Final Report for IBSc and MEng Third Year Group Project

User Interface for Demonstrations of Auditory Illusions

Author Name:

Huang Yilin

Beth Maughan

Techawin Manoonporn

Joshua Sia

Sabrina Lim

Sam Turner

Yi Teng Voon

Supervisor: Dr Tobias Reichenbach

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Abstract

Auditory illusions occur when real acoustical stimuli are misperceived by our auditory system. This relatively new illusory field has found a place in entertainment, influencing musical scores and films. It has also elucidated some of the workings of the human auditory system benefitting medical developments and research revolving around acoustical stimuli. This project aims to develop a public outreach tool, in the form of a User Interface (UI), to generate interest and improve understanding of auditory illusions. To achieve this, research from multiple sources was collated on 13 illusions. Each illusion was created independently on GarageBand, Sibelius or MATLAB. The UI itself was produced using HTML5, Cascaded Style Sheets (CSS) and Javascript. The result, thus far, is a website that includes 11 completed illusions and integrated surveys to collect data concerning user perception and characteristics. This report also proposes further improvements to the current UI and illusions, as well as future plans, such as creating a Virtual Reality experience to augment the illusions. The potential impact of the UI in the field of auditory illusions is also explored.

Acknowledgement

Many thanks to our project supervisor, Dr. Tobias Reichenbach, for his time and invaluable advice.

Contents

1 Introduction

Many people are familiar with optical illusions; when presented with confusing visual inputs the brain may jump to impossible conclusions. For example, the Penrose triangle shown in Figure 1 below depicts a shape which violates the laws of geometry by containing three right-angles [1].

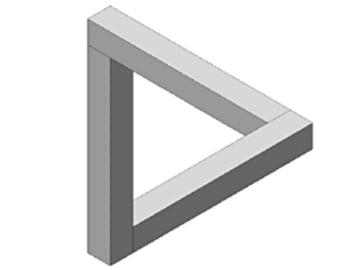

Figure 1: The Penrose Triangle

This object cannot be built and can only be seen in perspective drawings. Similar to optical illusions, auditory inputs to the hearing system can be confusing and misinterpreted too. In other words, auditory illusions occur when real acoustic stimuli are misperceived. This definition creates a distinction from auditory hallucinations, which are perceived without a stimulus [2]. One notable example of an auditory illusion is the viral "Yanny or Laurel" audio clip from 2018, which split the public into two groups - those who heard Yanny, and those who heard Laurel [3]. Much like how studying optical illusions has revealed the neural mechanisms underlying visual processing pathways [4], further research into auditory illusions can also provide insights into how the brain processes sounds.

A search for auditory illusions will likely return a number of blogs and articles. These are great for capturing people's attention but offer little detail on the illusions themselves. The most established user interface (UI) to date is a website by a leading researcher in the field of auditory illusions named Diana Deutsch [5]. Her website provides a solid understanding of 13 illusions but is limited since it focuses predominantly on her work. Currently, there is no existing UI that incorporates illusions and research from multiple sources and is an effective public outreach tool. Hence, a UI that can fill this gap is proposed.

1.1 Aims

To demonstrate auditory illusions through a UI which allows the public to understand more about the topic.

1.2 Objectives

Three sub-groups are formed which focus on the following objectives: First, background research has to be thoroughly searched and selected for all the auditory illusions to be published on the UI. This includes writing simple and detailed explanations for the public, taking into consideration the different levels of knowledge and understanding of the neural system, music and auditory illusions. Next, multiple software will be used to design the illusions effectively, depending on the desired effect. All the illusions will be accompanied with voice-overs to introduce listeners to each illusion. Finally, a user-friendly and functional UI will be developed to link and display all elements of the project in an organised manner.

2 Background

Research into auditory illusions only began little over fifty years ago, with most of the auditory illusions known today being discovered during this time. To kickstart the project, Diana Deutsch's research on auditory illusions was studied. Her 2019 publication, 'Musical Illusions and Phantom Words: How Music and Speech Unlock Mysteries of the Brain' has served as an invaluable guide throughout the project [6]. This book introduced a vast range of illusions, many of which are included in the UI. These were joined with a few illusions outside of Deutsch's research. Table 1 illustrates all the illusions currently included on the UI. The illusions are covered in the corresponding section numbers under Illusion Generation (Section 3.2) in Methods (Section 3).

Section	**Illusion**	**Brief Description**
3.2.2	Octave Illusion	Alternating high and low tones are presented to the right and to the left ear. Individuals report hearing a variety of patterns, most often high tones in one ear and low tones in the other.
3.2.3	Distortion Product Otoacoustic Emissions (DPOAE)	Two frequencies are played at a specified ratio. They interact in the inner ear and a distortion product is formed, which can be faintly heard as a third frequency by the listener.
3.2.4	Continuity Illusion	When a sound contains an interval filled with an abrupt noise, it may instead be perceived as continuous.
3.2.5	Shepard-Risset Glissando	Utilises the principle of pitch circularity to produce a series of tones which appear to be forever rising or falling in pitch in one *continuous*, gliding sound.
3.2.6	Shepard's Tone	Utilises the principle of pitch circularity to produce a series of tones which appear to be forever rising or falling in *discrete* pitch steps.
3.2.7	Tritone Paradox	A pair of tritones is played. Some people hear them rising in pitch, others perceive them falling.
3.2.8	Timbre Illusion	Two tones that differ in timbre (A and B), alternately play in the pattern ABA.When the timbre difference is large a different pattern is heard than when it is small.
3.2.9	Galloping rhythm	The pattern ABA is played. As the pitch of A and B get closer, it becomes hard to distinguish the separate tones and the pattern is perceived as one connected galloping rhythm.
3.2.10	Timing/Sequence Perception	Illustrates that pauses placed in appropriate places make sequences easier to remember.
3.2.11	Scale Illusion	Patterns of notes jumping in pitch are presented to each ear. The brain reorganises the inputs to form smoother pitch contours. As a result, some notes are perceived as originating from the opposite ear they present to.
3.2.12	Mysterious Melody	A well known tune is played but with each note moved to a different octave, making it difficult to discern. If the listener is informed what the original tune is, they find it easier to recognise the melody.
3.2.13	Interleaved melodies	Two familiar melodies are played simultaneously, displaced so that they are similar in pitch. This makes them difficult to distinguish, yet when played in separate octaves they are easily recognisable.

Table 1: A list of selected illusions thus far in the project with brief explanations for each one.

While it seems that the field is still in its infancy with many fascinating avenues left to be explored, previous auditory illusion research has already produced some interesting results. For example, continuity illusion studies have highlighted how top-down processing can modulate our auditory perception. When listening to familiar and unfamiliar songs containing noise intervals, participants claimed not to hear any such intervals more often in familiar songs, which suggests that perceptions relies in part on expectations [7].

Moreover, even prior to their official discovery, Shepard's tones had been incorporated into a variety of musical pieces. Tchaikovsky's Pathetique Passage, which first premiered in 1893, simulates the illusion of eternally rising pitch using string instruments [8]. Since Shepard's paper in 1964, however, more perfect recreations of the illusion have been produced in electroacoustic music, including some sound effects in the blockbuster Batman film 'The Dark Knight' [9].

Finally, some auditory illusions have even found purpose in medicine. Binaural beats are illusory sounds heard when two similar real frequencies are played in separate ears, perceived at the frequency difference between the two. Research has shown that these imaginary 'beats' can have many similar benefits to meditation [10]. In addition, Distortion Product Otoacoustic Emissions (DPOAEs) have been utilised for clinically testing newborn babies' hearing. DPOAEs are oscillations produced by the inner ear when two pure tones interact in the cochlea [11]. These are just a few examples of how auditory illusion research has proved beneficial, which will be explored in greater detail on our web page.

3 Methods

3.1 Research

For each illusion, research was undertaken in order to write up an information section about the individual illusions on the UI. The required steps to effectively deliver each write up were planned beforehand and are summarised in Figure 2. The overall aims were to explain to the listener: First, what they would hear when the illusion was played and what to look out for, if relevant. Next, an explanation of how the illusion works and a brief description of how it was created. Finally, a summary of the background research on each illusion and detailed research for curious readers.

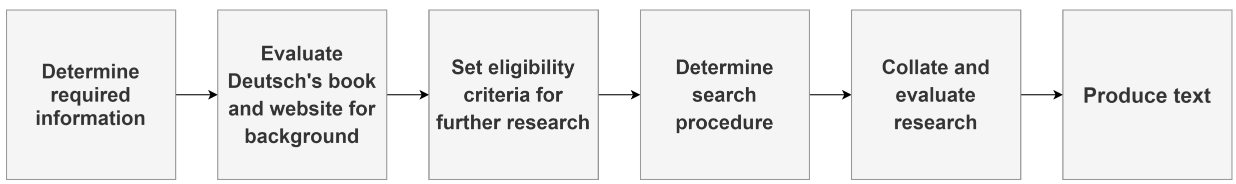

Figure 2: The flowchart of the steps involved to undertake the research and write up the relevant sections.

