	11	11	12	13	9	23	24	20
5	12	15	15	14	12	14	26	27	29
6	11	13	12	15	22	11	26	35	23
7	11	19	17	19	15	17	30	34	34
8	12	11	12	6	10	7	18	21	19
9	12	15	15	5	21	14	17	36	29
10	12	11	12	16	7	15	28	18	27
Non- Musicians									
1	11	17	12	21	20	11	32	37	23
2	9	12	18	8	8	18	17	20	36
3	10	12	13	17	13	18	27	25	31
4	13	12	14	20	11	10	33	23	24
5	8	10	14	5	10	14	13	20	28

6	10	15	7		11	17	3		21	32	10
7	12	13	11		8	9	6		20	22	17
8	10	9	13		15	7	17		25	16	30
9	9	15	10		13	13	7		22	28	17
10	11	13	13		13	12	14		24	25	27
Average (%)	49.32	59.32	58.86		54.79	53.75	52.29		52.17	56.41	55.43

Appendix 5.Sonification Tutorial Materials

The following tutorial document was given to participants during the reference pattern tests (chapter 5). Other sections containing information relevant to subsequent tests were added as required, and each is listed in turn.

Sonification Tutorial

This tutorial explains the use of non-speech audio to convey information, using a process known as sonification. Sonification of information or data can be performed in various ways, and existing examples of such sonification can help to explain the technique. You may ask questions of the examiner at any point in time.

Existing Sonification Methods

Sonar and the Gieger Counter are well known examples where data (either from underwater objects or radioactive materials) is conveyed to the user by audio means. Alarm sounds and other alerts (such as sirens used by emergency services) can be considered as a means of representing data (in this case a warning) through audio. Mobile phones have distinct audio events for messages, and in allowing different ringtones to be assigned to individuals or groups use sonification to convey data (in this case who's calling).

Data Sets

These tests form part of a PhD thesis on the use of sonification with common data sets for the purposes of analysis. The data used is taken from survey questions about favourite food, drink, film genre, music style and so on.

Index	Colour	Radio Station	Movie Genre
1	Red	FM104,	Action
2	Blue	98FM	Sci-Fi
3	Yellow	98FM	Action
4	Yellow	98FM	Comedy
5	Blue	LyricFM	Sci-Fi
6	Green	FM104,	Romance
7	Yellow	SpinFM	Comedy

Test Questions

N.B. this section was amended during the contour icon tests, as pattern combination questions were not asked.

The data from these surveys will be sonified during the tests, and questions will be asked about that data. You will be asked 2 types of questions during the tests- point estimation and pattern combination questions.

Point estimation questions determine the amount of times a specific value occurs within the sonification. For example:

How many people chose FM104?

How many people like Jazz music?

Pattern combination questions determine the amount of times a specific combination of values occurs within a sonification. For example:

How many people chose the drink Milk and the colour Red?

How many people chose the newspaper Irish Times and Sci-Fi novels?

Pattern Matching

Most people have a favourite song and are usually capable of recognising it quickly and easily. This capability for pattern matching is used during these tests to convey information. If you consider each melodic pattern as a distinct event, then you can determine its occurrence within a piece of music, e.g:

Pattern 1 Pattern 2 Pattern 3 Pattern 4

Four melodic patterns are shown above and each of these patterns could be used to represent a different data value. So consider the following data set of favourite styles of music and possible associated mappings:

Pattern 1
Rock

Pattern 2
Jazz

Pattern 3
Classical

Pattern 4
Blues

If you are now played this output sequence of patterns as a sonification then you should be able to hear each data value in the set:

In this case 2 people liked Rock music, while 1 liked Classical music and another liked Jazz. The important point is not the number of Rock fans, but that musical patterns can be used to represent information. By participating in a test you are required to assign musical patterns to each data value, and then listen to the output sonification of those data values. You will then be required to answer questions about the data you have sonified, with the results being used to assess how well that sonification can convey information to you.

The following section was added for the contour icon tests. The reference pattern condition section is listed first, followed by the tutorial section given to participants during the contour icon condition.

1. Reference pattern condition

Patterns Used

In the following tests, you will be given the choice of 8 musical patterns. Each pattern is to be used to sonify a specific value within a set of survey data, and you will then be asked questions about that data.

Each pattern is listed numerically within the software, and you can take as long as you wish to listen to each. Remember that you will not be asked to use all 8 patterns together, so try to choose those you feel you can recognise easily during the tests. Once you have listened to the patterns, you will be asked to identify each one at random. This is to ensure that you can recognise all the available patterns used, prior to using them within a sonification during the tests. If you cannot identify all 8 patterns first time, you will be given additional time to listen to them again. After this, you will be asked to identify them again at random. If you still cannot identify them, you will not be asked to sit the tests.

You will now hear an example sonification using these patterns. You will also be given a diagram listing each pattern you will hear as it occurs within the sonification. The diagram also shows a listing of the data value represented by each pattern. The questions asked during the tests will require you to remember which pattern represents a certain data value and how often it occurs.

2. Contour icon condition

Patterns Used

In the following tests, you will be given the choice of 8 musical patterns known as contour icons. Each pattern is to be used to sonify a specific value within a set of survey data, and you will then be asked questions about that data.

Each contour icon is shown within the software, and you can take as long as you wish to listen to each. Remember that you will not be asked to use all 8 contour icons together, so try to choose those you feel you can recognise easily during the tests. Once you have listened to the contour icons, you will be asked to identify each one at random. This is to ensure that you can recognise all the available contour icons used, prior to using them within a sonification during the tests. If you cannot identify all 8 contour icons first time, you will be given additional time to listen to them again. After this, you will be asked to identify them again at random. If you still cannot identify them, you will not be asked to sit the tests.

You will now hear an example sonification using these contour icons. You will also be given a diagram listing each contour icon you will hear as it occurs within the sonification. The diagram also shows a listing of the data value represented by each contour icon. The questions asked during the tests will require you to remember which contour icon represents a certain data value and how often it occurs.

The following section was added for the harmonic combination tests. The pattern combination question section listed above was included again, and the contour icon pattern section was used in both conditions (without the example sonification paragraph). This was followed by more information on pattern combinations for each condition.

Consonance and Dissonance

Consonance and dissonance are musical terms used to describe the harmonic combination of different vocal or instrumental parts. A simple example would be 2 people humming the same tune, which would be considered a harmonic unison if they were both in tune. In contrast, if one person was to hum a different tune, the clash between the 2 tunes could potentially be considered as dissonant.

Although this explanation does not cover the vast possibilities of harmonic combination that are possible in music, the definition for the purposes of testing merely requires you to detect when different contour icons are played by different instruments at the same time, or when more than one instrument plays the same contour icon at the same time.

Pattern Combination

In these tests, the use of multiple contour icons to convey combinations within the data is important. For each sonification, you will be asked to listen for the occurrence of a specific combination of contour icons. The way these contour icons are combined is the focus of testing, and so you will be required to detect consonant and dissonant combinations at certain stages. You will now be played 4 example sonifications of contour icons in various combinations .To ensure you can recognise multiple instruments in consonant and dissonant combination, you will be asked to state:

1. The number of instruments present.
2. The contour icon(s) used.
3. How many instruments played the same contour icon.

If you do not answer all 3 questions correctly for all combinations, you will be given an additional demonstration of each type of combination. After this, you will be asked to listen to another 4 example sonifications. If you still do not answer all 3 questions correctly for all combinations, you will not be asked to sit the tests.

1. non-harmonic combination condition

You will now hear an example sonification using these contour icons. You will also be given a diagram listing each of the contour icons you will hear as they occur within the sonification. The diagram also shows a listing of the data values represented by each contour icon. The questions asked during the tests will require you to remember which contour icon represents a certain data value and how often it occurs. The questions will also ask you to remember certain combinations of contour icons that correspond to combinations of interest within the data, and how often they occur.

2. *harmonic combination condition*

You will now hear an example sonification using these contour icons. You will also be given a diagram listing each of the contour icons you will hear as they occur within the sonification. The diagram also shows a listing of the data values represented by each contour icon. The questions asked during the tests will require you to remember which contour icon represents a certain data value and how often it occurs. The questions will also ask you to remember certain harmonic combinations of contour icons that correspond to combinations of interest within the data, and how often they occur.

The following section was added for the rhythmic parsing tests. The existing sonification methods, pattern matching, patterns used, consonance and dissonance and pattern combination sections were included (excluding the example sonification paragraph). This was followed by more information on rhythmic parsing in the tutorial for that condition.

Data Sets

These tests form part of a PhD thesis on the use of sonification with common data sets for the purposes of analysis. The data used is taken from fictitious examination results of students from 4 different courses who have all sat 3 common examinations, such as in the following example table.

Student Number	Course	Exam 1	Exam 2	Exam 3
1	1	A	C	C
2	1	A	C	B
3	1	B	A	C
4	1	C	C	A
5	1	C	C	C
6	2	B	A	B
7	2	C	C	B
8	2	B	A	A
9	2	C	B	A

10	2	A	A	A
11	3	B	A	C
12	3	B	B	C
13	3	A	A	C
14	3	A	B	B
15	3	A	C	A
16	4	A	C	B
17	4	A	A	A
18	4	A	A	A
19	4	C	B	C
20	4	B	A	A

Test Questions

These examination results will be sonified during the tests, and questions will be asked about them. You will be asked 3 types of questions during the tests- point estimation, pattern combination and group comparison questions.

Point estimation questions determine the amount of times a specific value occurs within the sonification. For example:

How many students got an A for exam 1?

How many students got a C for exam 2?

Pattern combination questions determine the amount of times a specific combination of values occurs within a sonification. For example:

How many students got a C for all 3 exams?

How many students got a B for exams 1 and 2?

Group comparison questions take the results for each course group, and determine the highest within a sonification. For example:

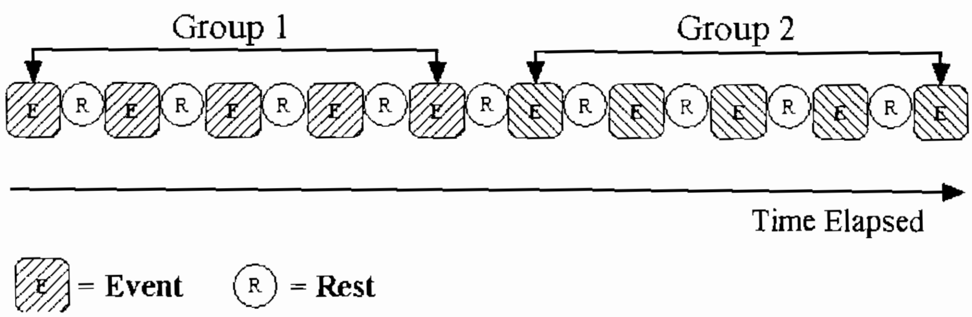
Which group got the most A passes for all 3 exams?

Which group got the most B passes for exam 2?

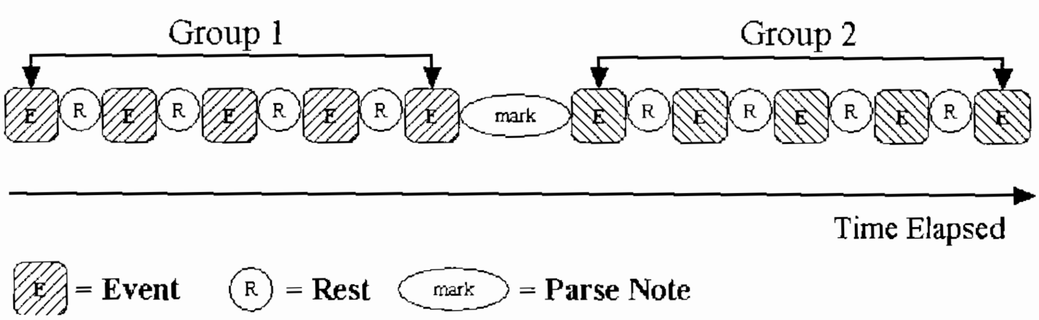
1. Rhythmic parsing condition

Rhythmic Parsing

Rhythmic parsing is a technique whereby events in a sonification are grouped together, so that comparisons can be made between them. This is achieved by the addition of a long rest known as a ***parse note*** between each group. Although the hierarchical structures found within music contain complex relations of rhythm and metre, a musical rest can simply be thought of as a gap for the purposes of these tests. In the tests, each contour icon is separated from the next by a short rest:



To highlight the groups within the data, a ***further*** rest (parse note) is added between the contour icons of each group:



Thus, when group comparisons must be made there is no need to retain the index of each group during the sonification. This allows you collate the relevant statistic for each group without having to remember where each group begins and ends.

