IS THERE A RELATIONSHIP BETWEEN PITCH PERCEPTION AND INDIVIDUAL PREFERENCE OF CONCERT HALL REVERBERATION TIME?

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1 INTRODUCTION

Musical notes are complex tones that are made up of multiple frequencies including a fundamental frequency and multiple harmonic frequencies. The fundamental frequency is the lowest frequency in a complex tone and the harmonic frequencies are the frequencies that are higher than the fundamental. The pitch of a complex tone is usually perceived from the frequencies of the lower harmonic components, but most often the pitch is perceived almost entirely from the fundamental frequency. As such, it is expected that the pitch of a complex tone without a fundamental frequency would be perceived based on the lowest harmonic frequencies present in the tone. However, this is not always the case, with some people perceiving pitch based on the harmonics that are present in the complex tone and some perceiving pitch based on the missing fundamental. In the past, it has been suggested that pitch perception is based on the periodicity of the tone rather than the location of the excitement on the basilar membrane[1].

Reverberation time is a common indicator of quality of concert halls and generally has a great effect on individual preference. Previous research of individual preference of various concert hall preference parameters, including reverberation time, suggests that there are two distinct preference groups: those that prefer a shorter reverberation time and those that prefer a longer reverberation time[2]. As there are two preference groups for concert hall reverberation time and two listener groups for pitch perception, the aim of this research is to investigate if there is a relationship between these groups.

Previous work suggests that musical training can influence an individual's perception of pitch, with jazz musicians being more likely to perceive pitch of complex tones based on the harmonic frequencies than classical musicians[3]. This conclusion suggests that through musical training, an individual's hearing can be trained to perceive pitch the way that would most benefit their musicianship. However, these individuals were not tested before learning their instruments, so while it seems very likely, considering the trends amongst musicians of the same instrument type, it is not known for certain that receiving musical training changes perception of pitch.

To investigate differences in perception in an experiment, individuals are presented with two complex tones, both with the fundamental frequency absent from the tone, and are asked to describe if they heard the pitch increase or decrease across the two tones. This occurs, for example, when the frequency of the fundamental decreases and the frequencies of the harmonics increase. Participants then report if they heard the pitch increase or decrease which indicates clearly if they perceived pitch based on the fundamental frequency that is not present in the tones or the harmonic frequencies that are present. This is an effective method for investigating perception

of complex tones, as shown in past work[3]. This method was used as a basis for the research described within this paper.

From looking at previous work, investigating a relationship between pitch perception and reverberation time preference is a novel area of research. The research that was undertaken for this paper will offer further insight into reverberation time preference and its relationship with pitch perception.

2 METHOD

The online experiment was split into two parts, the first was a pitch perception test and the second was a preference test. The pitch perception test consisted of pairs of complex tones with missing fundamental frequencies, the second part was pairs of different reverberation times applied to two different musical pieces. The method for creating the stimuli and the listening test itself is detailed below.

2.1 Pitch Perception

A total of 20 complex pitch tones with missing fundamental frequencies were generated in MATLAB and put into pairs. Each tone in the pairs had the same frequency for the highest present harmonic, however, the lower harmonics and fundamental frequency of each tone were different. Either increasing or decreasing from the first tone in the pair. The order of whether the fundamental frequency increased or decreased was random throughout the test, this was done to reduce order effect.

There is evidence to suggest that if the differences between frequencies for each tone are too great then it may not be possible to have results that show a mixture of fundamental and harmonic listeners[4]. To ensure that the pairs of tones were able to produce both fundamental and harmonic listener responses, it was important to keep the frequency content of the tones similar. In order to do this, the top present frequency in both tones of the pair was the same, as done in previous research on pitch perception of missing fundamental tones[3].

In the experiment, there were 10 unique pairs of tones, three were randomly selected to be repeated once and one pair was randomly selected to be repeated twice. It was randomised if these repeated pairs played the tones in the same order as the first time the pair was played or if the order was reversed. There were 15 pairs of test tones in total, an odd number of pairs ensures a definite result from each participant.

The online listening experiment was carried out by creating a Google Form that could then be shared via a link. Google Form does not allow audio files to be embedded, so it was necessary that the pairs of tones were put into videos that could be embedded into the form. This was done by uploading the videos to YouTube and then embedding these unlisted YouTube videos into the Google Form. While using videos to play participants the pairs of tones ensured that they listened to the tones in the intended order, it meant that the order of the pairs could not be randomised between participants. The order of the tones and pairs was randomised for the test, however, due to the layout and mechanics of Google Forms, it was not possible to change this order for each participant.