A vast amount of information was garnered from Diana Deutsch's website and from her book "Musical Illusions and Phantom Words: How Music and Speech Unlock Mysteries of the Brain"[6]. These sources provided detailed descriptions of many of the illusions and the higher processing involved. In order to look outside of Diana Deutsch's research, illusions that were not included in her book were sought and a literature review was undertaken on each illusion.

The eligibility criteria to select relevant papers included: A preference for papers in English in peer reviewed journals; Papers that focused on the specific illusion or utilised the illusion for other research; A preference for research on neural processing, however this was not always available so other topics were included.

The criteria was relaxed to be able to survey all available research and because some illusions had very few papers dedicated to them.

Studies were identified by searching the following databases and journals, *Google Scholar*, *Web of Science*, *PubMed* and the *Acoustical Society of America*. Often, auditory illusions had another name; for example, interleaved melodies are also referred to as 'melodic fission' in the psychoacoustic field. In these cases, all known names of the illusion were searched in the databases and journals previously mentioned .

A subjective approach was taken to select which research would be included on the website. As a general rule, research that focused on neural processing or topics that appeared frequently were preferred. It was also desirable to be able to explain the research in a manner that would be appropriate for the general public.

Finally, all the information was collated and included on the UI. Feedback from peers was sought to improve each written section.

3.2 Illusion Generation

MATLAB (MathWorks), GarageBand (Apple) and Sibelius (Sibelius Software Limited) were chosen to generate the different illusions. MATLAB allows for a pure tone with a single frequency to be created. On the other hand, GarageBand and Sibelius offer a wide variety of timbres (sound qualities) which were used to generate illusions containing tones with complex harmonics. A list of musical terms and their definitions are given in Appendix B.

3.2.1 Pure Tone in MATLAB

The sound function in MATLAB is mainly used for the generation of auditory illusions. It can convert a matrix of signal data to sound. The two inputs for sound function are the audio signal and the sampling frequency.[12] Most of auditory illusions are created based on piano keys tone. The frequency of the No. n piano key tone can be obtained by the formula [13]:

$$f(n) = (\sqrt[12]{2})^{n-49} * 440Hz \tag{1}$$

After obtaining the frequency, the audio signal needs to be synthesized by a sine function which is shown below:

$$AudioSignal = Asin(2\pi ft) \tag{2}$$

where A is the amplitude of the audio signal, f is the frequency of the audio frequency and t is the time duration.

In some cases of auditory illusion, the auditory signals exported from left channel and right channel are different (e.g. Scale Illusion). To solve this issue, each auditory signal needs to be synthesized separately first and then put into a 2-column matrix. By convention, left channel signal is on the first column and the right channel is on the second column. After placing the audio signal in the right place, the sound function will be able to export different signals to left and right channel. The pure tone generation MATLAB code can be found in Appendix D. It also includes codes to generate the scale illusion.

3.2.2 Octave Illusion in MATLAB

The notes chosen were A3 (220 Hz) and A4 (440 Hz), which are one octave apart. The left channel is a sequence of A3 followed by A4. The right channel is a sequence of A4 followed by A3. The duration played for each tone is 0.25 s which is equivalent to a tempo of 240 BPM. The MATLAB code for this illusion is based on the pure tone code in Appendix D. The music sheet for Octave Illusion is shown in Figure 3.

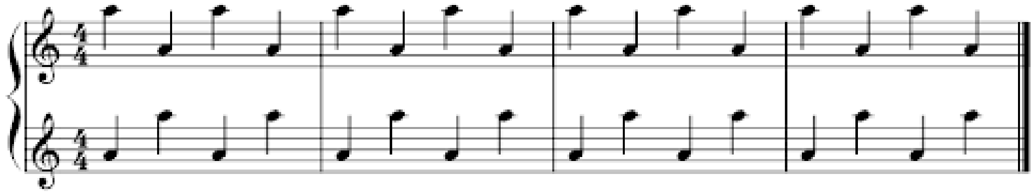

Figure 3: Music sheet to visualise the Octave Illusion. The top melody was played to the right ear, the bottom melody was played to the left ear.

3.2.3 Distortion Product Otoacoustic Emissions (DPOAE) in MATLAB

This phenomenon was created using the sound function described in Section 3.2.1. The first step is to create two pure tones that stayed constant for a time period of 1.5 seconds. The two tones were at 1300 Hz and 1560 Hz respectively. The second step is to change the frequency of the second tone, so that it increases linearly from 1560 Hz to 1998 Hz. This was done using the 'chirp' function on MATLAB. The second part lasted for 2.5 seconds. Lastly, the two parts were combined and was saved to a sound file using the 'audiowrite' function [14]. The plot of the frequencies as a function of time is shown below in Figure 4 and the code can be found in Appendix E.

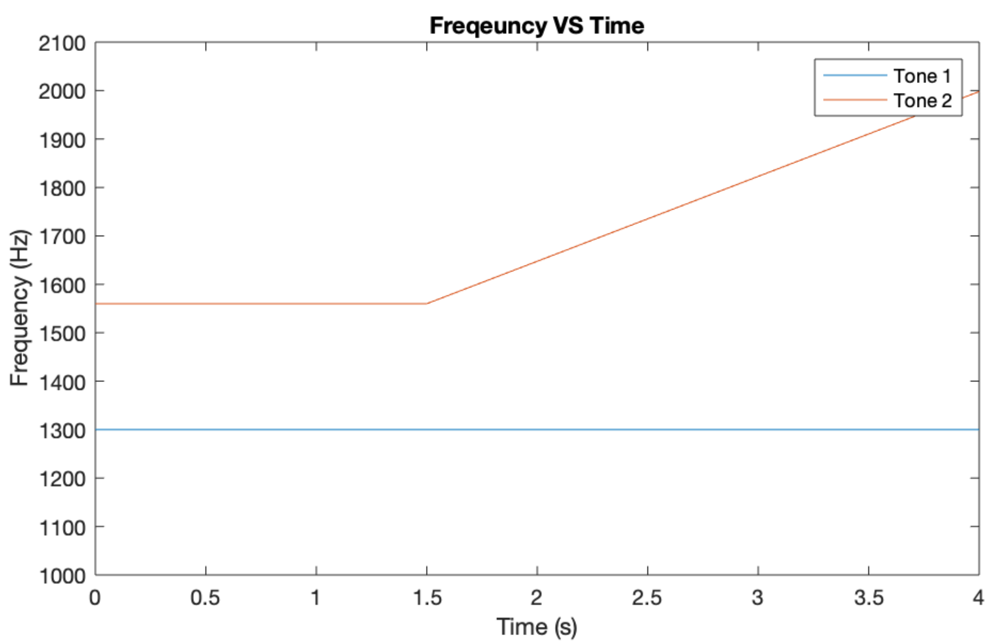

Figure 4: Frequency as a function of time plot of the two tones used to demonstrate DPOAEs. Tone 1 has a constant frequency throughout the demonstration while Tone 2 starts increasing its frequency linearly after 1.5 s.

3.2.4 Continuity Illusion in MATLAB

This phenomenon was also created using the sound function described in Section 3.2.1. There were two tones involved: a long pure tone, and a short complex tone. The frequency of the long tone was 1000 Hz while the complex tone consists of four random frequencies of 1200 Hz, 1350 Hz, 980 Hz and 800 Hz superimposed together. The long tone lasted 2.2 s with a 0.2 s pause in between. When this pause is replaced by the short complex tone that lasted 0.2 s, it gave the illusion of continuity. To create pauses in the sound file, arrays filled with zero were needed to be included. The sequence of the tones and the pauses is illustrated below in Figure 5 and the code written can be found in Appendix F.

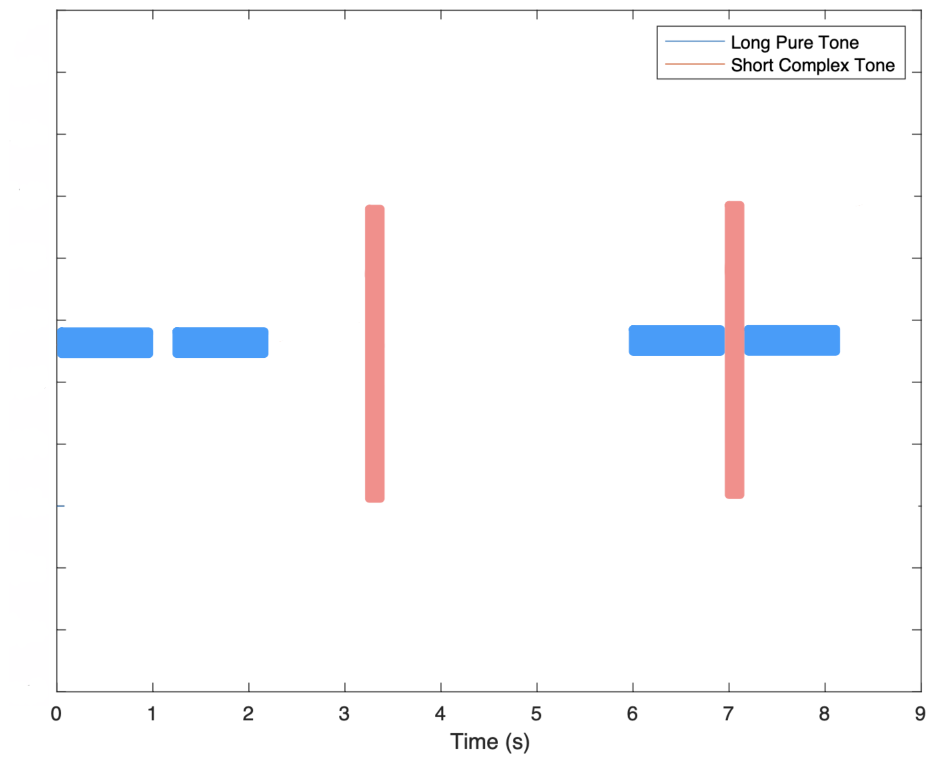

Figure 5: Illustration of the timing of the tones and the pauses. The blue rectangle represents the long pure tone. The red rectangle represents the short and complex tone.