This section of the tutorial was common to both non-rhythmic and rhythmic conditions

You will now hear an example sonification of fictitious examination results using contour icons. You will also be given a diagram listing each of the contour icons you will hear as they occur within the sonification. The diagram also shows a listing of the results represented by each contour icon. The questions asked during the tests will require you to remember which contour icon represents a certain data value and how often it occurs. The questions will also ask you to remember certain harmonic combinations of contour icons that correspond to combinations of interest within the data, and how often they occur. When listening to the sonifications during testing, group comparison questions will be asked about the results obtained by different courses. You will be required to determine the results each group obtained for a particular examination or combination of examinations and then specify which group achieved the highest.

Appendix 6.Reference Pattern Test Questions

TrioSon Test Schedule (Session 1)

Thank you for taking part in this test. The following tests are intended to assess the viability of Data sonification and its associated parameters and so ARE NOT a reflection upon the subject in any way. You will be asked basic questions about the data you have sonified and also about the way you have sonified it. The purpose of these questions is to define what works and what doesn't within basic data sonification and so you will also be asked a few simple questions about how you performed during the tests and what you feel could be improved upon within the software.

Test 1: Single Parameter Condition (use **2Variable Test1** File)

for the **bassline** parameter, sonify **Fruit**.
for the **chord** parameter, sonify **Vegetables**.
for the **melody** parameter, sonify **Dairy**.

Question1: __MUTE the Chord and Melody.__ Define the following:

a: How many Apples are there..

b: How many Oranges are there..

c: Are there more Oranges or Apples.......................................

Question 2: __MUTE the Bassline and Melody.__ Define the following:

a: How many Onions are there..

b: How many Potatoes are there..

c: Are there more Potatoes than Onions…………………………………………

Question 3: ***MUTE the Bassline and Chord.*** *Define the following:*

a: How many times does Milk occur…………………………………………

b: How many times does Cream occur………………………………………

c: Is there more Milk or Cream………………………………………………

Test 2: Single Parameter Condition (use **3Variable Test1** File)

for the **bassline** parameter, sonify **Fruit**.
for the **chord** parameter, sonify **Vegetables**.
for the **melody** parameter, sonify **Dairy**.

*Question1: **MUTE the Chord and Melody.** Define the following:*

a: How many Apples are there..

b: How many Pears are there...

c: Are there more Oranges or Apples..

d: Are there more Apples or Pears...

*Question 2: **MUTE the Bassline and Melody.** Define the following:*

a: How many Onions are there..

b: How Much Lettuce is there..

c: Are there more Potatoes than Onions...

d: Are there more Potatoes than Lettuce...

*Question 3: **MUTE the Bassline and Chord.** Define the following:*

a: How many times does Milk occur..

b: How many times does Cheese occur..

c: Is there more Milk or Cream...

d: Is there more Cream or Cheese……………………………………………………

Test 3: Single Parameter Condition (use **4Variable Test1** File)

for the **bassline** parameter, sonify **Fruit**.
for the **chord** parameter, sonify **Vegetables**.
for the **melody** parameter, sonify **Dairy**.

*Question1: **MUTE the Chord and Melody.** Define the following:*

a: How many Oranges are there...

b: How many Pears are there..

c: How many Bananas are there..

d: Are there more Oranges or Apples..

e: Are there more Bananas or Oranges...

*Question 2: **MUTE the Bassline and Melody.** Define the following:*

a: How many Onions are there...

b: How many Potatoes are there...

c: How Many Carrots is there..

d: Are there more Potatoes than Onions...

e: Are there more Carrots than Lettuce..

*Question 3: **MUTE the Bassline and Chord.** Define the following:*

a: How many times does Milk occur..

b: How many times does Cheese occur...

c: How many times does Butter occur..

d: Is there more Milk or Butter..

e: Is there more Cream or Cheese...

Test 4: Dual Parameter Condition (use **2Variable Test2** File)

for the **bassline** parameter, sonify **Dairy**.
for the **chord** parameter, sonify **Vegetables**.
for the **melody** parameter, sonify **Fruit**.

*Question1: **MUTE the Bassline.** Define the following:*

a: How many Apples are there...

b: How many Oranges are there...

c: Are there more Oranges or Apples..

d: How many Onions are there...

e: How many Potatoes are there...

f: Are there more Potatoes than Onions..

g: How many People chose Onions and Apples...

h: How many People chose Oranges and Potatoes.....................................

Test 5: Dual Parameter Condition (use **3Variable Test2** File)

for the **bassline** parameter, sonify **Dairy**.

for the **chord** parameter, sonify **Vegetables**.

for the **melody** parameter, sonify **Fruit**.

*Question1: **MUTE the Bassline.** Define the following:*

a: How many Apples are there..

b: How many Pears are there...

c: Are there more Apples or Pears...

d: How many Onions are there..

e: How Much Lettuce is there..

f: Are there more Potatoes than Onions...

g: How many People chose Onions and Apples...

h: How many People chose Pears and Lettuce..

Test 6: Dual Parameter Condition (use **4Variable Test2** File)

for the **bassline** parameter, sonify **Dairy**.

for the **chord** parameter, sonify **Vegetables**.

for the **melody** parameter, sonify **Fruit**.

*Question1: **MUTE the Bassline.** Define the following:*

a: How many Oranges are there..

b: How many Bananas are there..

c: Are there more Apples or Bananas..

d: How many Carrots are there..

e: How Much Lettuce is there...

f: Are there more Potatoes than Carrots...

g: How many People chose Carrots and Oranges...

h: How many People chose Bananas and Lettuce...

TrioSon Test Schedule (Session 2)

Thank you for taking further part in this test. The following tests are intended to assess the viability of Data sonification and its associated parameters and so ARE NOT a reflection upon the subject in any way. As before, you will be asked basic questions about the data you have sonified and also about the way you have sonified it. The purpose of these questions is to define what works and what doesn't within basic data sonification and so again you will also be asked a few simple questions about how you performed during the tests and what you feel could be improved upon within the software.

Test 1: (use **2Variable Test3** File)

for the **bassline** parameter, sonify **Colour**.
for the **chord** parameter, sonify **Radio Station**.
for the **melody** parameter, sonify **Movie Genre**.

a: How many Reds are there..

b: How many Blues are there..

c: Are there more Reds or Blues..

d: How many people chose 98FM..

e: How many people chose FM104..

f: Which station had the greater number...

g: How many people like Action films..

h: How many people like Comedy films...

i: Which is the more popular genre..

j: How many people chose 98FM and Comedy..

k: How many people chose FM104 and Red...

l: How many people chose 98FM,Blue and Action..

Test 2: (use **3Variable Test3** File)

for the **bassline** parameter, sonify **Colour**.

for the **chord** parameter, sonify **Radio Station**.

for the **melody** parameter, sonify **Movie Genre**.

a: How many Blues are there...

b: How many Greens are there...

c: Are there more Reds or Greens.......................................

d: How many people chose 98FM..

e: How many people chose SpinFM..

f: Did more people choose SpinFM or FM104 ....

g: How many people like Romance films...

h: How many people like Comedy films..

i: Did more people choose Action or Romance...

j: How many people chose FM104 and Romance.......................................

k: How many people chose SpinFM and Green...

l: How many people chose Fm104,Red and Romance..................................

Test 3: (use **4Variable Test3** File)

for the **bassline** parameter, sonify **Colour**.
for the **chord** parameter, sonify **Radio Station**.
for the **melody** parameter, sonify **Movie Genre**.

a: How many Greens are there……………………………………………………

b: How many Blues are there……………………………………………………

c: Are there more Yellows or Reds…………………………………

d: How many people chose LyricFM………………………………………………

e: How many people chose SpinFM………………………………………………

f: Did more people choose 98FM or FM104……………………………………

g: How many people like Sci-Fi films……………………………………………

h: How many people like Romantic films…………………………………………

i: Did more people choose Action or Comedy……………………………………

j: How many people chose LyricFM and Action…………………………………..

k: How many people chose 98FM and Yellow……………………………………..

l: How many people chose FM104,Green and Romance…………………………

Appendix 7. TrioSon example data files

Below are listings of the data files used during all pattern tests carried out in this thesis (chapters 5-8). Listings are provided for reference pattern, contour icon, harmonic combination and rhythmic parsing tests. All files are in .csv (Comma Separated Value) format.

Reference pattern tests

A single set of tests were carried out using reference patterns, which were subsequently used as a basis of development for the rest of the thesis. A total of 9 files were used during 9 test questions split over 2 sessions.

2Valuetest1.csv	**3Valuetest1.csv**	**4Valuetest1.csv**
Index,Fruit,Vegetables,Dairy	Index,Fruit,Vegetables,Dairy	Index,Fruit,Vegetables,Dairy
1,Apple,Onion,Milk	1,Apple,Onion,Milk	1,Apple,Carrot,Milk
2,Orange,Potato,Cream	2,Orange,Potato,Cheese	2,Orange,Potato,Cheese
3,Orange,Onion,Cream	3,Pear,Onion,Cream	3,Pear,Onion,Cream
4,Apple,Potato,Milk	4,Apple,Lettuce,Milk	4,Banana,Lettuce,Butter
5,Orange,Onion,Cream	5,Orange,Onion,Cream	5,Orange,Carrot,Cream
6,Orange,Onion,Cream	6,Orange,Lettuce,Cheese	6,Orange,Potato,Butter
7,Orange,Onion,Milk	7,Orange,Onion,Milk	7,Orange,Onion,Butter
8,Apple,Onion,Cream	8,Apple,Onion,Cream	8,Apple,Onion,Butter
9,Apple,Potato,Milk	9,Pear,Lettuce,Milk	9,Pear,Carrot,Milk
10,Orange,Potato,Milk	10,Orange,Potato,Milk	10,Banana,Carrot,Cheese
2Valuetest2.csv	**3Valuetest2.csv**	**4Valuetest2.csv**
Index,Fruit,Vegetables,Dairy	Index,Fruit,Vegetables,Dairy	Index,Fruit,Vegetables,Dairy
1,Orange,Onion,Cream	1,Pear,Lettuce,Cream	1,Pear,Lettuce,Cream
2,Orange,Potato,Milk	2,Orange,Potato,Milk	2,Orange,Potato,Butter
3,Apple,Onion,Cream	3,Apple,Lettuce,Cream	3,Apple,Lettuce,Cream
4,Apple,Potato,Milk	4,Pear,Lettuce,Cheese	4,Pear,Lettuce,Cheese
5,Apple,Onion,Cream	5,Apple,Lettuce,Cheese	5,Banana,Carrot,Butter
6,Orange,Potato,Cream	6,Pear,Potato,Cream	6,Pear,Potato,Cream
7,Orange,Onion,Milk	7,Orange,Lettuce,Milk	7,Orange,Lettuce,Butter
8,Apple,Onion,Cream	8,Apple,Onion,Cream	8,Apple,Onion,Cream
9,Apple,Potato,Milk	9,Apple,Lettuce,Cheese	9,Apple,Lettuce,Cheese
10,Apple,Potato,Milk	10.Pear,Potato,Milk	10,Pear,Potato,Milk

2Valuetest3.csv	3Valuetest3.csv	4Valuetest3.csv
Index,Colour,Radio Station,Movie Genre	Index,Colour,Radio Station,Movie Genre	Index,Colour,Radio Station,Movie Genre
1,Red,FM104,Action	1,Red,FM104,Action	1,Red,FM104,Action
2,Blue,98FM,Comedy	2,Blue,98FM,Action	2,Blue,98FM,SciFi
3,Blue,FM104,Comedy	3,Blue,SpinFM,Romance	3,Yellow,98FM,Action
4,Red,98FM,Action	4,Blue,SpinFM,Comedy	4,Blue,98FM,SciFi
5,Blue,98FM,Comedy	5,Blue,98FM,Comedy	5,Blue,LyricFM,Action
6,Blue,98FM,Comedy	6,Blue,FM104,Comedy	6,Yellow,SpinFM,Comedy
7,Blue,FM104,Action	7,Green,FM104,Romance	7,Green,FM104,Romance
8,Blue,FM104,Comedy	8,Green,98FM,Action	8,Red,98FM,Action
9,Red,98FM,Action	9,Green,98FM,Romance	9,Green,LyricFM,Romance
10,Blue,98FM,Action	10,Blue,98FM,Comedy	10,Blue,SpinFM,Romance

Contour icon Tests

Two test sessions were carried out during the contour icon tests, one using reference patterns and one using contour icons. A total of 10 files were used, 5 for each test condition.