2.2 Reverberation Time Preference

In order to assess individual preference of reverberation time, pairs of a music sample with different reverberation times had to be created. To do this, anechoic recordings of an orchestra had to be obtained so that the stimuli in the experiment were not affected by reverberation of an unknown length that existed when the recordings were done.

Recording of Anechoic Symphony Music[5] was read when researching past work with anechoic recordings of an orchestra. Through liaison with Lokki, it was possible to obtain the recordings that were taken for this paper and use these for the reverberation time preference section of this experiment.

The anechoic orchestral recording wav files were loaded into GarageBand where reverberation could be added digitally. Some of the recordings were quiet and needed gain added to them. This was suitable for two of the three selected music pieces, however the third needed so much gain to be a comfortable volume that there was a substantial amount of noise on the track after the gain was added. It was decided that the noise made the quality of the music poor and could affect the results. Therefore, this piece of music was excluded from the research and only two pieces were used for the experiment.

The selected musical pieces for the experiment were G. Mahler's *Symphony no.1, IV Movement* and L. van Beethoven's *Symphony no.7, I Movement*. 10-15 seconds of each piece were used for the reverberation time preference section of the listening experiment, the length 16 of the sample depended on the phrase length at the point of the piece that was selected. It was important to include a phrase or two at a point in each music piece that was dynamically and musically interesting.

Initially, the intention was to use three different pieces, however due to multiple reasons it was concluded that two different pieces of music would be sufficient for the experiment. The two music pieces that were the most different to each other in terms of dynamic range, tempo and instruments playing the melody were selected. Previous work carried out indicates that the music piece can influence reverberation time preference[6], so it was essential that at least two different music pieces with dissimilar characteristics were used for this experiment. The same reverberation times were applied to both pieces of music, so by comparing a participant's reverberation time preference results for both pieces, it would be possible to see if the music piece impacted preference for the participants of this experiment.

Gain was applied to the selected recordings as they were initially very quiet. The 10-15 second long samples that would be used for the experiment were chosen from the two pieces, and the volume of these were adjusted by three individuals so that they were subjectively the same. This method is not perfect as it was not possible to confirm mathematically if the volume of each sample was in fact the same. It was decided, however, that this method of subjectively setting the gain and using multiple listeners to agree on the perceived volume of the samples was sufficient for this listening experiment. As this is a test on perception and preference, not objective parameters, unnoticeable discrepancies in volume should not impact results.

The reverberation times displayed on the Garageband plugin were verified using MATLAB then applied to the sample that was chosen from each music piece. There were five pairs of reverberation times applied to the samples, the reverberation times were between 1.2 seconds and

4 seconds. The same five pairs of reverberation times were applied to each piece of music. The pairing of the reverberation times was not random as it was important to have two sufficiently different reverberation times per pair for the participant to clearly differentiate them and indicate their preference. The purpose of this preference test was to investigate if individuals prefer longer or shorter reverberation time, so it was important to have reverberation times that were notably longer or shorter than the other in each pair.

When the different reverberation times were applied to both samples, they were made into YouTube videos and embedded in the Google Form in the same way that the pairs for the pitch perception part of the experiment were. Like with the first part of the experiment, the order of the stimuli was randomised at first but could not be randomised for each participant due to the way Google Form works, so each participant was faced with the exact same test. It is not believed that this significantly impacted the results.

2.3 Listening Test

The experiment was made using Google Forms. There are alternative websites such as Go Listen, but Google Forms was decided to be the most suitable for this experiment. It is highly likely that most of the participants would have done a survey using Google Forms before and would be familiar with the platform.

Due to the nature of the research, many responses were needed to get a significant pattern in the results, an online experiment was selected to reach more participants. Online listening experiments have many benefits, the main one being that they can gather a large number of participants as they are not limited to a certain place or an appointment system to do the experiment. An online experiment cannot guarantee repeatability and the research undertaken cannot be overly detailed and complex in the setup, therefore the setup for this experiment was kept simple. The experiment only required a smartphone/tablet/laptop/PC and a pair of headphones or earphones. It is more likely that people will have a good quality pair of earphones/headphones than good quality speakers at home.