3.2.5 Shepard-Risset Glissando in MATLAB

To produce the Shepard-Risset Glissando which is continuous in pitch, multiple signals sweeping up or down are superposed together. This is achieved by using the chirp function in MATLAB [15] which produces a swept-frequency cosine signal. However, the superposition of auditory signals containing complex harmonics produces noise which is undesirable. To circumvent this, a Gaussian distribution was used as an envelope for the amplitude of the different harmonics in order to attenuate the amplitude of the noise. The MATLAB code to generate this envelope can be found in Appendix G. The mean, standard deviation and amplitude of the envelope has to be adjusted for different harmonics. One such envelope is shown below in Figure 6.

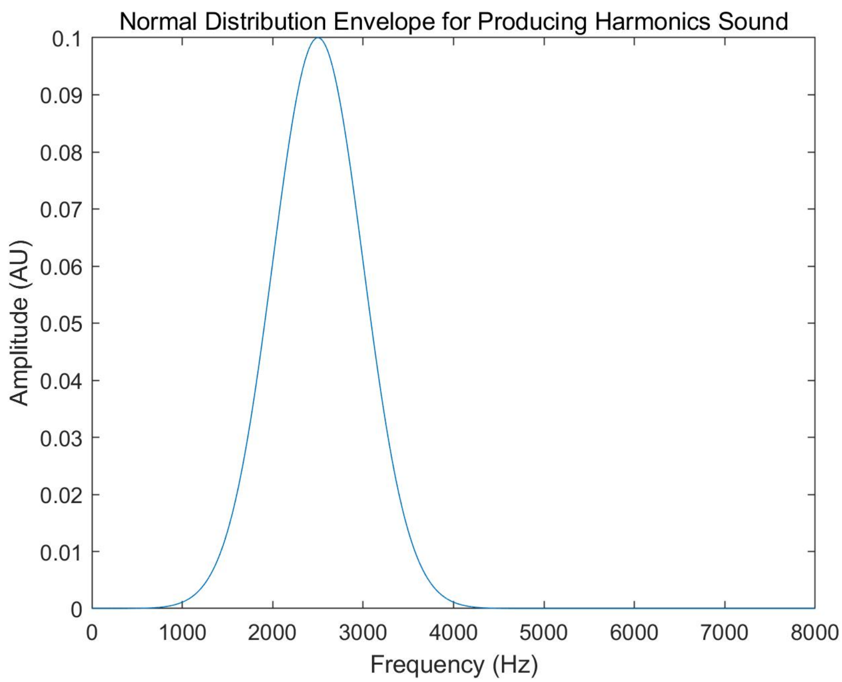

Figure 6: The normal distribution envelope for the amplitude of the harmonics frequencies. The mean frequency is this case is 2500 Hz and the standard deviation is 500 Hz. The y-axis indicates that the amplitude is 1/10 of the original amplitude. This is for producing a more decent harmonics sound.

An effective method to generate the this illusion is by breaking it into identical sections, creating the unit section, then combining the desired number of unit sections to generate the complete version. To create one section of the illusion, multiple logarithmic increased swept-frequency cosines are combined by superposition. The frequency range of the logarithmic increased swept-frequency cosines used are from 100 Hz - 200 Hz, 200 Hz - 400 Hz, 400 Hz - 800 Hz, 800 Hz - 1.6 kHz, 1.6 kHz - 3.2 kHz, 3.2 kHz - 6.4 kHz, and 6.4 kHz - 12.8 kHz. Following this, the section is filtered by a Gaussian envelope. The frequency spectrum of one section is shown below in Figure 7.

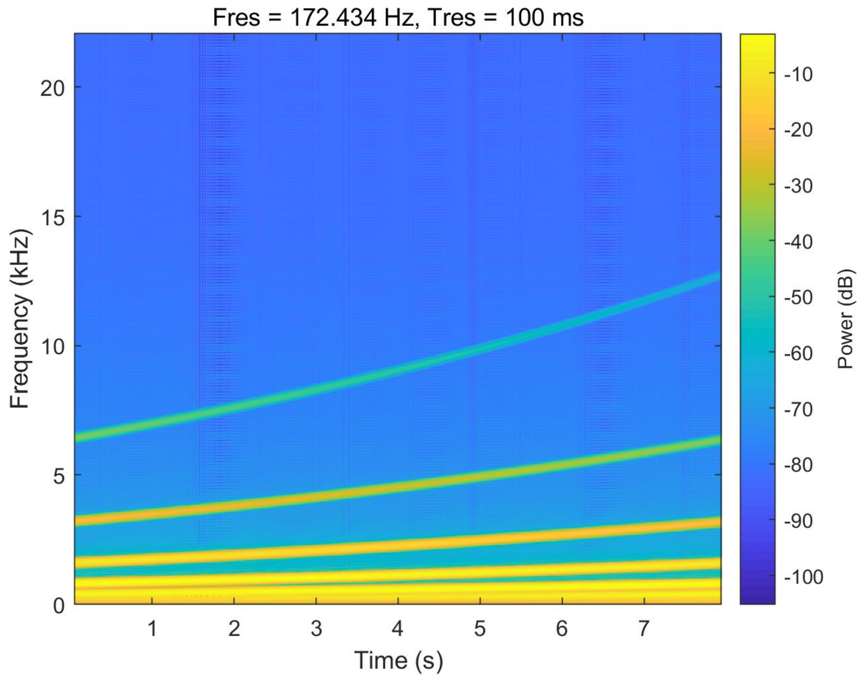

Figure 7: The spectrum of one section of the continuous Shepherd's Tone. There are overlapping at the bottom of the figure due to relatively small frequency range of the beginning swept-frequency cosine. Because of the Gaussian envelope, as the frequency increase, the line fades away which is an indication of decrease on amplitude. Each section is 8 seconds long which is shown on the x axis.

Next, the individual sections are combined into an array that fully describes the illusion. The mechanism behind this is that the swept-frequency cosines from one section will be connected with the swept-frequency cosine of the neighbour sections to form a full logarithmic increased swept-frequency cosine. For example, the 200 Hz - 400 Hz swept-frequency cosine in the second section will be connected to the 100 Hz - 200 Hz swept-frequency cosine in the first section and the 400 Hz - 800 Hz swept-frequency cosine in the third section, which will form a full 100 Hz - 800 Hz swept-frequency cosine. In addition, the array is normalised by the maximum value of the array such that the maximum value will be 1. This is done in order to prevent any signal loss during conversion of the array to a .WAV sound file. The well-commented MATLAB code to generate the Shepard-Risset Glissando can be found in Appendix H. The spectrum of the entire illusion is shown below in Figure 8.

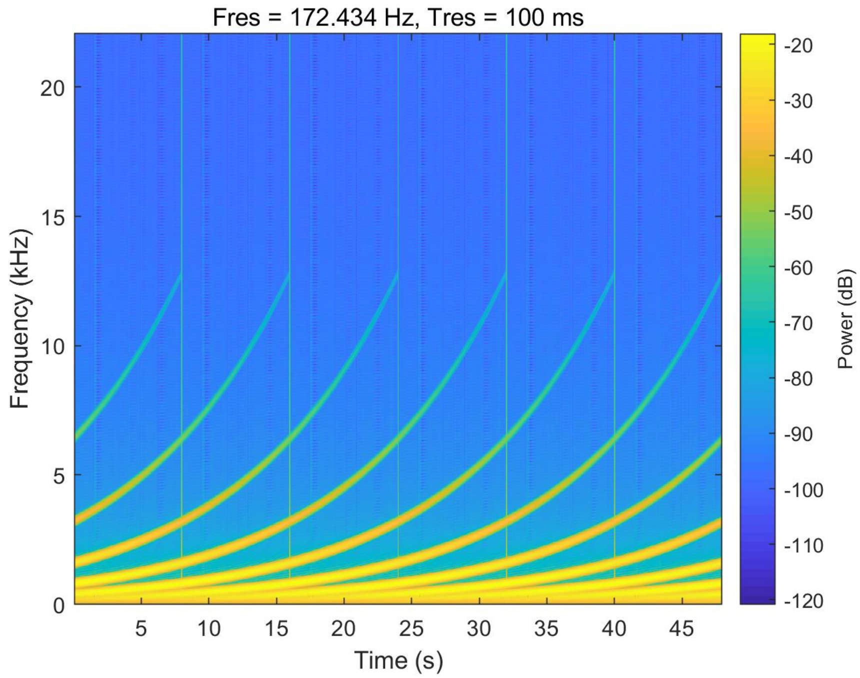

Figure 8: The spectrum of the Shepard-Risset Glissando. The frequency of a full logarithmic increased swept-frequency cosine is from 100 Hz to 12800 Hz. It is noticeable that there is a vertical line between each section, which may be due to a sudden attenuation in the frequency.