Reference pattern condition

test1.csv	test2.csv	test3.csv
Index,Film	Index, Music	Index,Literature
1,Action	1,Rock	1,Biography
2,Comedy	2,Pop	2,Horror
3,Action	3,Pop	3,Biography
4,Comedy	4,Rock	4,Romance
5,Action	5,Jazz	5,Sci-Fi
6,Comedy	6,Pop	6,Horror
7,Comedy	7,Jazz	7,Sci-Fi
8,Action	8,Rock	8,Biography
9,Action	9,Pop	9,Sci-Fi
10,Action	10,Pop	10,Sci-Fi

test4.csv	test5.csv

Index,Colour	Index,Drink
1,Red	1,Tea
2,Blue	2,Coffee
3,Green	3,Tea
4,Blue	4,Water
5,Red	5,Beer
6,Yellow	6,Water
7,Blue	7,Wine
8,Purple	8,Orange Juice
9,Red	9,Beer
10,Green	10,Tea

Contour icon condition

test1.csv	**test2.csv**	**test3.csv**
Index,Colour	Index,Literature	Index,Drink
1,Red	1,Sci-Fi	1,Tea
2,Blue	2,Sci-Fi	2,Tea
3,Red	3,Biography	3,Coffee
4,Blue	4,Biography	4,Water
5,Red	5,Sci-Fi	5,COffee
6,Blue	6,Biography	6,Orange Juice
7,Blue	7,Sci-Fi	7,Tea
8,Red	8,Sci-Fi	8,Water
9,Red	9,Horror	9,Orange Juice
10,Blue	10,Horror	10,Tea

test4.csv	**test5.csv**
Index,Film	Index,Music
1,Action	1,Classical
2,Gangster	2,Jazz
3,Romance	3,Pop
4,Romance	4,Pop
5,Documentary	5,Jazz
6,Action	6,Folk
7,Gangster	7,Rock
8,Gangster	8,Soul
9,Comedy	9,Rock
10,Comedy	10,Jazz

Harmonic combination tests

Two test sessions were carried out during the harmonic combination tests, both using contour icons. In the first condition contour icons were allocated uniquely to each data value, in the second contour icons were harmonically combined as required. A total of 10 files were used, 5 for each test condition.

Non-harmonic combination Test Session

test1.csv	**test2.csv**	**test3.csv**
Index,Fruit,Colour	Index,Drink,Film	Index,Colour,Music
1,Apple,Red	1,Tea,Action	1,Red,Pop
2,Orange,Red	2,Water,Comedy	2,Blue,Rock
3,Orange,Blue	3,Water,Action	3,Blue,Pop
4,Apple,Blue	4,Tea,Action	4,Green,Jazz
5,Apple,Red	5,Coffee,Sci-Fi	5,Red,Rock
6,Orange,Blue	6,Tea,Comedy	6,Yellow,Classical
7,Apple,Red	7,Coffee,Sci-Fi	7,Coffee,Jazz
8,Orange,Blue	8,Coffee,Comedy	8,Blue,Pop
9,Orange,Blue	9,Coffee,Comedy	9,Red,Rock
10,Apple,Blue	10,Tea,Comedy	10,Green,Classical

test4.csv	**test5.csv**
Index,Fruit,Drink,Radio Station	Index,Film,Colour,Music
1,Apple,Tea,Today FM	1,Action,Red,Rock
2,Apple,Coffee,Today FM	2,Comedy,Blue,Pop
3,Orange,Coffee,Spin FM	3,Comedy,Blue,Rock
4,Apple,Tea,Today FM	4,Action,Blue,Rock
5,Apple,Coffee,Spin FM	5,Comedy,Red,Rock
6,Orange,Coffee,Today FM	6,Comedy,Blue,Pop
7,Apple,Coffee,Spin FM	7,Action,Red,Pop
8,Orange,Tea,Today FM	8,Comedy,Blue,Pop
9,Orange,Tea,Spin FM	9,Action,Blue,Rock
10,Orange,Coffee,Spin FM	10,Action,Blue,Rock

Harmonic combination Test Session

test1.csv	test2.csv	test3.csv
Index,Radio Station,Newspaper	Index,Colour,Food	Index,Film,Literature
1,Today FM,Irish Times	1,Red,Indian	1,Action,Crime
2,Spin FM,Irish Independent	2,Blue,Indian	2,Comedy,Travel
3,Spin FM,Irish Times	3,Blue,Italian	3,Romance,Biography
4,Spin FM,Irish Independent	4,Red,Chinese	4,Comedy,Travel
5,Today FM,Irish Independent	5,Green,Indian	5,Action,Crime
6,Spin FM,Irish Times	6,Blue,Italian	6,Cartoon,Biography
7,Today FM,Irish Independent	7,Green,Chinese	7,Romance,Sci-Fi
8,Spin FM,Irish Times	8,Green,Italian	8,Comedy,Crime
9,Today FM,Irish Independent	9,Red,Indian	9,Action,Biography
10,Spin FM,Irish Independent	10,Green,Chinese	10,Cartoon,Sci-Fi
test4.csv	**test5.csv**	
Index,Music,Fruit,Radio Station	Index,Drink,Colour,Film	
1,Rock,Apple,Spin FM	1,Tea,Blue,Comedy	
2,Pop,Orange,Today FM	2,Coffee,Blue,Action	
3,Rock,Orange,Spin FM	3, Tea,Green,Comedy	
4,Rock,Orange,Spin FM	4,Tea,Blue, Action	
5,Pop,Apple,Spin FM	5,Tea,Green,Action	
6,Pop,Apple,Today FM	6, Coffee,Blue,Comedy	
7,Rock,Orange,Today FM	7, Tea,Green,Comedy	
8,Pop,Orange,Spin FM	8, Coffee,Blue,Comedy	
9,Rock,Apple,Today FM	9,Coffee,Green,Action	
10,Rock,Orange,Today FM	10, Coffee,Green,Comedy	

Rhythmic parsing tests

Two test sessions were carried out during the rhythmic parsing tests, both using harmonically combined contour icons. In the first condition all events were rendered sequentially, in the second events were grouped using rhythmic parsing. A total of 10 files were used, 5 for each test condition.

Non-rhythmic parsing Test Session

test1.csv	**test2.csv**	**test3.csv**
Index,Exam 1,Exam 2	Index,Exam 1,Exam 2	Index,Exam 1,Exam 2
1,Pass,Pass	1,B,B	1,A,A
2,Fail,Pass	2,C,A	2,Fail,Fail
3,Fail,Pass	3,C,C	3,B,B
4,Pass,Pass	4,A,C	4,Fail,Fail
5,Pass,Fail	5,B,C	5,A,B
6,Fail,Fail	6,A,C	6,C,C
7,Pass,Fail	7,B,B	7,A,A
8,Fail,Fail	8,B,B	8,A,Fail
9,Pass,Fail	9,A,A	9,C,C
10,Fail,Pass	10,A,A	10,A,C
11,Pass,Pass	11,B,B	11,A,A
12,Fail,Pass	12,C,A	12,B,C
13,Pass,Fail	13,B,C	13,B,Fail
14,Pass,Pass	14,B,A	14,C,C
15,Pass,Fail	15,A,C	15,Fail,Fail
16,Pass,Fail	16,B,B	16,B,A
17,Pass,Pass	17,C,B	17,A,B
18,Fail,Pass	18,B,C	18,A,Fail
19,Pass,Pass	19,A,A	19,C,B
20,Fail,Fail	20,A,C	20,Fail,A

test4.csv	**test5.csv**
Index,Exam 1,Exam 2,Exam 3	Index,Exam1,Exam 2,Exam 3
1,Pass,Pass,Fail	1,Pass,Pass,Fail
2,Fail,Pass,Fail	2,Fail,Pass,Fail
3,Fail,Pass,Pass	3,Fail,Pass,Pass
4,Pass,Pass,Pass	4,Pass,Pass,Pass
5,Pass,Fail,Pass	5,Pass,Fail,Pass
6,Fail,Fail,Fail	6,Fail,Fail,Fail
7,Pass,Fail,Pass	7,Pass,Fail,Pass
8,Fail,Fail,Fail	8,Fail,Fail,Fail
9,Pass,Fail,Pass	9,Pass,Fail,Pass
10,Fail,Pass,Fail	10,Fail,Pass,Fail
11,Pass,Pass,Fail	11,Pass,Pass,Fail
12,Fail,Pass,Pass	12,Fail,Pass,Pass
13,Pass,Fail,Pass	13,Pass,Fail,Pass
14,Pass,Pass,Pass	14,Pass,Pass,Pass

15,Pass,Fail,Pass	15,Pass,Fail,Pass
16,Pass,Fail,Pass	16,Pass,Fail,Pass
17,Pass,Pass,Fail	17,Pass,Pass,Fail
18,Fail,Pass,Pass	18,Fail,Pass,Pass
19,Pass,Pass,Pass	19,Pass,Pass,Pass
20,Fail,Fail,Pass	20,Fail,Fail,Pass

Rhythmic parsing Test Session

test1.csv	**test2.csv**	**test3.csv**
Index,Exam 1,Exam 2	Index,Exam 1,Exam 2	Index,Exam 1,Exam 2
1,Pass,Fail	1,A,C	1,C,A
2,Fail,Pass	2,A,B	2,A,Fail
3,Pass,Pass	3,B,C	3,B,B
4,Fail,Fail	4,B,B	4,Fail,Fail
5,Pass,Fail	5,C,C	5,A,A
6,Mark,Mark	6,Mark,Mark	6,Mark,Mark
7,Pass,Fail	7,B,A	7,B,B
8,Pass,Pass	8,C,C	8,C,A
9,Pass,Pass	9,A,B	9,B,B
10,Pass,Fail	10,B,B	10,B,B
11,Pass,Pass	11,C,C	11,C,A
12,Mark,Mark	12,Mark,Mark	12,Mark,Mark
13,Fail,Pass	13,C,A	13,C,A
14,Fail,Fail	14,A,A	14,B,C
15,Pass,Pass	15,C,C	15,B,Fail
16,Pass,Fail	16,A,B	16,A,A
17,Fail,Pass	17,A,C	17,Fail,Fail
18,Mark,Mark	18,Mark,Mark	18,Mark,Mark
19,Pass,Fail	19,B,C	19,B,C
20,Fail,Pass	20,A,A	20,B,B
21,Pass,Pass	21,A,A	21,C,Fail
22,Pass,Fail	22,B,B	22,Fail,B
23,Pass,Pass	23,C,C	23,Fail,C
test4.csv	**test5.csv**	

Index,Exam 1,Exam 2,Exam 3	Index,Exam 1,Exam 2,Exam 3
1,Pass,Fail,Fail	1,Pass,Fail,Fail
2,Fail,Pass,Pass	2,Fail,Pass,Pass
3,Pass,Pass,Fail	3,Pass,Pass,Fail
4,Fail,Fail,Fail	4,Fail,Fail,Fail
5,Pass,Fail,Pass	5,Pass,Fail,Pass
6,Mark,Mark,Mark	6,Mark,Mark,Mark
7,Pass,Pass,Fail	7,Pass,Pass,Fail
8,Pass,Fail,Fail	8,Pass,Fail,Fail
9,Pass,Pass,Pass	9,Pass,Pass,Pass
10,Pass,Fail,Fail	10,Pass,Fail,Fail
11,Pass,Pass,Pass	11,Pass,Pass,Pass
12,Mark,Mark,Mark	12,Mark,Mark,Mark
13,Fail,Pass,Fail	13,Fail,Pass,Fail
14,Fail,Fail,Pass	14,Fail,Fail,Pass
15,Pass,Fail,Pass	15,Pass,Fail,Pass
26,Fail,Pass,Pass	26,Fail,Pass,Pass
17,Fail,Pass,Fail	17,Fail,Pass,Fail
18,Mark,Mark,Mark	18,Mark,Mark,Mark
19,Pass,Fail,Pass	19,Pass,Fail,Pass
20,Pass,Pass,Pass	20,Pass,Pass,Pass
21,Pass,Pass,Pass	21,Pass,Pass,Pass
22,Pass,Fail,Pass	22,Pass,Fail,Pass
23,Pass,Pass,Pass	23,Pass,Pass,Pass

Appendix 8.Reference Pattern Test Results

All test results are listed below with totals for each test, session and overall results also listed. Each session comprised of frequency and combination tests, with each test containing varying numbers of questions based on variable and value count.