Participants were instructed not to adjust the volume of their device during each part of the experiment, however they could adjust it between sections to ensure that the volume remained at a comfortable level. Previous work indicates that perception of missing fundamental tones may change when volume is altered[4]. To not influence the results, it was critical that participants did not adjust the volume of their device during each section of the experiment. While the instructions state this, without being present during the test it is not possible to confirm undeniably that the volume was not adjusted.

The start of the Google Form included some information on the experiment including brief instructions, approximate duration, and where and how the information would be stored. Participants could then give informed consent to take part in the experiment. Participants had to be over 18 years of age and have unimpaired hearing, giving consent also indicated that they understood this and met the requirements. Participants were asked a few questions including their age and if they had received musical training in the past and if so, what instrument and for how long. This additional information was collected to investigate if these factors influence pitch perception and/or reverberation time preference.

For both the pitch perception and reverberation time preference parts of the experiment, participants were forced to decide between two options for each pair of stimuli. Due to the nature of this research, a definitive answer is required and so including an option for participants to select when they are unsure is not helpful to the research. If the participant only notices a slight difference in pitch in the tones or only slightly prefers one reverberation time over another, this is far more useful in analysis than responses of “unsure”. However, this does not mean that all participants will be certain with their responses and so some may not be an accurate representation of what participants experienced. In previous work, some results have been excluded from analysis on the basis that those participants were guessing or were unsure of their response[7]. Despite this, a forced choice test was deemed to be the best method for this research.

3 RESULTS

3.1 Experiment Results

Enclosed in this section of the report are the results of the online listening experiment.

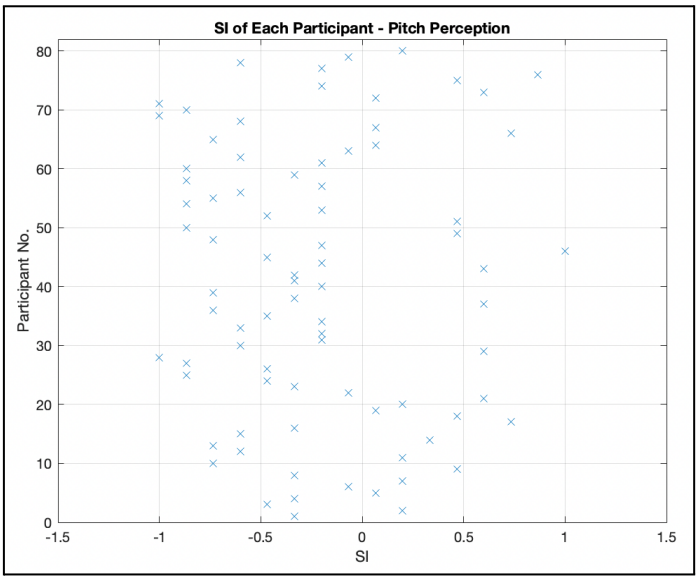

Figure 1 - Plot showing all experiment participants’ pitch perception SI.

Figure 1 is a plot of the Schneider index (SI)[8] of each participant’s pitch perception experiment responses. SI is a way of mathematically analysing the results of a missing fundamental pitch test, by using the following equation:

$$SI = \frac{sp - f0}{sp + f0} \quad (1)$$

Where sp is the total number of spectral responses and f0 is the total number of harmonic responses per participant. Harmonic responses are noted as 1 in the results and fundamental responses are noted as -1 in the results, this results in the SI being between -1 and 1. An SI greater than zero indicates that the participant is a spectral listener, and an SI less than zero indicates that the participant is a fundamental listener.

The plot in Figure 1 shows the SI of all 80 participants' responses to the pitch perception section of the listening experiment. The results indicate that 55 of those 80 are fundamental listeners and 25 of the 80 participants are spectral listeners.

The below figures show the comparison of pitch perception and reverberation time preference results.