3.2.6 Shepard's Tone in GarageBand

Similar to the Shepard-Risset Glissando created on MATLAB, multiple ascending scales were overlapped and played together to create this illusion. However, in this illusion, the pitch increases in discrete steps. The software instrument used was the Steinway Grand Piano. The tempo was set to 120 BPM and the length of each note was 0.0.2.0. The score to create the Shepard's Tone is shown below in Figure 9.

Figure 9: Music sheet to create the Shepard's Tone illusion involving three ascending octaves played together. The amplitude of the notes are adjusted to allow for fading in and out of the notes.

To give the illusion of an infinite rise in frequency, the amplitude of each note needs to be regulated. The amplitude of each note can be adjusted by the velocity parameter in GarageBand which can be set on a scale of 0-127. For the scale at the higher octave, the velocity of each successive note has to decrease in order to create the effect of fading out. The velocity used was 110 to 30, decreasing linearly. For the scale at the lower octave, the opposite needs to happen to allow for a smooth introduction of the lower notes. The velocities used are 30 to 110, increasing linearly. For the middle octave scales, the velocity stayed constant for all the notes at 110.

3.2.7 Tritone Paradox in GarageBand

Four sets of tri-tones were made to demonstrate the tritone paradox. Each set contains two sounds that are three tones (or six semitones) apart. The first sound was created by overlapping five of the same notes at different octaves and the second sound was created by overlapping four of the same notes at different octaves. The notes of the second sound will be in between the notes of the first sound, thus creating the ambiguity of an ascend or descend in pitch. The software instrument used was the Classic Electric Piano. The tempo was set to 150 BPM. The music sheet to create the Tritone paradox is shown below in Figure 10.

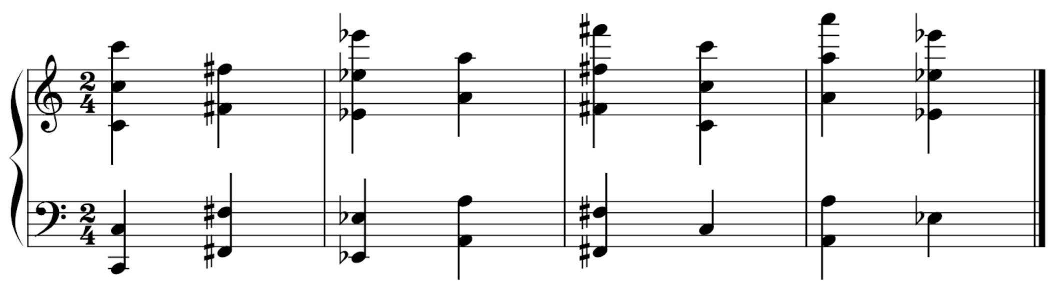

Figure 10: Music sheet to create the Tritone paradox involving 4 sets of tri-tones. The notes from the second sound of each set of tri-tone are in between the notes from the first sound.

3.2.8 Timbre Illusion in GarageBand

GarageBand has many different timbres to choose from which made it the best choice to create the timbre illusion. Four instruments were needed for this demonstration. The two that are close in timbre: "Roots Rocks" and "Classic Clean"; and the two that are very different in timbre: "Hard Rock" and "Acoustic Guitar". The tempo was set to 90 BPM.

The two instruments that are close in timbre play alternating notes (in gray) of the three-tone ascending pitch line below. The same was repeated with the instruments that are different in timbre. The music sheet to create the Timbre illusion is shown below in Figure 11.

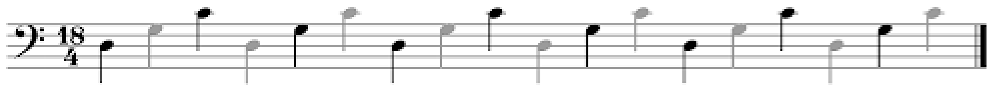

Figure 11: Music sheet to create the Timbre illusion which marks the three-tone ascending pitch lines the two instruments play. One of the instruments plays the black notes while the other plays the grey notes.

3.2.9 Galloping Rhythm in GarageBand

The software instrument used was the Classic Electric Piano. The tempo was set to 160 BPM and the length of each note was 0.0.1.0. The first part of the demonstration is made by repeating sets of tones that are less than three semitones apart to exhibit the galloping rhythm. The music sheet to create the Galloping Rhythm illusion is shown below in Figure 12.

Figure 12: Music sheet to create the Galloping Rhythm illusion. This melody sounds like a galloping rhythm when played at a high tempo.

To show that this phenomenon only works when the notes are less than three semitones apart, the middle note of the three-notes pattern was changed to a decreasing scale. The music sheet to demonstrate when Galloping rhythm can be heard is shown below in Figure 13.

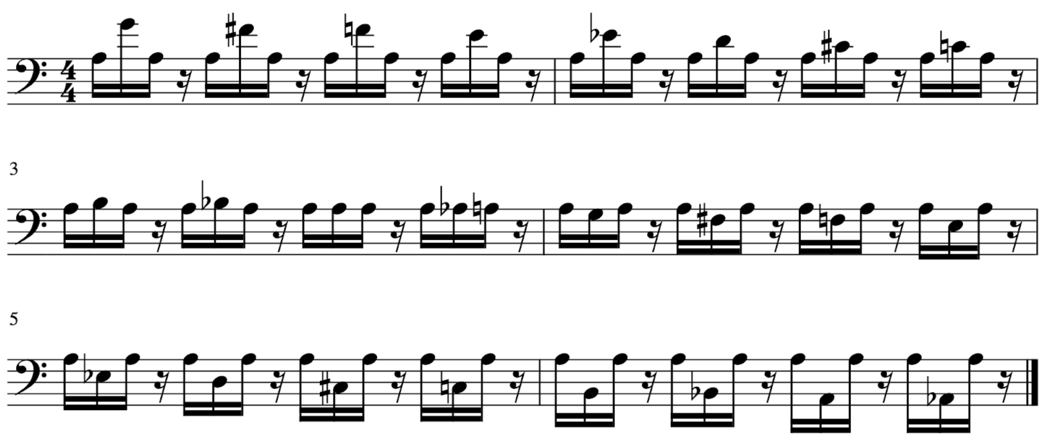

Figure 13: Music sheet to demonstrate when Galloping rhythm works. A melody that alternates between a note of constant pitch and a note that is decreasing in pitch. The galloping rhythm will only be heard in the middle of this melody, when the notes are less than three semitones apart.

3.2.10 Timing and Sequence in GarageBand

The software instrument used was the Classic Electric Piano. The tempo was set to 160 BPM and the length of each note was 0.0.1.0. The first part was created by playing four repeated patterns with no pauses in between. The music sheet for the first part of the Timing and Sequence demonstration is shown below in Figure 14.

Figure 14: Music sheet for the first part of the Timing and Sequence demonstration. Here are four repeated patterns with no pauses.

The second part was created by inserting a pause between each repeated pattern to emphasise the structure of the pattern. The music sheet for the second part of the Timing and Sequence demonstration is shown below in Figure 15.

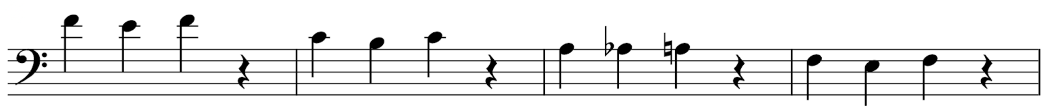

Figure 15: Music sheet for the second part of the Timing and Sequence demonstration. Four repeated patterns with pauses in between each set which emphasises the repeated pattern.

The final part was created by inserting pauses at random locations to break up the expression of repeated patterns. The music sheet for the third part of the Timing and Sequence demonstration is shown below in Figure 16.

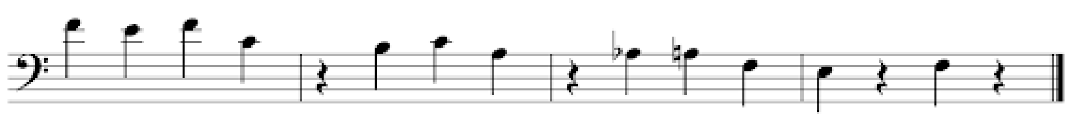

Figure 16: Music sheet for the third part of the Timing and Sequence demonstration. Four repeated patterns with pauses inserted at random locations to break up the repeated pattern.