Test 1										
Question	1a	1b	1c	2a	2b	2c	3a	3b	3c	Total
Marks	2	2	2	2	2	2	2	2	2	18
Musician										
1	2	2	2	2	2	2	2	2	2	18
2	1	1	2	2	2	2	2	2	2	16
3	2	2	2	2	2	2	2	2	2	18
4	1	1	2	2	2	2	2	2	2	16
5	2	2	2	2	2	2	2	2	2	18
6	2	2	2	2	2	2	2	2	2	18
7	2	2	2	2	2	2	2	2	2	18
8	2	2	2	2	2	2	2	2	2	18
9	2	2	2	2	2	2	2	2	2	18
10	1	2	2	2	2	2	2	2	2	17
Non-musician										
1	2	1	2	1	1	2	1	2	0	12
2	0	0	0	1	1	0	2	1	2	7
3	1	0	0	0	1	0	1	1	2	6
4	1	2	2	1	1	2	2	2	2	15
5	2	1	2	1	0	0	1	1	2	10
6	2	0	0	0	1	0	1	1	2	7
7	0	0	0	1	0	0	1	1	2	5
8	1	0	0	1	1	2	1	0	0	6
9	2	2	2	1	1	2	1	2	2	15
10	2	1	2	2	2	2	1	1	2	15

Test 2													
Question	1a	1b	1c	1d	2a	2b	2c	2d	3a	3b	3c	3d	Total
Marks	2	2	2	2	2	2	2	2	2	2	2	2	24
Musician													
1	2	2	2	2	2	2	2	2	1	2	0	2	21
2	1	2	2	0	2	2	2	2	1	2	2	0	18

3	2	2	2	2	2	2	2	2	2	2	2	2	24
4	0	0	2	0	2	2	2	2	2	1	2	2	17
5	2	2	2	2	2	2	2	2	2	2	2	2	24
6	2	0	0	0	2	2	2	2	2	2	2	2	18
7	2	2	2	2	1	2	2	0	1	2	2	0	18
8	2	2	2	2	2	2	2	2	2	1	2	0	21
9	0	0	0	0	2	2	2	2	2	1	2	2	15
10	2	1	1	0	2	1	2	2	2	2	2	2	19
Non-musician													
1	2	0	0	0	2	2	2	2	2	2	2	2	18
2	1	1	0	0	2	1	1	0	2	1	2	2	13
3	1	2	2	2	1	0	1	0	2	2	2	2	17
4	1	1	2	2	2	1	1	0	2	1	1	2	16
5	2	1	0	0	0	1	2	0	2	1	0	0	9
6	2	2	0	2	1	2	2	2	2	0	2	0	17
7	1	1	0	0	0	1	0	0	1	2	0	0	6
8	1	0	0	0	2	1	0	0	1	2	1	0	8
9	2	2	2	2	2	2	1	2	1	2	1	0	19
10	1	0	2	0	2	2	2	2	1	2	0	2	16

Test 3															
Question	1a	1b	1c	1d	1e	2a	2b	2c	2d	2e	3a	3b	3c	3d	3e	Total
Marks	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	30
Musician																
1	2	2	2	2	2	2	1	1	2	2	1	2	2	2	0	25
2	1	2	2	0	2	1	1	2	2	2	2	1	2	2	0	22
3	1	1	0	2	2	0	0	0	0	0	0	0	0	0	0	6
4	1	2	2	0	2	1	1	2	2	2	2	1	2	2	0	22
5	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	30
6	0	2	2	0	0	2	2	2	2	2	2	2	2	2	2	24
7	2	2	2	2	2	2	2	1	2	2	1	2	2	2	0	26
8	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	30
9	1	1	2	0	2	1	1	2	2	2	1	1	2	0	0	18
10	1	1	2	0	0	2	1	2	2	0	2	2	2	2	2	21
Non-musician																
1	1	1	0	2	2	1	2	1	0	2	1	1	2	2	0	18
2	0	1	1	2	2	1	2	2	2	0	2	1	0	0	0	16
3	1	0	1	0	2	2	2	1	0	2	1	1	0	0	2	15
4	2	1	2	0	2	1	1	0	0	0	2	2	1	0	2	16

5	1	1	0	0	2	1	0	2	0	2	2	1	2	2	2	18
6	1	1	2	2	2	2	1	2	2	0	0	1	2	0	0	18
7	0	1	2	0	2	1	1	0	0	0	2	1	0	0	0	10
8	1	1	0	0	2	1	1	2	0	2	2	1	1	2	2	18
9	2	2	1	2	1	2	1	0	2	2	2	1	1	2	2	23
10	0	0	1	0	0	1	1	2	0	2	1	1	0	0	2	11

Test 4									
Question	1a	1b	1c	1d	1e	1f	1g	1h	Total
Marks	2	2	2	2	2	2	2	2	16
Musician									
1	2	2	2	2	2	2	2	2	16
2	1	2	2	1	1	0	1	2	10
3	2	2	2	2	2	2	2	2	16
4	0	0	0	2	2	2	2	1	9
5	2	2	2	2	2	2	1	2	15
6	2	2	2	1	1	0	1	2	11
7	2	2	2	2	2	2	1	0	13
8	2	2	2	2	2	2	1	0	13
9	1	1	2	1	1	0	1	2	9
10	2	1	2	1	2	2	2	2	14
Non-musician									
1	2	2	2	1	2	0	1	0	10
2	1	1	2	2	0	2	2	0	10
3	2	2	2	1	1	2	1	0	11
4	2	1	2	1	1	2	0	0	9
5	1	1	0	2	1	2	0	0	7
6	1	1	2	2	2	2	0	0	10
7	2	1	0	1	1	2	0	0	7
8	1	2	2	1	0	0	0	0	6
9	2	2	2	2	2	2	1	1	14
10	0	1	0	2	2	2	1	0	8

Test 5									
Question	1a	1b	1c	1d	1e	1f	1g	1h	Total
Marks	2	2	2	2	2	2	2	2	16
Musician									
1	1	1	0	0	1	0	1	1	5

2	2	1	2	1	1	2	2	0	11
3	2	2	2	2	2	2	2	1	15
4	2	1	0	0	0	0	2	0	5
5	2	2	2	2	2	0	1	2	13
6	2	2	2	1	0	2	1	2	12
7	1	2	0	2	0	2	2	1	10
8	2	2	2	2	2	2	2	2	16
9	2	2	2	1	2	0	1	2	12
10	1	2	2	2	2	0	1	1	11
Non-musician									
1	1	1	2	2	1	2	0	1	10
2	1	1	0	1	2	2	1	0	8
3	2	1	2	0	1	0	0	0	6
4	2	2	2	1	1	2	1	0	11
5	1	1	2	0	1	0	0	0	5
6	1	2	2	2	2	2	0	1	12
7	1	0	0	1	0	0	0	0	2
8	2	1	2	1	1	2	0	0	9
9	2	2	2	2	1	2	1	0	12
10	0	2	2	2	2	0	1	0	9

Test 6										
Question	1a	1b	1c	1d	1e	1f	1g	1h	Total	**Session 1 Total**
Marks	2	2	2	2	2	2	2	2	16	
Musician										
1	2	2	2	0	2	0	2	1	11	96
2	1	2	2	0	2	2	2	1	12	89
3	2	2	2	2	2	0	1	0	11	90
4	1	2	0	0	2	0	0	0	5	74
5	2	2	2	1	1	0	2	1	11	111
6	1	0	0	2	1	0	0	1	5	88
7	2	2	0	1	0	2	1	0	8	93
8	1	2	0	1	1	2	2	0	9	107
9	2	0	0	1	1	0	0	0	4	76
10	1	0	0	1	0	0	1	0	3	85
Non-musician										
1	1	1	2	0	2	0	1	0	7	75
2	1	0	0	1	1	2	1	0	6	60
3	1	0	0	2	1	0	0	0	4	59

4	2	2	2	1	1	2	0	0	10	77
5	1	0	0	1	0	0	0	1	3	52
6	1	1	2	0	1	2	1	0	8	72
7	0	0	0	1	1	0	0	0	2	32
8	1	0	0	0	0	0	0	0	1	48
9	2	2	2	1	1	2	1	0	11	94
10	0	1	2	1	0	0	0	0	4	63

Test 7													
Question	1a	1b	1c	1d	1e	1f	1g	1h	1i	1j	1k	1l	Total
Marks	2	2	2	2	2	2	2	2	2	2	2	2	24
Musician													
1	2	1	2	2	1	1	1	0	2	2	0	0	14
2	1	2	0	1	2	2	1	2	2	1	0	0	14
3	2	1	2	2	2	1	2	2	2	0	0	0	16
4	1	0	0	2	1	2	1	2	2	0	0	0	11
5	2	2	2	2	2	2	1	1	0	1	1	0	16
6	1	1	2	2	1	2	2	0	0	0	1	0	12
7	2	0	2	2	2	1	2	1	2	1	1	0	16
8	1	1	0	2	1	2	1	1	2	0	2	1	14
9	2	2	2	1	2	0	2	1	0	0	0	0	12
10	2	2	2	2	2	2	1	2	2	1	0	0	18
Non-musician													
1	0	1	0	1	1	1	2	1	0	1	0	0	8
2	1	0	0	1	2	2	2	0	0	0	0	0	8
3	0	1	0	1	2	0	2	0	1	0	0	0	7
4	1	1	2	1	1	0	1	2	2	1	0	0	12
5	1	1	0	1	1	2	0	1	0	0	0	0	7
6	2	1	0	1	1	2	1	0	0	1	0	0	9
7	1	0	0	1	1	2	1	0	0	0	1	0	7
8	1	1	2	0	1	0	1	1	0	0	0	0	7
9	2	2	2	2	1	2	1	1	0	1	0	0	14
10	1	0	0	1	1	2	1	1	0	0	0	0	7

Test 8													
Question	1a	1b	1c	1d	1e	1f	1g	1h	1i	1j	1k	1l	Total
Marks	2	2	2	2	2	2	2	2	2	2	2	2	24
Musician													

1	1	1	0	2	1	0	1	2	2	0	1	0	11
2	1	2	1	0	1	0	1	1	2	1	0	0	10
3	2	0	1	2	0	2	1	1	0	1	0	0	10
4	2	0	0	2	0	0	1	2	0	0	1	0	8
5	1	2	2	2	0	0	1	1	2	0	0	0	11
6	2	0	0	1	1	2	1	1	2	1	1	0	12
7	2	0	1	1	2	0	1	1	2	1	0	0	11
8	2	1	2	2	0	2	1	0	0	0	0	1	11
9	0	0	1	2	0	1	1	1	0	0	1	0	7
10	0	2	0	2	1	2	1	1	0	1	1	0	11
Non-musician													
1	1	1	0	2	1	0	1	2	2	0	0	0	10
2	1	1	0	0	2	1	1	1	0	0	0	0	7
3	1	0	0	0	2	0	1	1	2	0	0	0	7
4	2	1	2	1	1	0	1	0	0	0	0	0	8
5	1	1	2	1	1	2	0	0	0	0	0	0	8
6	1	1	2	1	1	0	1	1	0	0	0	0	8
7	1	1	0	0	0	0	0	0	0	0	0	0	2
8	1	2	2	1	0	0	0	1	0	0	0	0	7
9	2	1	0	1	1	2	1	0	0	0	0	0	8
10	1	1	0	1	1	2	1	2	0	0	0	0	9

Test 9															
Question	1 a	1 b	1 c	1 d	1 e	1 f	1 g	1 h	1 i	1 j	1 k	1 l	Total	**Session 2 Total**	**Overall Total**
Marks	2	2	2	2	2	2	2	2	2	2	2	2	24	72	192
Musician															
1	0	1	0	2	0	0	2	0	0	1	0	0	6	31	127
2	0	1	0	1	1	2	0	1	0	0	1	0	7	31	120
3	1	1	2	1	0	0	0	1	0	0	0	0	6	32	122
4	1	0	1	1	1	2	0	1	0	1	0	0	8	27	101
5	2	1	1	2	1	0	2	0	0	0	0	0	9	36	147
6	1	1	0	1	2	0	1	1	0	0	1	0	8	32	120
7	0	1	0	2	1	2	1	1	0	0	0	0	8	35	128
8	1	0	0	2	1	2	0	2	0	0	0	0	8	33	140
9	1	2	0	1	0	0	2	1	0	1	0	0	8	27	103
10	1	1	2	1	0	0	0	1	0	0	0	0	6	35	120
Non-musician															
1	1	1	0	2	1	0	2	1	0	0	0	0	8	26	101