3.2.11 Scale Illusion in GarageBand

The software instrument used was the Classic Electric Piano. The tempo was set to 180 BPM. Two Classic Electric Piano was needed to play two different melodies. One of the pianos was panned to the right ear (+63) while the other was panned to the left ear (-63). Panning the melodies will play one of the melodies to the right ear and the other to the left ear. The music sheet for the Scale Illusion is shown below in Figure 17.

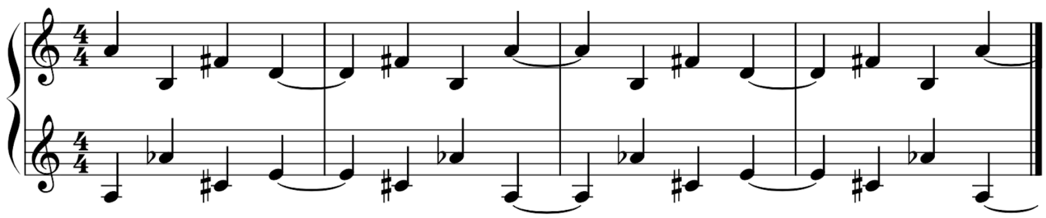

Figure 17: Music sheet for the Scale Illusion. The top melody will be played to the right ear while the bottom melody will be played to the left ear.

3.2.12 Mysterious Melody in Sibelius

A section from a well known piano piece, "The Entertainer", was extracted and used as the original melody to create the illusion. The Mysterious Melody was created by shifting each note up one octave, down one octave, or stays at the original octave, this process keeps the sequence of note names the same (C-D-E remains C-D-E) but scatters the notes among 3 octaves. The software instrument used was the classical piano. The tempo was set to 100 BPM. The music sheet to visualise the Mysterious Melody is shown below in Figure 18.

Figure 18: Music sheet to visualise the Mysterious Melody. The melody at the top is a section from "The Entertainer" and it represents the original melody. The melody at the bottom is the altered melody; blue notes indicate notes shifted up one octave, red notes indicate notes shifted down one octave and black notes indicate non-shifted notes.

3.2.13 Interleaved Melody in Sibelius

Sections from two well known melodies, "Twinkle, Twinkle, Little Star" and "Yankee Doodle", were extracted to form the Interleaved Melody. The first illusion was created by oscillating each consecutive note from one melody to the other melody. The second illusion allows listeners to hear two interleaved melodies apart from one another, this was done by shifting one of the melodies up one octave. The software instrument used was the classical piano. The tempo was set to 400 BPM. The music sheet to visualise the Interleaved Melody is shown below in Figure 19.

Figure 19: Music sheet to visualise the Interleaved Melody. Black notes indicate "Twinkle, Twinkle, Little Star", red notes indicate "Yankee Doodle". Top section contains the two melodies in the same octave. Bottom section contains the two melodies in different octaves.

3.3 User Interface

A website was chosen as the UI due to its ease of accessibility across multiple devices. The website features a user survey form to collect the user's background information which may influence how the user perceives an illusion. For illusions that prompt different perceptions in different individuals such as the Octave Illusion, Mysterious Melody, Tritone Paradox and Interleaved Melodies, there are polls that users can answer, and statistics for them to view how their perceptions of the illusions compare to that of others in the form of pie charts.

To ensure that the website is built efficiently and in an organised manner, GitHub, is used to ease collaboration. Each member is able to make their own changes to the website, which can then be merged together. With Github, all versions of the website can be tracked easily so that older versions can be restored if any changes are undesirable. This makes sure that all progress is backed up properly for the entire development process.

The system architecture of the website can be split into two parts: the front-end and the back-end. The user interacts with the front-end which is the UI. On the other hand, the back-end comprises the database which stores the user's background information and responses to the poll.

Preliminary designs of the website were done in Microsoft PowerPoint before building the front end in HTML5, Cascaded Style Sheets (CSS) and JavaScript. HTML5 was used to structure the layout of the web pages, CSS was used to design the pages, and JavaScript for functionality. To represent each auditory illusion on the website visually, icons designed using a combination of PowerPoint, Adobe Illustrator and Photoshop were used. Additionally, images are also used to give the website a more professional look. All images used are authorised and licensed by Shutterstock.

In terms of the back end, PHP was used to connect the website to the PostgreSQL database. When the user fills in the poll, their response is sent to the database as an integer that corresponds to the choice number. Once the user submits their response, PHP queries all stored responses from the databases and passes it into the Google Charts API in order to generate the pie chart. The code for the website can be found on the Github repository named NeuSense (https://github.com/yv17/NeuSense).

4 Result

The website consists of four distinct pages: Landing page, User Survey form, Overview page, and the Illusion pages. When users visit the website, the first page shown is the Landing page. Landing page is split into three sections. The first section is shown below in Figure 20.

Figure 20: The first section of Landing Page

Scrolling down the Landing Page will go to the next section of the page, which contains a brief introduction to auditory illusions shown in Figure 21.

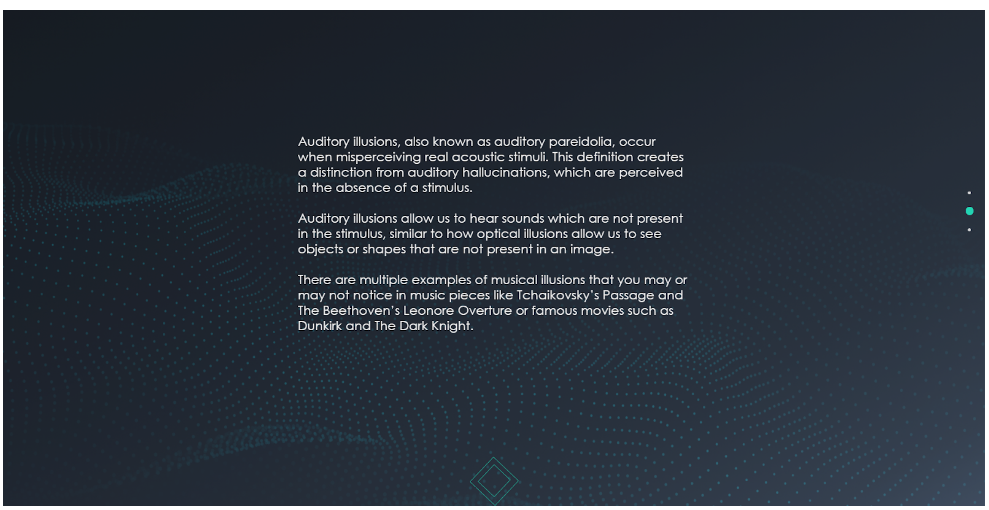

Figure 21: The second section of Landing page

In the last section of the Landing page shown in Figure 22, the factors that may influence one's perception of illusions are explained to the users so that they understand why a survey is necessary. To start the survey, users can click on the button at the bottom of the page.

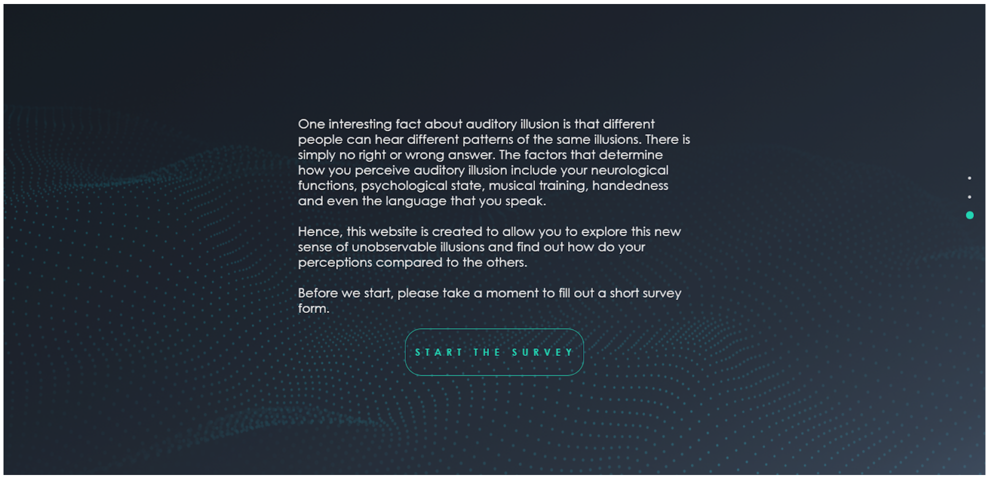

Figure 22: The third section of Landing page

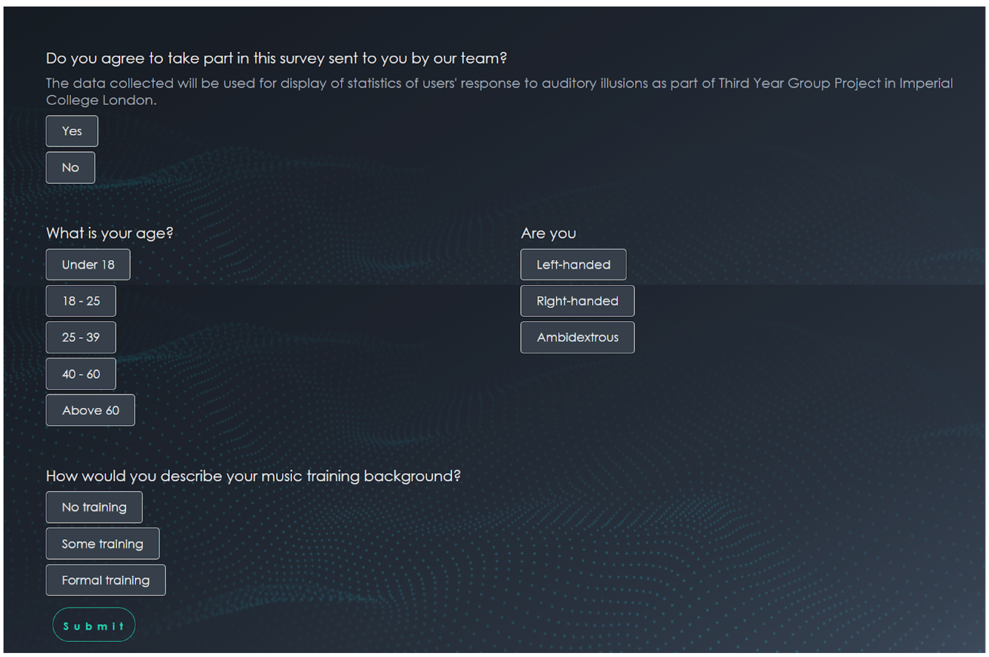

Figure 23: User Survey form

Upon completion of the survey, users will be directed to the Overview page shown below in Figure 24. This page displays a table of auditory illusions with their respective icons. Each icon is a link to the description page of that illusion, which is the Illusion page. There are currently a total of 11 auditory illusions on the Overview page.

Figure 24: Overview page

The Illusion page shown below in Figure 25 gives a sample of the text for Octave Illusion. The complete version of the text can be found in Appendix I. Additionally, the page has audio control to play the illusion. The Home button on the navigation bar allows users to go back to the Overview page, whereas the List button contains a drop-down menu of all the illusions. Users can use either of the buttons to navigate between Illusion pages.

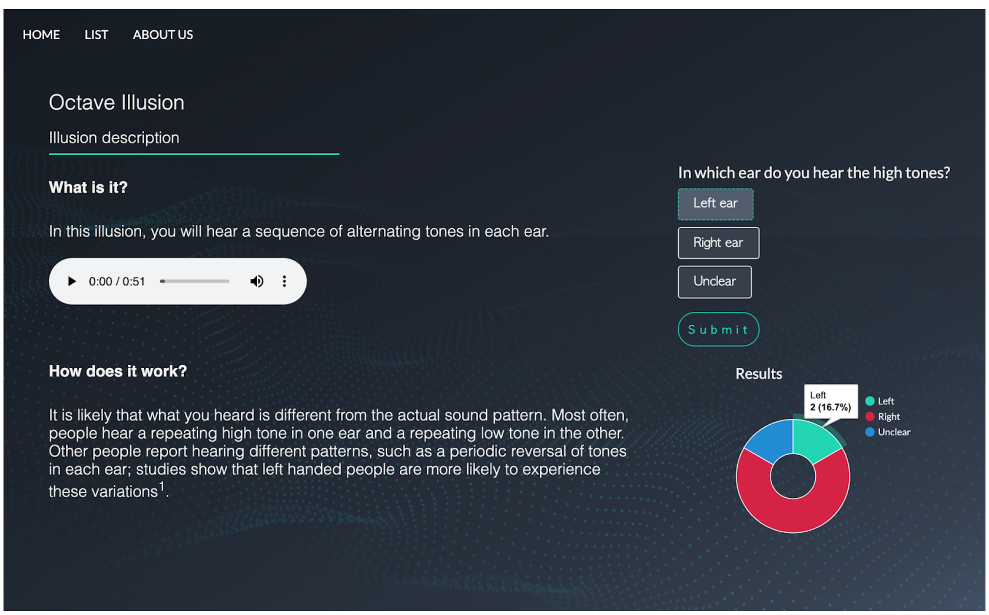

Figure 25: The illusion page.

On the right hand side of the Illusion page, users can also fill in a poll. The response is sent to a database, and a pie chart is generated based on all the responses stored in the database, which can be seen in Figure 26 below.

	id [PK] bigint	mm integer	oi integer	im integer	tp1 integer	tp2 integer	tp3 integer
1	5	3	2	0	0	0	1
2	6	1	1	3	1	0	1
3	7	0	1	2	1	0	1
4	8	3	1	2	0	1	0
5	10	1	1	3	1	1	0
6	9	0	1	0	1	0	1
7	11	1	1	2	1	0	0
8	12	1	2	1	0	0	0
9	1	0	0	1	0	1	1
10	2	2	1	3	0	0	0
11	3	2	1	0	0	0	0

Figure 26: Database containing poll responses. The column names correspond to the user ID (id), and the different illusions such as Mysterious Melody (mm), Octave Illusion (oi), Interleaved Melodies (im) and Tritone Paradox (tp). The numbers correspond to the choice number in the poll.

5 Discussion

5.1 Current Achievements

The illusions were developed effectively using MATLAB, GarageBand and Sibelius. Tests on people, both in and outside the group, indicated that the illusions produced their desired effects.

The UI has a simple and intuitive layout which is easy for users to navigate between the various sections. It has a successfully integrated survey form and the ability to graphically show users the poll responses. This improves user interaction and experience, and also has the potential to collect data for future research projects.

With regards to the survey questions, they will collect data about user's age, musical training and handedness. Handedness is particularly pertinent to illusory perception, Deutsch showed that right handers perceive both the octave and scale illusion differently to left handers [16][17]. Musical training can improve people's ability to distinguish between pitch, timbre and general pattern recognition. It will be interesting to see if these factors affect how users perceive the illusions on our UI.

The review of literature revealed that auditory illusions are a powerful tool to research the human auditory system. Details of the research are included for curious readers and hopefully will engage people. There were some surprising and intriguing results such as research into Autism Spectrum Disorder and even medical alarm design [18][19]. The simple writing style is appropriate for the majority of people using the UI, even if they do not have any previous background in auditory illusions.

5.2 Limitations and Further Improvements

Lack of time was the biggest limitation to the project and there are improvements to undertake in the future. With regards to auditory illusion development, feedback on illusory perception will be sought from a large number of people. It was difficult to analyse results for the illusory perception because there was very little data. Feedback and data would help to refine the illusions and identify any relationships between listener characteristics and perception. Additionally, it should be possible to erase a glitch sound that is present after each loop in the continuous Shepard's tone.

To improve the UI layout in the future, initially, details of further research could be hidden and a 'read more' button could be included that would reveal this section. This would make the layout simpler and easier to read. Moreover, it would be helpful to seek feedback on aspects of the UI from more people outside the group and as aforementioned, to collect more data on user perception of the illusions. These statistics would be showcased on the illusions page to improve user interaction.

Concerning the survey questions, it would be useful to collect user data about their linguistic background. A number of papers have linked this with affecting perception of the tritone paradox [20][21]. Additionally, it has been linked with absolute pitch, the remarkable ability to musically identify a pure tone [22]. Multiple questions are required to determine linguistic background, which made it difficult to implement in the survey. In the future, the project will seek a simple way to collect this data.

A large difficulty with research was that there are different terms for the same illusion. For example, interleaved melodies are referred to as melodic fission and DPOAEs are referred to as combination tones in clinical and psychoacoustic fields respectively. Searching different terms for the same illusion unearthed different research papers and made it difficult to unite the research. Perhaps, this UI can help to connect the myriad research in a single interface.

In addition, some of the figures included in the research write ups are taken from other sources and referenced from other research papers. Before publication, these will be reevaluated and replaced by figures created internally by our group. The new figures will be tailored specifically for this UI so they will convey information more effectively and fit aesthetically with the background.

5.3 Future Plans

In the future, more illusions will be added to the UI. These include binaural beats and phantom words. Furthermore, it could be possible to integrate a Virtual Reality (VR) experience to augment some of the illusions. Furthermore, it could be possible to integrate a Virtual Reality experience to augment some of the illusions. These could include a visual simulation of falling with the descending Shepard's tone or a visual representation of tones with the DPOAEs. Perhaps most importantly, more data will be collected and analysed on each illusion.

6 Conclusion

It is important to capture people's interest in order to drive further research into auditory illusions. The field has proven to be important in entertainment; the illusions themselves are fascinating and included in a number of articles, blogs and websites. Perhaps most importantly, auditory illusions offer a unique insight into the working of the human auditory system, which could potentially help to produce better speech recognition systems, cochlear implants and ability to accurately test newborn baby's hearing. Through this project, a variety of auditory illusions were successfully created with collated research on each one. These were integrated on a user-friendly UI. The aim to create a UI for public outreach was successfully met. This project's UI will help to generate interest and hopefully, drive further research in the field, which is paramount to continue improving.