2	1	0	0	1	1	0	0	1	0	0	0	0	4	19	79
3	1	1	0	1	0	0	1	2	0	0	0	0	6	20	79
4	1	1	0	1	0	0	2	0	0	0	0	0	5	25	102
5	1	0	0	1	0	0	0	1	0	0	0	0	3	18	70
6	1	2	0	0	1	0	1	1	0	0	0	0	6	23	95
7	0	0	0	0	0	0	0	0	0	0	0	0	0	9	41
8	0	0	0	0	0	0	0	0	0	0	0	0	0	14	62
9	1	1	2	0	1	0	1	1	0	0	0	0	7	29	123
10	1	0	0	1	0	1	1	0	0	0	0	0	4	20	83

Overall Results Summary

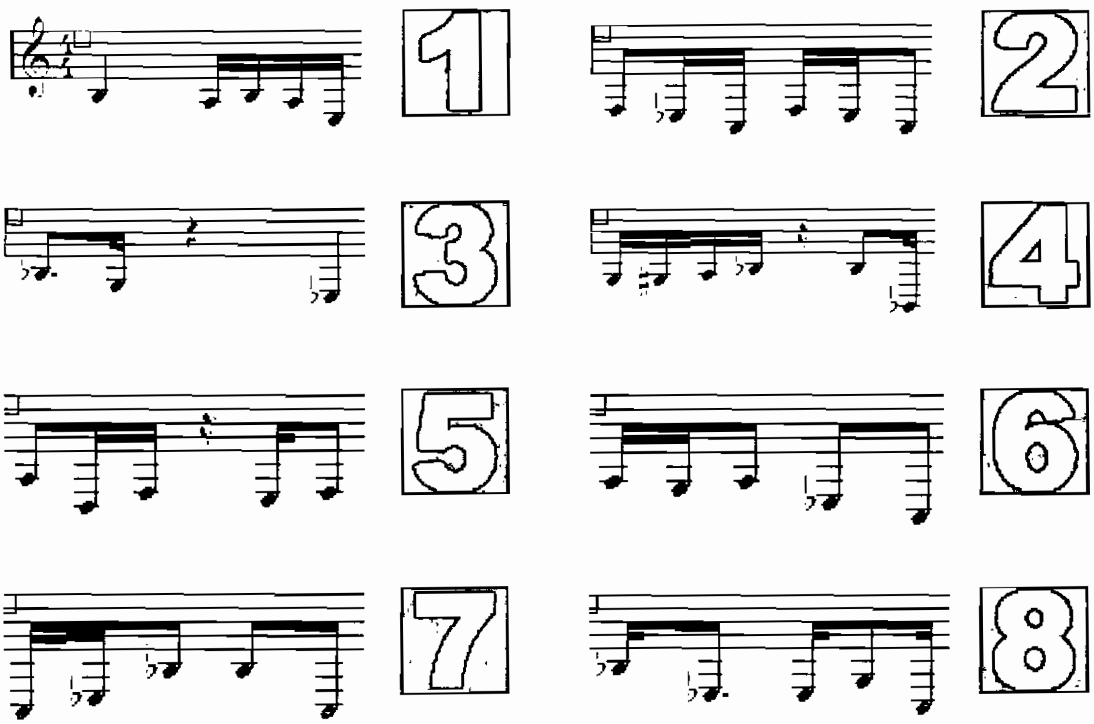
Group	**Bass**	**Chord**	**Melody**	**Frequency %**	**Combination %**	**Overall Results %**
Musicians						
1	100	93.33	77.5	70.37	43.33	66.15
2	66.38	93.33	77.5	67.28	36.67	62.5
3	86.67	66.67	66.67	69.75	30	63.54
4	53.89	93.33	85.83	58.02	23.33	52.60
5	100	100	100	83.95	36.67	76.56
6	55	100	100	67.28	36.67	62.5
7	100	84.17	77.5	74.07	26.67	66.67
8	100	100	87.5	79.63	36.67	72.92
9	53.33	93.33	75.83	58.64	26.67	53.65
10	57.78	85.83	100	67.90	33.33	62.5
Non-Musicians						
1	56.11	75.56	70	59.88	13.33	52.60
2	28.33	51.11	66.94	46.29	13.33	41.15
3	48.05	37.22	68.89	48.15	3.33	41.15
4	76.11	45.56	81.67	61.73	6.67	53.12
5	53.61	34.72	64.72	42.59	3.33	36.46
6	62.78	58.05	48.89	56.79	10	49.48
7	25	16.39	44.72	24.69	3.33	21.35
8	23.05	54.72	48.89	38.27	0	32.29
9	93.33	74.72	71.11	72.84	16.67	64.06
10	43.61	86.67	56.39	50	6.67	43.23
Average	64.15	72.24	73.53	59.91	20.33	53.72

Appendix 9.Reference Pattern TLX Results

Listed below are the Task Load Index statistics for the reference pattern tests. Each participant completed a TLX questionnaire after the second test session.

TLX Category	Mental	Physical	Temporal	Performance	Effort	Frustration	Overall
musician							
1	20.00	0.00	4.00	2.00	7.33	20.00	53.33
2	24.00	0.00	17.33	8.00	5.33	26.67	81.33
3	30.00	0.00	5.33	10.67	26.67	11.33	84.00
4	22.67	0.00	8.00	6.67	18.00	4.33	59.67
5	23.33	0.00	1.00	4.00	22.67	0.67	51.67
6	25.00	0.00	13.00	12.00	11.33	8.00	69.33
7	21.33	0.00	13.00	9.00	5.67	22.67	71.67
8	14.00	0.00	18.67	16.67	9.33	3.00	61.67
9	28.33	0.00	20.00	6.67	18.00	3.33	76.33
10	23.33	0.00	21.33	9.00	4.67	10.67	69.00
Average							67.80
non-musician							
1	30.00	0.00	10.67	6.00	4.33	13.00	64.00
2	25.00	0.00	6.00	9.33	5.33	18.67	64.33
3	17.00	0.00	17.33	5.33	8.67	9.33	57.67
4	16.00	0.67	10.00	10.00	2.33	1.67	40.67
5	22.67	0.00	20.00	8.67	4.67	10.67	66.67
6	21.33	5.33	28.33	3.33	19.00	0.00	77.33
7	31.67	0.00	10.00	10.00	15.00	20.00	86.67
8	31.67	0.00	12.00	7.00	3.67	5.33	59.67
9	17.33	0.33	7.00	12.00	6.00	1.67	44.33
10	30.00	10.67	3.33	5.33	26.67	11.33	87.33
Average							64.87

Appendix 10. Reference patterns used in contour icon tests



Appendix 11.Contour icon test questions

The contour icon test schedule contained 2 sets of tests, 1 for reference patterns and 1 for contour icons. Each set of test questions is listed below.

Reference pattern Test Session

Sonify test1.csv and identify:

How many people chose Action films?..

How many people chose Comedy films?..

Sonify test2.csv and identify:

How many people chose Rock music?..

How many people chose Pop music?..

How many people chose Jazz music?..

Sonify test3.csv and identify:

How many people chose Biography books?..

How many people chose Sci-Fi novels?..

How many people chose Horror books?..

How many people chose Romance novels?..

Sonify test4.csv and identify:

How many people chose the colour Red?..

How many people chose the colour Blue?..

How many people chose the colour Yellow?..

How many people chose the colour Green?..

How many people chose the colour Purple?..

Sonify test5.csv and identify:

How many people chose Tea?..

How many people chose Water?..

How many people chose Coffee?..

How many people chose Beer?..

How many people chose Wine?..

How many people chose Orange Juice?..

Contour Icon pattern Test Session

Sonify test1.csv and identify:

How many people chose the colour Red?..

How many people chose the colour Blue?..

Sonify test2.csv and identify:

How many people chose Sci-Fi books?..

How many people chose Horror novels?..

How many people chose Biographies?..

Sonify test3.csv and identify:

How many people chose Tea?..

How many people chose Water?..

How many people chose Orange Juice?..

How many people chose Coffee?..

Sonify test4.csv and identify:

How many people chose Action films?..

How many people chose Documentaries?..

How many people chose Gangster films?..

How many people chose Romance films?..

How many people chose Comedy films?..

Sonify test5.csv and identify:

How many people chose Jazz music?..

How many people chose Classical music?..

How many people chose Rock music?..

How many people chose Pop music?..

How many people chose Soul music?..

How many people chose Folk music?..

Appendix 12. Contour Icon Test Results

Listed below are the results of the contour icon test schedule, which compared point estimation performance between reference patterns and contour icons. Overall results are also listed.

	reference patterns				contour icons		
Question 1	a	b	Total		a	b	Total
Marks	2	2	4		2	2	4
1	2	2	4		2	1	3
2	0	1	1		2	2	4
3	1	1	2		2	2	4
4	1	1	2		2	1	3
5	1	2	3		2	0	2
6	1	2	3		2	2	4
7	1	2	3		1	2	3
8	1	1	2		2	1	3
9	1	1	2		2	2	4
10	2	1	3		2	1	3
11	1	2	3		2	2	4
12	2	1	3		2	1	3
13	1	1	2		2	2	4
14	2	1	3		2	1	3
15	1	2	3		2	2	4
16	2	1	3		2	2	4
17	1	2	3		2	2	4
18	2	2	4		2	2	4
19	2	1	3		2	2	4
20	2	1	3		2	1	3

	reference patterns					contour icons			
Question 2	a	b	c	Total		a	b	c	Total
Marks	2	2	2	6		2	2	2	6
1	2	2	1	5		2	1	1	4
2	2	1	2	5		2	2	2	6
3	1	0	2	3		1	2	2	5
4	2	2	1	5		2	1	2	5
5	2	2	1	5		2	2	1	5

6	2	1	2	5		2	1	2	5
7	1	1	1	3		1	2	1	4
8	1	2	1	4		2	2	1	5
9	1	2	0	3		2	1	2	5
10	2	0	2	4		2	2	2	6
11	2	1	1	4		2	1	2	5
12	1	0	0	1		1	2	1	4
13	1	2	0	3		1	2	2	5
14	2	1	1	4		2	1	1	4
15	1	0	1	2		2	0	2	4
16	0	1	2	3		1	2	2	5
17	2	2	1	5		2	2	1	5
18	2	1	2	5		2	1	2	5
19	1	2	1	4		2	2	1	5
20	1	2	2	5		1	2	2	5

	reference patterns						**contour icons**				
Question 3	a	b	c	d	Total		a	b	c	d	Total
Marks	2	2	2	2	8		2	2	2	2	8
1	1	2	1	0	4		2	2	1	2	7
2	2	2	1	0	5		2	2	1	0	5
3	0	1	2	2	5		2	1	2	2	7
4	2	1	1	0	4		2	2	1	0	5
5	2	2	1	2	7		2	1	2	1	6
6	0	1	1	1	3		2	2	1	0	5
7	1	2	0	1	4		1	2	2	1	6
8	1	1	1	1	4		1	2	1	0	4
9	1	2	1	1	5		1	1	1	1	4
10	2	1	2	0	5		2	1	1	2	6
11	2	0	1	0	3		2	0	1	2	5
12	2	1	2	0	5		2	1	2	1	6
13	1	1	0	1	3		1	2	1	1	5
14	1	2	2	0	5		1	2	1	0	4
15	2	1	1	1	5		2	0	1	1	4
16	1	2	1	0	4		1	2	1	2	6
17	2	1	2	2	7		2	1	2	1	6
18	1	1	1	0	3		2	2	1	0	5
19	1	1	0	1	3		1	2	2	1	6
20	2	1	2	0	5		2	1	1	1	5

	reference patterns							contour icons					
Question 4	a	b	c	d	e	Total		a	b	c	d	e	Total
Marks	2	2	2	2	2	10		2	2	2	2	2	10
1	1	2	0	1	0	4		1	2	2	1	1	7
2	2	0	1	0	1	4		2	0	1	2	1	6
3	2	1	0	0	0	3		0	1	0	0	2	3
4	1	2	0	2	1	6		2	0	0	2	1	5
5	0	0	0	0	1	1		0	0	2	0	1	3
6	0	1	1	0	0	2		0	1	1	0	0	2
7	1	0	0	1	0	2		1	2	0	0	1	4
8	1	1	0	1	1	4		1	1	0	1	1	4
9	0	2	1	1	0	4		1	0	2	1	0	4
10	2	0	1	1	1	5		2	1	2	1	1	7
11	0	2	1	0	0	3		1	2	0	2	0	5
12	2	1	0	1	1	5		2	1	1	0	2	6
13	1	0	1	0	0	2		1	0	1	2	1	5
14	2	1	0	1	0	4		2	2	1	1	0	6
15	1	2	0	0	0	3		1	0	0	0	1	2
16	1	2	1	1	0	5		1	0	0	1	0	2
17	0	1	0	0	0	1		2	1	1	0	0	4
18	1	0	2	0	1	4		1	2	1	0	1	5
19	1	0	1	1	0	3		1	2	1	2	0	6
20	1	1	0	0	1	3		1	2	0	1	1	5

	reference patterns								contour icons						
Question 5	a	b	c	d	e	f	Total		a	b	c	d	e	f	Total
Marks	2	2	2	2	2	2	12		2	2	2	2	2	2	12
1	2	1	0	1	0	0	4		2	1	2	1	1	2	9
2	0	1	0	0	0	0	1		1	1	1	0	1	0	4
3	0	0	1	1	1	0	3		0	0	2	0	0	0	2
4	2	1	0	0	0	0	3		2	2	0	1	2	0	7
5	1	2	0	0	0	0	3		2	2	0	0	0	2	6
6	2	1	0	1	0	0	4		2	1	0	1	2	0	6
7	1	1	1	0	1	0	4		1	1	2	0	0	0	4
8	0	2	0	0	1	0	3		1	2	0	0	1	0	4
9	0	2	1	1	0	1	5		0	0	2	1	0	1	4
10	2	1	0	0	0	0	3		0	1	0	0	1	0	2