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Appendix

A Project Management

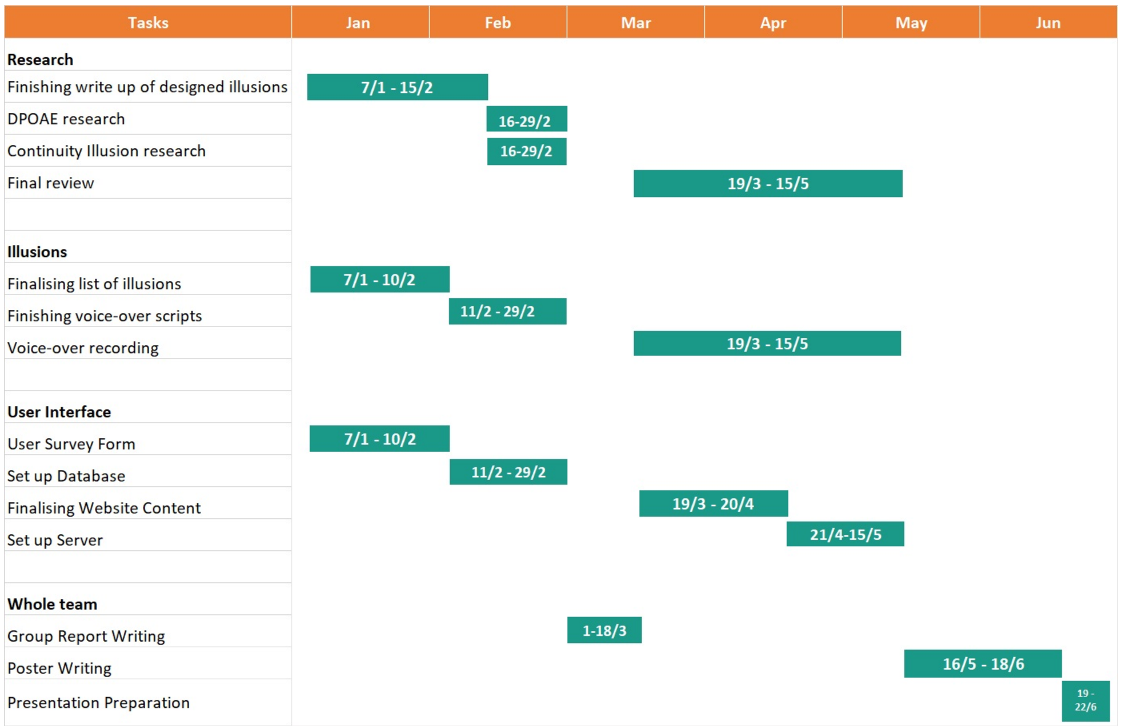


Figure 27: Gantt Chart, showing the current stage of the project

The team consisted of 7 students under Dr Tobias Reichenbach as supervisor. The Gantt Chart in Figure 27 allows each sub-group to match their progress to the chart, which ensures that the group is working efficiently. Weekly meetings were held to evaluate and discuss the progress of the project. Every team member was involved in the initial brainstorming and background research. Depending on individual strengths and interests, the groups are divided into three sub-groups.

Research
Sam Turner
Beth Maughan

Illusion Generation
Sabrina Lim
Techawin Manoonporn

UI
Huang Yilin
Joshua Sia
Yi Teng Voon

B Musical Terms

Terms	**Explanations**
Pure tone	A sound with a single frequency.
Octave	The interval of one musical pitch and another with double its frequency. For instance, in the Octave Illusion, the notes that are played were A3 (220Hz) and A4 (440Hz) and they are described to be one octave apart.
Harmonics	As opposed to a pure tone with one single frequency, most sounds have a fundamental frequency superposed by *harmonic* frequencies which makes the sound complex and unique.
Timbre	A quality or texture of sound. *Timbre* is what allows a piano and a guitar playing the same note to sound distinct.
Semitone	A *semitone* is the smallest interval between two notes in Western tonal music. There are 12 semitones in an octave.
Tritone	A *tritone* is a pair of tones that are 6 semitones apart.
Panning	*Panning* describes the amplitude of sound that is played to the left or right channels of the output (e.g. headphones, speaker)
Velocity	In some audio creation software such as GarageBand, *velocity* is correlated to amplitude and it is a measure of how forcefully a piano key is struck.

C Ethics

Some of the ethical considerations raised during project development and brainstorming included:

Copyright issues
To make sure all the content on the UI does not infringe on the copyright of others, references were carefully made. The images used on the UI are also appropriately licensed by Shutterstock.

Data Protection
The user's consent to submit personal information will be asked for at the start of the survey form. For users who do not wish to give their personal information, the survey form will be voided. This is done to ensure that the UI is in compliance with General Data Protection Regulation (GDPR).

D MATLAB Code For Pure Tone Generation

```
%% Pure tone illusion

% Parameters
fs = 44100; % sampling frequency
amp = 2;  % amplitude of the sound
num = 11; %number of tones generated
cons = nthroot(2,12);
sec = 2; % sec is number of seconds you want to play for each tone
t = 0:1/fs:sec;

% Pure tones
feq_A3 = (cons)^(37-49)*440;
feq_A3_up = (cons)^(38-49)*440;
feq_B3 = (cons)^(39-49)*440;
feq_C3 = (cons)^(40-49)*440;
feq_C3_up = (cons)^(41-49)*440;
feq_D3 = (cons)^(42-49)*440;
feq_D3_up = (cons)^(43-49)*440;
feq_E3 = (cons)^(44-49)*440;
feq_F3 = (cons)^(45-49)*440;
feq_F3_up = (cons)^(46-49)*440;
feq_G3 = (cons)^(47-49)*440;
feq_G3_up = (cons)^(48-49)*440;
feq_A4 = (cons)^(49-49)*440;
feq_A4_up = (cons)^(50-49)*440;
feq_B4 = (cons)^(51-49)*440;
feq_C4 = (cons)^(52-49)*440;
A3=amp*sin(2*pi*feq_A3*t);
A3_up = amp*sin(2*pi*feq_A3_up*t);
B3 = amp*sin(2*pi*feq_B3*t);
C3 = amp*sin(2*pi*feq_C3*t);
C3_up = amp*sin(2*pi*feq_C3_up*t);
D3 = amp*sin(2*pi*feq_D3*t);
D3_up = amp*sin(2*pi*feq_D3_up*t);
E3 = amp*sin(2*pi*feq_E3*t);
F3 = amp*sin(2*pi*feq_F3*t);
F3_up = amp*sin(2*pi*feq_F3_up*t);
G3 = amp*sin(2*pi*feq_G3*t);
G3_up = amp*sin(2*pi*feq_G3_up*t);
A4 = amp*sin(2*pi*feq_A4*t);
A4_up = amp*sin(2*pi*feq_A4_up*t);
B4 = amp*sin(2*pi*feq_B4*t);
C4 = amp*sin(2*pi*feq_C3*t);

[row, col] = size(t); % obtain the total number of elements in t; row always equals to 1 ...
    in this case.

%% Scale illusion
silent = zeros(1,col*num); %used to silence one channel
% By convention, left channel is first column, right channel is second column
right = [C4 D3 A4 F3 F3 A4 D3 C4];
left = [C3 B4 E3 G3 G3 E3 B4 C3];
right = [right right right silent silent silent right right right right right right];
```

```
left = [left left left left left left silent silent silent left left left]; % repeat 3 times
scale_illusion = [left(:),right(:)];
% Generate the sound
sound(scale_illusion,fs);
% Write the sound to a wav file
audiowrite('scale_illusion.wav',scale_illusion,fs)
```

E MATLAB Code For DPOAE

```
%% DPOAE

% Parameters
x = 1.3; % a factor to make changing initial frequency easier
fs = 10000; % sampling frequency
Ts = 1/fs; % Smapling period
t = 0 : Ts : 1.5; % period for the first part of demonstration
f = 350;
f1 = 1000*x; % frequency of the first tone
f2 = 1200*x; % frequency of the second tone initially
f4 = f2 + 2*f ; % frequency of the end of second tone

% Producing the sine waves, 0.5 factor was used because sound will be
% clipped off if superimposed amplitude is higher than 1
x = 0.5*sin(2*pi*f1*t);
y = 0.5*sin(2*pi*f2*t);
sum = x + y ; % superimposing the two sounds together
pause(1); % pause used to "warm up" MATLAB so that the next sound will sound smoothly

t = 0 : Ts :2.5; % period for the second part of demonstration
x = 0.5*sin(2*pi*f1*t);

f_2 = 0.5*chirp(t,f2,4,f4,'linear'); % function to increase the second tone linearly

sum_2 = x + f_2 ; % superimposing the constant first tone and the increasing second tone

mCombined = [sum sum_2]; % combining the first and second parts together so they can be ...
    played continuously

sound(mCombined,fs) % playing the created sound

audiowrite('DPOAE.wav',mCombined,fs); % writing the sound to a sound file that can be ...
    played elsewhere
```