11	2	0	0	1	0	0	3		2	0	2	1	0	0	5
12	1	1	0	1	0	0	3		1	1	0	1	2	0	5
13	2	2	0	0	1	1	6		2	0	2	0	1	1	6
14	0	2	0	0	1	0	3		0	2	0	1	0	0	3
15	2	0	0	0	0	1	3		0	0	1	0	0	1	2
16	0	0	1	0	0	0	1		0	0	1	0	0	2	3
17	1	1	0	1	0	0	3		1	1	2	1	2	0	7
18	2	1	0	0	1	0	4		2	1	0	0	2	0	5
19	1	0	0	1	0	0	2		1	0	0	0	0	0	1
20	0	0	1	0	0	0	1		1	2	1	0	1	0	5

Overall results (by condition)

	reference patterns			**contour icons**	
Overall	Total	Percentage		Total	Percentage
Marks	40	100		40	100
1	21	52.5		30	75
2	16	40		25	62.5
3	16	40		21	52.5
4	20	50		25	62.5
5	19	47.5		22	55
6	17	42.5		22	55
7	16	40		21	52.5
8	17	42.5		20	50
9	19	47.5		21	52.5
10	20	50		24	60
11	16	40		24	60
12	17	42.5		24	60
13	16	40		25	62.5
14	19	47.5		20	50
15	16	40		16	40
16	16	40		20	50
17	19	47.5		26	65
18	20	50		24	60
19	15	37.5		22	55
20	17	42.5		23	57.5
Average		**44**			**56.875**

Appendix 13. Contour Icon TLX Results

Listed below are the Task Load Index statistics for the contour icon tests. Each participant completed a TLX questionnaire for each test condition (reference patterns and contour icons).

TLX Category	Mental	Physical	Temporal	Performance	Effort	Frustration	Overall
reference patterns							
1	20.00	0.00	7.33	6.00	5.33	20.00	58.67
2	12.00	2.00	2.67	16.00	7.00	12.00	51.67
3	15.00	0.00	6.00	13.00	8.00	9.33	51.33
4	11.00	0.67	10.67	14.67	2.00	8.67	47.67
5	22.67	0.00	7.33	15.00	9.33	10.67	65.00
6	25.00	0.33	2.67	13.00	9.00	1.67	51.67
7	14.00	0.00	9.00	13.33	13.00	5.00	54.33
8	21.33	0.00	12.00	16.00	5.33	4.33	59.00
9	6.00	0.00	6.00	20.00	2.00	8.00	42.00
10	20.00	0.00	6.00	4.67	11.00	17.33	59.00
11	14.00	1.00	16.00	8.33	8.67	10.67	58.67
12	20.00	0.00	9.33	3.67	8.00	8.67	49.67
13	15.00	2.00	8.00	9.33	7.33	2.00	43.67
14	0.00	2.00	8.00	9.33	12.00	7.00	38.33
15	10.00	1.67	20.00	6.00	10.00	8.33	56.00
16	14.67	1.33	22.67	6.00	2.67	4.33	51.67
17	15.00	2.67	14.67	6.00	5.00	3.33	46.67
18	8.67	0.00	3.33	7.00	6.67	7.33	33.00
19	3.33	2.00	4.00	9.33	14.00	1.67	34.33
20	26.67	0.00	4.67	17.33	5.00	0.67	54.33
Average							50.33
contour icons							
1	14.00	0.00	4.67	6.67	7.00	5.00	37.33
2	18.33	0.00	13.00	7.00	1.67	6.00	46.00
3	14.67	0.00	3.33	9.33	2.00	2.67	32.00
4	28.33	0.00	12.00	3.33	6.67	5.33	55.67
5	13.00	0.00	2.67	11.67	3.33	3.00	33.67
6	16.00	0.00	7.00	6.67	16.00	6.00	51.67
7	10.67	0.00	2.67	13.33	12.00	3.33	42.00
8	3.67	4.00	5.00	16.00	4.00	8.00	40.67

9	25.00	0.00	7.00	20.00	3.33	3.33	58.67
10	14.67	0.00	1.00	4.67	5.00	3.00	28.33
11	9.00	0.00	3.00	8.00	2.67	1.33	24.00
12	11.00	2.33	2.00	7.33	5.33	6.67	34.67
13	18.67	0.00	4.00	6.00	4.00	5.00	37.67
14	6.67	1.33	9.33	16.00	8.00	4.67	46.00
15	12.00	0.00	6.67	7.00	2.00	2.67	30.33
16	10.67	0.00	1.33	4.00	6.67	3.00	25.67
17	6.00	0.00	6.67	5.33	4.67	3.33	26.00
18	6.67	1.33	4.00	5.00	4.00	7.00	28.00
19	8.33	0.00	4.67	3.00	4.67	3.00	23.67
20	4.00	0.00	0.67	8.00	5.33	5.00	23.00
Average							36.25

Appendix 14.Harmonic Combination Test Questions

The harmonic combination test schedule contained 2 sets of tests, 1 for non-harmonic combination and 1 for harmonic combination. Each set of test questions is listed below.

Non-harmonic combination Test Session

Sonify test1.csv. Set Fruit to Bass and Colour to Mid and identify:

How many people chose the fruit Apple?...

How many people chose the colour Blue?...

How many people chose Orange and Red?...

How many people chose Apple and Blue?...

Sonify test2.csv. Set Drink to Mid and Film to Treble and identify:

How many people chose Water?...

How many people chose Comedy films?...

How many people chose Coffee and Sci-Fi?...

How many people chose Tea and Action?...

Sonify test3.csv. Set Colour to Bass and Music to Treble and identify:

How many people chose the colour Red?...

How many people chose Pop music?...

How many people chose Red and Rock?...

How many people chose Blue and Pop?...

Sonify test4.csv. Set Fruit to Bass, Drink to Mid and Radio Station to Treble and identify:

How many people chose Apples? ....

How many people chose Spin FM? ....

How many people chose Orange, Coffee and Spin FM? ....

How many people chose Apple, Tea and Today FM? ....

Sonify test5.csv. Set Film to Bass, Colour to Mid and Music to Treble and identify:

How many people chose the colour Green? ....

How many people chose Pop music? ....

How many people chose Comedy, Blue and Pop music? ....

How many people chose Action, Red and Rock music? ....

Harmonic combination Test Session

Sonify test1.csv. Set Radio Station to Bass and Newspaper to Mid and identify:

How many people chose Today FM? ....

How many people chose the Irish Independent? ....

How many people chose Today FM and Irish Independent? ....

How many people chose Spin FM and Irish Times? ....

Sonify test2.csv. Set Colour to Mid and Food to Treble and identify:

How many people chose Green? ....

How many people chose Chinese food? ....

How many people chose Blue and Italian food? ....

How many people chose Red and Indian food? ....

Sonify test3.csv. Set Film to Bass and Literature to Treble and identify:

How many people chose Cartoons? ....

How many people chose Crime novels? ....

How many people chose Action and Crime? ....

How many people chose Romance and Sci-Fi? ....

Sonify test4.csv. Set Music to Bass, Fruit to Mid and Radio Station to Treble and identify:

How many people chose Pop? ....

How many people chose Oranges? ....

How many people chose Pop, Apple and Today FM? ....

How many people chose Rock, Orange and Spin FM? ....

Sonify test5.csv. Set Drink to Bass, Colour to Mid and Film to Treble and identify:

How many people chose Coffee? ....

How many people chose the colour Blue? ....

How many people chose Tea, Green and Comedy? ....

How many people chose Coffee, Blue and Action? ....

Appendix 15. Harmonic Combination Test Results

Listed below are the results of the harmonic combination test schedule, which compared point estimation and pattern combination performance between non-harmonic and harmonic combination test conditions. Overall results are also listed.

	non-harmonic						harmonic				
Question 1	a	b	c	d	Total		a	b	c	d	Total
Marks	2	2	2	2	8		2	2	2	2	8
1	2	2	2	2	8		2	2	2	2	8
2	2	2	1	0	5		2	2	1	2	7
3	2	2	0	0	4		2	2	2	2	8
4	2	2	1	2	7		2	2	2	2	8
5	2	2	0	1	5		2	2	2	2	8
6	2	1	1	1	5		2	2	2	2	8
7	2	2	1	1	6		2	2	2	2	8
8	2	2	2	2	8		2	2	2	2	8
9	1	0	1	0	2		1	2	1	2	6
10	2	2	1	2	7		1	1	2	2	6
11	2	2	2	2	8		2	2	2	2	8
12	2	1	1	2	6		2	2	1	2	7
13	2	2	2	0	6		2	2	2	2	8
14	1	1	0	1	3		2	2	2	2	8
15	2	2	0	2	6		2	2	2	2	8
16	2	1	0	1	4		1	2	1	2	6
17	1	0	0	0	1		1	0	1	0	2
18	1	2	0	0	3		1	2	1	1	5
19	1	0	0	2	3		0	1	0	2	3
20	2	2	1	0	5		2	2	2	2	8
	non-harmonic						harmonic				
Question 2	a	b	c	d	Total		a	b	c	d	Total
Marks	2	2	2	2	8		2	2	2	2	8
1	2	2	2	2	8		2	2	2	2	8
2	2	1	0	2	5		2	1	2	2	7
3	2	0	0	0	2		1	2	2	1	6
4	0	2	1	1	4		1	2	2	2	7
5	2	1	0	1	4		2	1	2	2	7

6	1	0	1	0	2		2	2	2	2	8
7	2	1	0	1	4		2	2	2	2	8
8	2	2	2	2	8		2	2	2	2	8
9	1	2	1	1	5		2	1	1	1	5
10	2	2	1	0	5		1	2	2	1	6
11	2	2	1	2	7		1	1	2	2	6
12	1	2	0	2	5		2	1	2	2	7
13	2	1	1	2	6		2	1	2	2	7
14	2	2	1	1	6		1	2	2	2	7
15	2	0	1	2	5		2	2	1	2	7
16	1	1	2	1	5		1	0	2	0	3
17	1	0	2	0	3		2	2	1	0	5
18	2	2	2	2	8		1	1	2	1	5
19	2	2	1	1	6		2	1	0	1	4
20	2	0	1	2	5		2	2	2	2	8
	non-harmonic						**harmonic**				
Question 3	a	b	c	d	Total		a	b	c	d	Total
Marks	2	2	2	2	8		2	2	2	2	8
1	2	2	1	0	5		2	2	2	2	8
2	2	0	2	0	4		2	2	2	1	7
3	2	1	1	0	4		2	2	2	2	8
4	2	1	2	1	6		2	2	2	1	7
5	1	2	2	1	6		2	2	1	1	6
6	2	1	2	0	5		2	2	1	2	7
7	2	1	2	2	7		2	2	1	1	6
8	2	2	1	2	7		1	0	2	0	3
9	1	0	2	0	3		2	2	1	2	7
10	2	2	1	0	5		2	2	2	2	8
11	1	1	2	1	5		2	1	2	2	7
12	2	2	1	2	7		2	2	2	2	8
13	1	2	0	1	4		2	2	1	1	6
14	2	2	2	2	8		2	2	1	1	6
15	2	2	1	0	5		2	2	2	2	8
16	1	1	0	1	3		0	0	1	0	1
17	2	2	1	2	7		2	2	2	0	6
18	2	1	0	0	3		1	1	0	2	4
19	2	2	1	0	5		1	1	1	0	3
20	2	2	2	2	8		2	2	2	2	8
	non-harmonic						**harmonic**				

Question 4	a	b	c	d	Total		a	b	c	d	Total
Marks	2	2	2	2	8		2	2	2	2	8
1	2	2	2	2	8		2	1	2	0	5
2	1	1	0	0	2		2	2	1	2	7
3	2	2	1	2	7		1	2	1	0	4
4	2	1	0	0	3		2	0	2	2	6
5	2	1	1	1	5		2	2	2	1	7
6	1	0	1	1	3		2	2	1	2	7
7	2	1	0	1	4		2	1	2	2	7
8	2	2	0	2	6		1	2	0	1	4
9	1	1	0	2	4		1	1	0	2	4
10	1	0	2	1	4		2	2	2	1	7
11	2	1	1	0	4		2	0	2	2	6
12	2	2	0	1	5		1	2	2	0	5
13	1	2	1	1	5		1	2	1	0	4
14	1	1	0	0	2		1	1	1	0	3
15	2	1	1	0	4		1	2	2	0	5
16	1	2	1	1	5		1	1	0	0	2
17	0	1	1	0	2		1	2	0	2	5
18	2	2	1	1	6		1	0	1	1	3
19	1	2	2	0	5		2	2	0	1	5
20	2	1	1	0	4		2	1	1	2	6
	non-harmonic						**harmonic**				
Question 5	a	b	c	d	Total		a	b	c	d	Total
Marks	2	2	2	2	8		2	2	2	2	8
1	2	0	0	1	3		2	2	1	0	5
2	2	1	0	1	4		2	2	1	2	7
3	1	2	0	1	4		2	2	0	2	6
4	2	0	1	2	5		2	1	2	2	7
5	2	1	0	0	3		1	2	2	1	6
6	1	2	1	1	5		1	2	1	2	6
7	1	1	1	1	4		2	2	1	2	7
8	2	1	0	1	4		1	0	1	1	3
9	1	2	0	1	4		2	1	1	0	4
10	2	2	1	1	6		2	2	0	2	6
11	1	2	0	0	3		2	2	2	2	8
12	2	0	1	0	3		2	2	1	2	7
13	2	1	1	0	4		1	2	2	1	6
14	1	1	2	0	4		2	2	1	0	5

15	1	1	0	1	3		1	1	0	0	2
16	0	0	1	0	1		1	2	0	0	3
17	2	2	1	0	5		2	2	1	1	6
18	2	2	0	1	5		1	1	1	1	4
19	2	0	0	1	3		1	1	2	1	5
20	1	1	2	0	4		2	2	1	2	7

Overall percentage results (by condition)

	point estimation				pattern combination			Overall
	2 value	**3 value**	**4 value**	**total**	**2 variable**	**3 variable**	**total**	**%**
non-harmonic								
1	100.00	75.00	100.00	75.00	33.33	12.50	25.00	50.00
2	100.00	50.00	50.00	75.00	16.67	50.00	30.00	52.50
3	100.00	50.00	75.00	75.00	50.00	12.50	35.00	55.00
4	100.00	75.00	75.00	75.00	41.67	62.50	50.00	62.50
5	75.00	25.00	75.00	55.00	50.00	25.00	40.00	47.50
6	100.00	75.00	75.00	80.00	41.67	37.50	40.00	60.00
7	100.00	100.00	75.00	85.00	100.00	50.00	80.00	82.50
8	25.00	75.00	100.00	65.00	50.00	37.50	45.00	55.00
9	100.00	100.00	25.00	65.00	50.00	50.00	50.00	57.50
10	100.00	100.00	100.00	95.00	66.67	37.50	55.00	75.00
11	75.00	75.00	50.00	75.00	66.67	12.50	45.00	60.00
12	100.00	75.00	100.00	80.00	66.67	37.50	55.00	67.50
13	50.00	100.00	75.00	70.00	33.33	12.50	25.00	47.50
14	100.00	50.00	100.00	75.00	75.00	37.50	60.00	67.50
15	75.00	50.00	100.00	70.00	41.67	37.50	40.00	55.00
16	25.00	25.00	50.00	25.00	25.00	25.00	25.00	25.00
17	75.00	100.00	100.00	95.00	58.33	37.50	50.00	72.50
18	25.00	100.00	75.00	75.00	33.33	37.50	35.00	55.00
19	100.00	50.00	100.00	75.00	41.67	25.00	35.00	55.00
20	100.00	75.00	100.00	75.00	66.67	25.00	50.00	62.50
Average								**58.68**
harmonic								
1	100.00	100.00	100.00	95.00	91.67	37.50	70.00	82.50
2	100.00	75.00	100.00	95.00	91.67	75.00	85.00	90.00
3	100.00	75.00	100.00	90.00	91.67	37.50	70.00	80.00
4	100.00	75.00	100.00	80.00	91.67	100.00	95.00	87.50
5	100.00	75.00	100.00	90.00	83.33	75.00	80.00	85.00

6	100.00	100.00	100.00	95.00	91.67	75.00	85.00	90.00
7	100.00	100.00	100.00	95.00	83.33	87.50	85.00	90.00
8	75.00	100.00	25.00	60.00	75.00	37.50	60.00	60.00
9	50.00	75.00	100.00	70.00	75.00	37.50	60.00	65.00
10	100.00	75.00	100.00	95.00	91.67	62.50	80.00	87.50
11	100.00	50.00	75.00	75.00	91.67	100.00	95.00	85.00
12	100.00	75.00	100.00	90.00	100.00	62.50	85.00	87.50
13	100.00	75.00	100.00	85.00	83.33	50.00	70.00	77.50
14	100.00	75.00	100.00	85.00	83.33	25.00	60.00	72.50
15	75.00	100.00	100.00	80.00	83.33	25.00	60.00	70.00
16	25.00	25.00	0.00	35.00	33.33	0.00	20.00	27.50
17	75.00	100.00	100.00	90.00	41.67	50.00	45.00	67.50
18	25.00	50.00	50.00	40.00	58.33	50.00	55.00	47.50
19	100.00	75.00	50.00	75.00	50.00	50.00	50.00	62.50
20	50.00	100.00	100.00	85.00	91.67	75.00	85.00	85.00
Average								**74.47**

Appendix 16. Harmonic Combination TLX Results

Listed below are the Task Load Index statistics for the harmonic combination tests. Each participant completed a TLX questionnaire for each test condition (non-harmonic and harmonic combination).

TLX Category	Mental	Physical	Temporal	Performance	Effort	Frustration	Overall
non-harmonic combination							
1	22.67	0.00	4.00	11.00	9.33	25.00	72.00
2	18.67	0.00	5.33	13.33	4.67	18.67	60.67
3	17.33	0.00	5.33	10.00	5.33	12.00	50.00
4	16.00	0.00	5.33	10.67	6.67	10.00	48.67
5	15.00	0.00	9.33	2.33	14.00	10.67	51.33
6	17.33	0.00	6.00	12.00	7.33	12.00	54.67
7	15.00	0.00	20.00	10.67	4.00	26.67	76.33
8	7.00	0.67	3.33	20.00	8.67	2.00	41.67
9	25.00	0.00	3.33	10.67	9.33	12.00	60.33
10	17.33	0.00	6.00	20.00	6.00	4.67	54.00
11	23.33	0.00	2.33	9.33	10.00	4.67	49.67
12	15.00	0.00	3.67	18.33	9.00	12.00	58.00
13	14.00	0.00	8.00	12.00	6.67	14.00	54.67
14	14.67	0.00	10.00	6.00	10.00	15.00	55.67
15	18.67	1.00	7.00	12.00	3.00	9.33	51.00
16	14.00	0.00	3.00	10.67	12.00	11.00	50.67
17	22.67	0.00	7.33	18.33	5.33	6.00	59.67
18	13.00	0.00	9.00	13.33	6.67	11.00	53.00
19	7.00	0.67	3.33	20.00	8.67	2.00	41.67
20	17.33	0.00	5.33	12.00	6.67	14.00	55.33
Average							54.95
harmonic combination							
1	14.67	0.00	5.00	12.00	5.33	7.33	44.33
2	9.00	0.00	5.00	10.00	6.00	1.00	31.00
3	10.00	0.33	0.00	8.33	9.33	6.00	34.00
4	16.00	0.00	3.33	10.00	7.00	1.67	38.00
5	16.00	0.00	7.00	8.00	2.33	8.00	41.33
6	13.33	0.00	7.00	6.67	6.00	1.33	34.33

7	2.67	0.33	6.00	2.67	5.33	5.00	22.00
8	9.33	0.00	8.00	5.00	7.00	1.33	30.67
9	12.00	0.00	4.67	8.00	10.67	4.00	39.33
10	13.00	0.00	2.00	13.33	4.67	12.00	45.00
11	16.00	0.00	3.33	6.00	7.00	8.00	40.33
12	25.00	0.00	8.00	10.00	4.00	1.00	48.00
13	26.67	0.00	4.67	8.00	3.00	10.67	53.00
14	8.00	0.00	4.67	10.00	8.00	2.00	32.67
15	16.00	0.33	0.00	5.00	9.33	6.00	36.67
16	23.33	0.00	3.33	8.00	5.00	1.33	41.00
17	14.00	0.00	14.67	6.00	6.67	16.00	57.33
18	11.00	0.00	4.67	10.00	8.00	2.67	36.33
19	16.00	0.00	7.00	5.00	7.00	1.33	36.33
20	16.00	0.00	3.33	10.00	6.00	1.00	36.33
Average							38.90

Appendix 17.Rhythmic Parsing Test Questions

The rhythmic parsing test schedule contained 2 sets of tests, 1 for the non-rhythmic parsing and 1 for the rhythmic parsing conditions. Each set of test questions is listed below.

Non-rhythmic parsing Test Session

Sonify test1.csv. Set Exam1 to Bass and Exam 2 to Mid and identify:

How many people Passed Exam 2?...

How many people Failed Exam 1?...

Which group had the most Passes for Exam 1?.......................................

Which group had the most Fails for Exam 2?...

Which group had the most Fails for both Exams?..................................

Sonify test2.csv. Set Exam1 to Bass and Exam 2 to Treble and identify:

How many people got an A for Exam 1?...

How many people got a B for Exam 2?..

Which group had the most C Passes for Exam 2?.......................................

Which group had the most B Passes for Exam 1?.......................................

Which group had the most A Passes for both Exams?..................................

Sonify test3.csv. Set Exam1 to Mid and Exam 2 to Treble and identify:

How many people got a C for Exam 2?..

How many people got a B for Exam 1?..

Which group had the most A Passes for Exam 2?.......................................

Which group had the most Fails for Exam 1?...

Which group had the most C Passes for both Exams?..................................

Sonify test4.csv. Set Exam1 to Bass, Exam 2 to Mid and Exam 3 to Treble and identify:

How many people Passed Exam 2? ....

How many people Failed Exam 3? ....

Which group had the most Passes for Exam 1? ....

Which group had the most Fails for Exam 2? ....

Which group had the most Passes for all 3 Exams? ....

Sonify test5.csv. Set Exam1 to Bass, Exam 2 to Mid and Exam 3 to Treble and identify:

How many people Failed Exam 1? ....

How many people Failed Exam 2? ....

Which group had the most Passes for Exam 3? ....

Which group had the most Fails for Exam 1? ....

Which group had the most Fails for all 3 Exams? ....

Rhythmic parsing Test Session

Sonify test1.csv. Set Exam1 to Bass and Exam 2 to Mid and identify:

How many people Passed Exam 1? ....

How many people Failed Exam 2? ....

Which group had the most Passes for Exam 2? ....

Which group had the most Fails for Exam 2? ....

Which group had the most Passes for both Exams? ....

Sonify test2.csv. Set Exam1 to Mid and Exam 2 to Treble and identify:

How many people got an A for Exam 2? ....

How many people got a C for Exam 1? ....

Which group had the most B Passes for Exam 1? ....

Which group had the most B Passes for Exam 2? ....

Which group had the most A Passes for both Exams?..................................

Sonify test3.csv. Set Exam1 to Bass, Exam 2 to Treble and identify:

How many people got a B for Exam 1?...

How many people Failed Exam 2?...

Which group had the most A Passes for Exam 2?...

Which group had the most Fails for Exam 1?...

Which group had the most B Passes for both Exams?..................................

Sonify test4.csv. Set Exam1 to Bass, Exam 2 to Mid and Exam 3 to Treble and identify:

How many people Passed Exam 2?...

How many people Failed Exam 1?...

Which group had the most Passes for Exam 2?...

Which group had the most Fails for Exam 3?...