F MATLAB Code For Continuity Illusion

```
%% Continuity Illusion

% Parameters
fs = 10000; % the sampling frequency used
Ts = 1/fs; % Smapling period
t = 0 : Ts : 1; % period for the long tone
f1 = 1000; %frequency of the long tone

%f2 to f4 are the frequencies included in the complex tone
f2 = 1200;
f3 = 1350;
f4 = 980;
f5 = 800;

% producing the long pure tone
x = 0.08*sin(2*pi*f1*t);

t = 0 : Ts : 0.2; %period of the short complex tone
y_2 = 0.1*sin(2*pi*f2*t);
y_3 = 0.1*sin(2*pi*f3*t);
y_4 = 0.1*sin(2*pi*f4*t);
y_5 = 0.1*sin(2*pi*f5*t);

%superimposing multiple sine waves to ceate a complex tone
z = y_2 + y_3 + y_4 + y_5;

% there are to create pauses in the sound file
a = zeros(1,length(y_2)); % 0.2s puase
b = zeros(1,10005); % 1s pause
c = zeros(1,25013); %2.5s pause

pause(1); % pause used to "warm up" MATLAB so that the next sound will sound smoothly

mCombined = [x a x b z c x z x]; % combining the first and second parts together so they ...
    can be played continuously

audiowrite('Continuity.wav',mCombined,fs); % writing the sound to a sound file that can be ...
    played elsewhere
```

G MATLAB Code For Gaussian Envelope

```
%% Gaussian envelope

% Parameters
fs = 44100; %sampling frequency
Ts = 1/fs;
t = 0 : Ts : 1;
f = 0:1:8000;
s = 500; %standard deviation
m = 2500; %mean

norm = (1/s*sqrt(2*pi))*exp(-(f-m).^2/(2*s^2)); %normal distribution function
norm_norm = norm./max(norm)*1/10; %set the amplitude to 1/10 of the original normal ...
    distribution
figure(1);
plot(f,norm_norm);
title("Normal Distribution Envelope for Producing Harmonics Sound")
xlabel("Frequency (Hz)")
ylabel("Amplitude (AU)")
ylim([0 0.1]);
```

H MATLAB Code For Shepard-Risset Glissando

```
%% Shepard-Risset Glissando

% Parameters
fs=44100;
t0 = 0; % start from zero
t1 = 56; % 7 harmonics, 8 sec for each harmonics, 56sec in total
t = t0:1/fs:t1; [¬,tmax]=size(t);
f = 0:1:tmax-1;
m = tmax/2.5; s=400000;

norm = (1/s*sqrt(2*pi))*exp(-(f-m).^2/(2*s^2)); % create an overall envelope
norm_norm = norm./max(norm); % normalize the envelope

figure; plot(f,norm_norm) % plot the envelope
xlabel("Frequency (Hz)"); ylabel("Amplitude");
title("Gaussian Envelope Used For Producing Shepherd's Tone");

sum=zeros(1,352801); % used to store all the harmonics

for i=1:7
    up_swip = chirp(0:1/fs:8,100*(2^(i-1)),8,200*(2^(i-1)),'logarithmic');
    if i==1
        %extract the envelope for the first harmonic
       envelope = norm_norm(1:1:8*fs+1);
    else
        %extract envelopes for other harmonics
       envelope = norm_norm((i-1)*8*fs:1:i*8*fs);

    end
    up_swip = up_swip.*envelope; %a pply the envelope to the harmonics
    sum = sum+up_swip; % add up harmonics
end
total=[sum sum sum sum sum sum];
% sound(total,fs)
mx=max(total);
total=0.5*total/mx; %normalization

%display the spectrum
figure;
pspectrum(sum,fs,'spectrogram','TimeResolution',0.1,'OverlapPercent',99,'Leakage',0.85)
audiowrite('shepherd_tone.wav',total,fs); %generate the .wav file
```

I Example of Text on the Illusion page

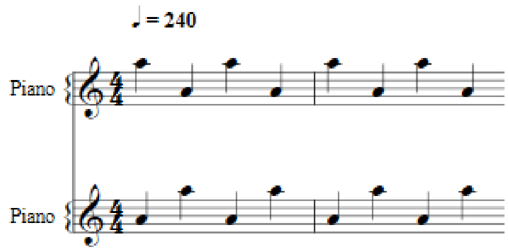
Octave Illusion

What is this?

In this illusion, you will hear a sequence of alternating tones in each ear. Try to determine the pattern.

How does it happen?

It is likely that what you heard is in fact different from the actual sound pattern. Most often, people hear a repeating high tone in one ear and a repeating low tone in the other. Other people report hearing different patterns, such as a periodic reversal of tones in each ear; studies show that left handed people are more likely to experience these variations [1]. The real sound pattern is presented below along with the most common perception.



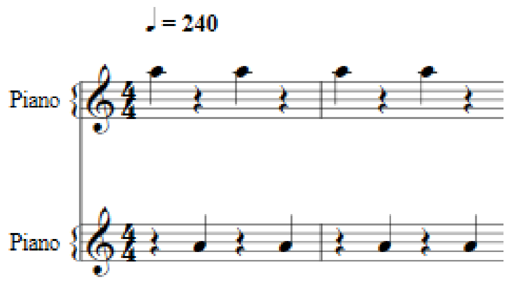


Figure 1. The above musical score illustrates that alternating pattern presented to each ear. The score below shows that the brain orders this pattern and you may perceive a high tone in one ear and a low tone in the other.

One hypothesis is that the illusion utilises the 'what' and 'where' pathways in the brain. The dominant ear determines the pitch of the perceived tone (for example, a high tone heard in the right ear) - the 'what' pathway. The ear that receives the high tone determines the location of the sound (in this example the tone would be localised to the right) - the 'where' pathway [2].

Is this used anywhere?

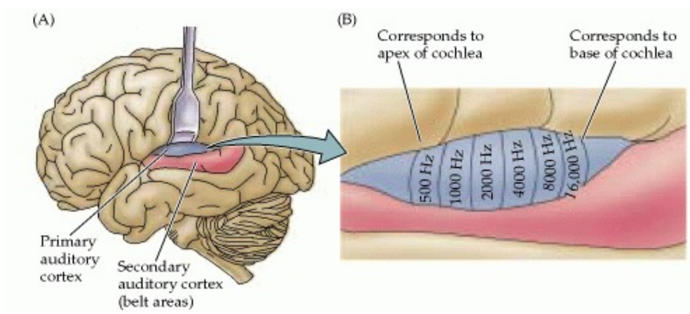
The octave illusion gave rise to further studies on the 'what' and 'where' pathways. Functional MRI studies have sought to determine the specific location of these pathways and subsequently, better understand neural sound processing.

What is in the detailed research?

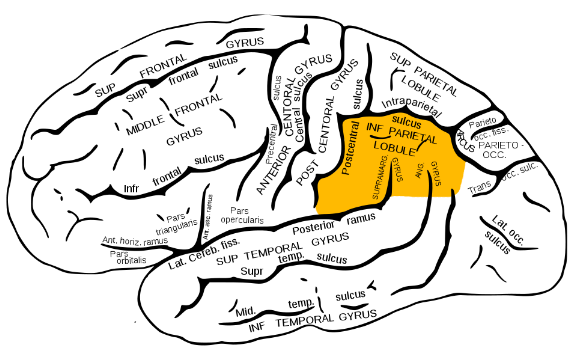
A 2018 study in Tokyo looked at identifying structures in the brain that are responsible for the illusory perception of the octave illusion. They tested 43 individuals and split them into two groups; those that reported hearing the illusory effect and those that did not perceive the illusion but heard the actual pattern of notes. The research team then conducted fMRI studies on each individual and played them the octave illusion whilst in the scanner.

The premise of the study was that by comparing the two groups they could identify neural structures that were involved in perceiving the illusory effect.

The research team identified several structures responsible for the octave illusion. Firstly, they found that the auditory cortex (area A1) was activated in both groups, which makes sense. A1 is most likely responsible for detecting changes in pitch and this has been established in previous studies.



The research team suggested that the aforementioned ‘what’ pathway lies in the anterior auditory cortex and comprises the planum polare. Activation of the planum polare was significantly increased in the illusory group and they suggest it is crucial for pitch determination. The team also suggested the ‘where’ pathway lies in the posterior auditory cortex and includes the inferior parietal lobule.



Additionally, they looked at activation differences in the right premotor cortex (PMC). This area is involved in processing sensory information and planning an appropriate motor response. It had previously been shown to activate in response to rhythmic auditory stimuli. The results of this study show that activation in the right PMC was greater in the non- illusory group. The research team suggest that since this group does not perceive the illusion, they hear a rhythmic octave jump in each ear and this activates the PMC. Possibly, the individual threshold for perceiving rhythm affects our perception of the octave illusion [3].

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