Which group had the most Fails for all 3 Exams?..................................

Sonify test5.csv. Set Exam1 to Bass, Exam 2 to Mid and Exam 3 to Treble and identify:

How many people Passed Exam 3?...

How many people Failed Exam 2?...

Which group had the most Passes for Exam 1?...

Which group had the most Fails for Exam 2?...

Which group had the most Passes for all 3 Exams?..................................

Appendix 18.Rhythmic Parsing Test Results

Listed below are the results of the rhythmic parsing test schedule, which compared overall point estimation, group comparison point estimation and group comparison pattern combination performance between non-rhythmic parsing and rhythmic parsing test conditions. Overall results are also listed.

	non-rhythmic							rhythmic					
Question 1	a	b	c	d	e	Total		a	b	c	d	e	Total
Marks	2	2	2	2	2	10		2	2	2	2	2	10
1	2	2	2	2	2	10		2	2	2	2	2	10
2	2	2	2	0	2	8		2	2	2	2	2	10
3	2	2	2	2	0	8		2	2	2	0	2	8
4	2	2	2	2	0	8		1	2	2	2	0	7
5	2	1	2	0	2	7		2	2	2	2	0	8
6	2	0	0	0	0	2		2	2	2	2	2	10
7	2	2	0	0	2	6		2	1	2	2	2	9
8	1	0	2	2	2	7		1	1	2	2	2	8
9	1	2	0	2	0	5		2	0	2	0	0	4
10	2	2	0	2	2	8		2	2	2	2	2	10
11	1	2	2	2	2	9		1	2	0	2	0	5
12	2	1	2	2	2	9		1	1	0	2	2	6
13	2	2	0	2	2	8		2	2	2	2	2	10
14	2	1	2	0	2	7		2	2	2	2	2	10
15	2	1	2	2	2	9		2	1	2	2	0	7
16	2	1	2	2	2	9		1	2	0	2	2	7
17	2	1	2	2	2	9		1	2	2	0	2	7
18	1	2	0	2	2	7		1	2	0	2	0	5
19	1	2	0	2	0	5		2	1	2	0	2	7
20	2	0	2	2	0	6		1	2	2	2	2	9
	non-rhythmic							rhythmic					
Question 2	a	b	c	d	e	Total		a	b	c	d	e	Total
Marks	2	2	2	2	2	10		2	2	2	2	2	10
1	2	2	0	2	2	8		2	1	0	2	2	7
2	2	1	0	2	2	7		2	2	2	0	2	8
3	2	1	2	2	2	9		2	2	2	0	2	8

4	2	1	2	2	0	7		2	1	2	2	2	9
5	2	2	0	2	0	6		2	2	2	2	0	8
6	1	1	2	0	2	6		2	2	2	0	2	8
7	2	2	0	2	0	6		1	2	2	2	2	9
8	2	2	2	2	2	10		2	2	0	2	2	8
9	2	2	0	0	2	6		1	2	2	0	2	7
10	2	2	2	0	2	8		2	2	2	2	0	8
11	1	1	0	2	2	6		1	2	0	2	0	5
12	2	2	2	0	2	8		2	1	2	2	2	9
13	2	2	2	2	2	10		2	2	2	0	2	8
14	1	0	0	2	2	5		2	2	0	2	2	8
15	1	1	0	2	0	4		1	2	2	0	2	7
16	2	2	0	0	2	6		0	2	0	2	2	6
17	2	0	0	2	0	4		2	2	0	2	2	8
18	2	0	0	2	2	6		2	2	2	0	2	8
19	1	2	2	0	2	7		1	2	0	0	2	5
20	1	1	2	0	2	6		2	2	2	0	2	8
	non-rhythmic							**rhythmic**					
Question 3	a	b	c	d	e	Total		a	b	c	d	e	Total
Marks	2	2	2	2	2	10		2	2	2	2	2	10
1	2	2	0	2	2	8		1	1	2	0	0	4
2	2	1	2	2	0	7		2	1	0	0	2	5
3	2	2	0	0	2	6		2	2	2	2	2	10
4	2	0	2	0	0	4		1	2	0	2	2	7
5	0	2	0	2	2	6		2	1	2	0	2	7
6	2	0	2	0	2	6		1	2	2	2	2	9
7	2	1	0	2	0	5		2	2	2	0	2	8
8	0	2	2	0	2	6		2	2	0	0	2	6
9	2	0	2	0	2	6		1	2	0	2	2	7
10	1	2	0	2	2	7		2	2	2	2	2	10
11	0	2	0	2	0	4		1	1	2	0	0	4
12	2	1	2	2	0	7		2	2	0	2	0	6
13	1	2	2	0	0	5		1	2	2	0	2	7
14	2	1	0	0	2	5		2	2	0	2	0	6
15	1	2	2	2	2	9		1	1	2	0	2	6
16	2	2	0	2	2	8		2	1	0	2	2	7
17	1	2	0	0	2	5		2	1	2	2	2	9
18	2	2	0	2	0	6		1	1	2	0	2	6
19	1	1	2	0	0	4		2	2	0	2	2	8

20	0	0	0	0	2	2		0	2	2	0	2	6
	non-rhythmic							**rhythmic**					
Question 4	a	b	c	d	e	Total		a	b	c	d	e	Total
Marks	2	2	2	2	2	10		2	2	2	2	2	10
1	2	2	2	2	2	10		2	2	2	2	0	8
2	2	2	0	2	0	6		1	2	0	2	2	7
3	2	1	2	0	2	7		2	2	2	2	2	10
4	2	1	2	2	2	9		2	2	2	0	0	6
5	1	1	0	2	0	4		1	2	2	2	0	7
6	1	0	0	2	2	5		2	2	2	0	2	8
7	2	2	0	0	2	6		1	2	0	2	2	7
8	2	2	0	2	0	6		2	2	2	0	2	8
9	2	1	0	2	0	5		1	2	0	2	2	7
10	2	2	0	2	2	8		2	2	0	2	0	6
11	2	2	2	0	2	8		1	2	2	2	2	9
12	1	1	2	2	2	8		2	2	2	0	2	8
13	1	1	2	2	2	8		2	2	2	0	2	8
14	2	2	0	2	0	6		2	1	2	2	2	9
15	1	1	2	2	2	8		2	2	2	2	0	8
16	2	2	2	2	2	10		2	0	2	2	2	8
17	2	2	2	0	2	8		2	2	0	2	2	8
18	2	1	0	2	0	5		2	2	2	2	2	10
19	2	2	0	0	2	6		2	2	2	2	2	10
20	2	2	0	2	2	8		2	1	2	0	2	7
	non-rhythmic							**rhythmic**					
Question 5	a	b	c	d	e	Total		a	b	c	d	e	Total
Marks	2	2	2	2	2	10		2	2	2	2	2	10
1	1	1	2	2	2	8		2	1	2	0	2	7
2	2	1	2	2	0	7		1	2	0	0	0	3
3	1	0	0	2	2	5		2	2	2	0	2	8
4	2	2	0	0	0	4		1	1	2	2	2	8
5	2	1	2	0	2	7		2	2	2	2	0	8
6	0	2	2	0	2	6		1	1	2	2	0	6
7	2	1	0	2	0	5		0	1	2	2	2	7
8	2	2	0	2	2	8		2	1	0	2	2	7
9	2	2	2	2	2	10		2	2	2	0	0	6
10	1	1	0	2	2	6		2	0	2	2	2	8
11	2	0	2	2	2	8		2	2	2	2	2	10
12	2	1	0	2	2	7		2	2	0	2	2	8

13	1	2	0	2	2	7		1	2	0	2	2	7
14	0	1	2	0	2	5		2	2	2	2	2	10
15	1	2	0	2	2	7		1	0	2	0	2	5
16	2	2	2	2	2	10		2	0	2	2	2	8
17	2	1	0	2	2	7		0	2	2	0	2	6
18	1	2	2	0	0	5		1	2	2	2	2	9
19	1	2	0	2	2	7		2	1	2	2	0	7
20	2	2	0	2	2	8		2	1	2	2	2	9

Overall percentage results (by condition)

	overall point estimation	**group point estimation**	**group pattern combination**	**Overall %**
non-rhythmic parsing				
1	90	80	100	88
2	85	70	40	70
3	95	70	100	86
4	75	40	60	58
5	70	50	60	60
6	75	60	80	70
7	90	30	40	56
8	75	70	80	74
9	80	50	60	64
10	85	50	100	74
11	65	70	80	70
12	60	40	80	56
13	80	70	80	76
14	80	70	20	64
15	65	80	80	74
16	45	40	80	50
17	75	50	80	66
18	75	50	40	58
19	75	80	80	78
20	60	50	80	60
Average	**75**	**58.5**	**71**	**67.6**
rhythmic parsing				
1	90	60	100	80
2	70	80	100	80
3	100	70	100	88

4	75	80	60	74
5	75	70	40	66
6	85	80	80	82
7	80	70	60	72
8	85	50	100	74
9	75	50	60	62
10	90	90	60	84
11	80	70	80	76
12	85	60	80	74
13	85	40	80	66
14	95	80	80	86
15	65	70	60	66
16	60	70	100	72
17	80	60	100	76
18	90	90	20	76
19	85	60	80	74
20	75	70	100	78
Average	**81.25**	**68.5**	**77**	**75.3**

Appendix 19.Rhythmic Parsing TLX Results

Listed below are the Task Load Index statistics for the rhythmic parsing tests. Each participant completed a TLX questionnaire for each test condition (non- rhythmic parsing and rhythmic parsing).

TLX Category	Mental	Physical	Temporal	Performance	Effort	Frustration	Overall
non-rhythmic parsing							
1	26.67	0.00	18.00	3.67	18.00	19.00	85.33
2	20.00	0.00	18.67	8.00	14.00	6.00	66.67
3	9.33	2.67	20.00	9.00	10.67	4.67	56.33
4	8.67	0.33	10.00	10.67	16.00	4.67	50.33
5	17.33	0.00	14.00	17.33	6.67	9.33	64.67
6	21.33	0.00	12.00	6.00	10.00	3.33	52.67
7	10.00	1.00	12.00	8.00	10.00	1.67	42.67
8	26.67	0.00	12.00	6.67	9.33	9.00	63.67
9	22.67	0.00	18.67	11.00	10.67	8.67	71.67
10	8.00	0.00	26.67	6.00	18.67	3.33	62.67
11	14.67	0.00	14.00	10.00	4.33	20.00	63.00
12	22.67	1.33	15.00	9.00	3.00	4.00	55.00
13	18.67	0.00	23.33	12.00	6.00	3.33	63.33
14	15.00	1.33	16.00	12.00	0.00	11.00	55.33
15	14.00	1.00	16.00	3.00	13.33	10.00	57.33
16	17.33	0.00	10.00	11.00	6.00	10.00	54.33
17	17.00	0.00	28.33	12.00	10.67	8.67	76.67
18	15.00	2.67	21.67	0.00	11.00	5.33	55.67
19	13.00	0.00	13.00	15.00	12.00	1.67	54.67
20	18.00	1.00	7.33	12.00	8.67	16.00	63.00
Average							60.75
rhythmic parsing							
1	23.33	0.00	6.00	9.33	2.67	4.00	45.33
2	20.00	0.00	9.00	8.00	9.00	4.67	50.67
3	14.00	0.00	6.67	9.00	4.67	6.67	41.00
4	23.33	0.33	11.00	10.67	2.33	1.33	49.00
5	15.00	0.33	7.00	10.00	2.33	5.33	40.00
6	13.00	0.00	11.67	8.00	3.33	2.33	38.33
7	20.00	0.00	6.00	10.67	3.33	2.67	42.67
8	14.00	0.00	10.67	6.67	2.33	6.67	40.33

9	15.00	0.33	8.00	3.33	1.33	1.00	29.00
10	18.33	2.33	5.33	7.00	9.00	2.33	44.33
11	18.67	0.00	4.67	8.33	2.00	2.00	35.67
12	17.33	0.00	8.33	4.67	3.33	7.33	41.00
13	14.00	0.00	5.33	5.33	8.00	2.67	35.33
14	8.00	2.67	13.33	5.33	6.00	9.33	44.67
15	17.33	0.00	5.33	8.33	1.67	6.00	38.67
16	24.00	0.00	6.00	7.00	8.00	8.00	53.00
17	21.67	0.00	6.67	2.00	6.00	4.00	40.33
18	20.00	0.00	12.00	13.33	4.67	1.67	51.67
19	20.00	0.00	4.67	3.00	7.00	1.00	35.67
20	9.33	0.67	5.33	8.00	4.67	2.00	30.00
Average							41.33

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