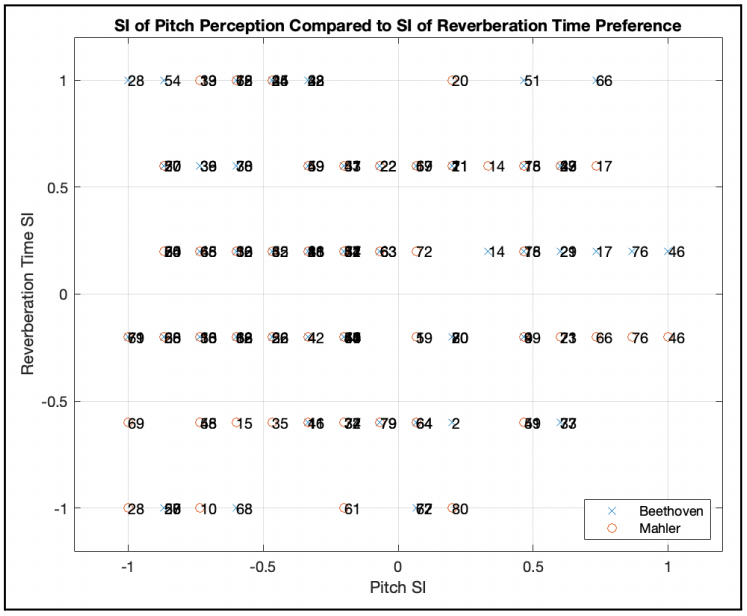

Figure 2 - Plot showing comparison of pitch perception SI and reverberation time preference SI for both music pieces with participants number indicated.

The method for calculating the SI of pitch perception was adapted to calculate the SI of reverberation time preference (SI_{RT}). A preference of longer reverberation time was noted as 1 and a preference of shorter reverberation time was noted as -1. The equation for Schneider index was adapted to the equation shown below:

$$SI_{RT} = \frac{RT_{long} - RT_{short}}{RT_{long} + RT_{short}} \quad (2)$$

Where RT_{long} is the total number of longer reverberation time preference responses and RT_{short} is the total number of shorter reverberation time preference responses per participant for each music piece. The results of the reverberation time SI (SI_{RT}) are to be interpreted similarly to those of the pitch SI results: an SI_{RT} greater than zero indicates that the participant prefers a longer reverberation time, and an SI_{RT} less than zero indicates that the participant prefers a shorter reverberation time.

At a glance it can be concluded that there is no clear indication that pitch perception affects reverberation time preference, at least consistently.

The participant number is plotted beside each participants' response in Figure 2 to make it possible to see if and how a participant's preference changed between music pieces. The above plot

indicates that while many participants' preference remained the same across music stimuli, some participants' preference changed depending on the music piece. Perhaps the most striking result is Participant 28 who has an SI of -1 for pitch perception, meaning they perceived the pitch based off the missing fundamental frequency 100% of the time, and indicated a consistent preference of longer reverberation time for the Beethoven music piece and a consistent preference of shorter reverberation time for the Mahler music piece.

As the plot in Figure 2 is obscured by the participant numbers, Figure 3 below shows the same plot but without participant numbers in order to make general patterns in the data more visible.

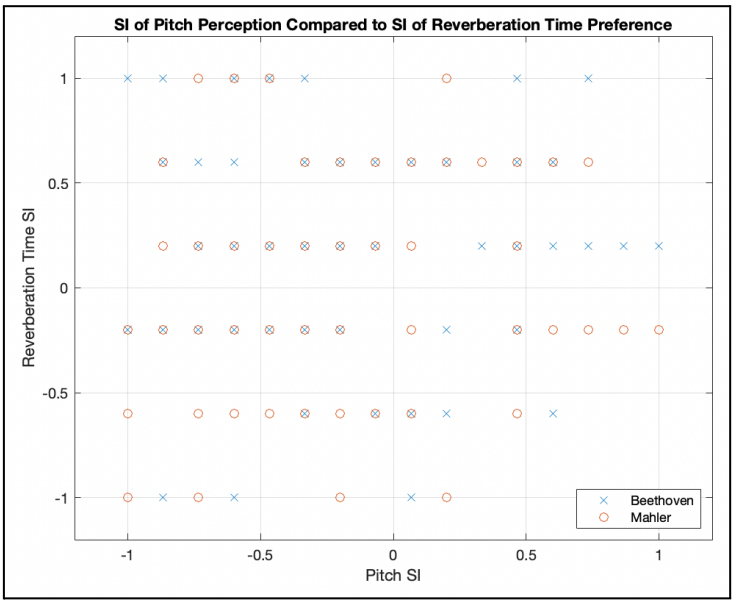

Figure 3 - Plot showing comparison of pitch perception SI and reverberation time preference SI for both music pieces.

The plot in Figure 3 indicates that most participants prefer a longer reverberation time for both music pieces. However, this majority is weaker for the Mahler piece, with 42 participants preferring a longer reverberation time, compared to 46 participants preferring a longer reverberation time for the Beethoven music piece.

Age did not appear to effect pitch perception or reverberation time preference.

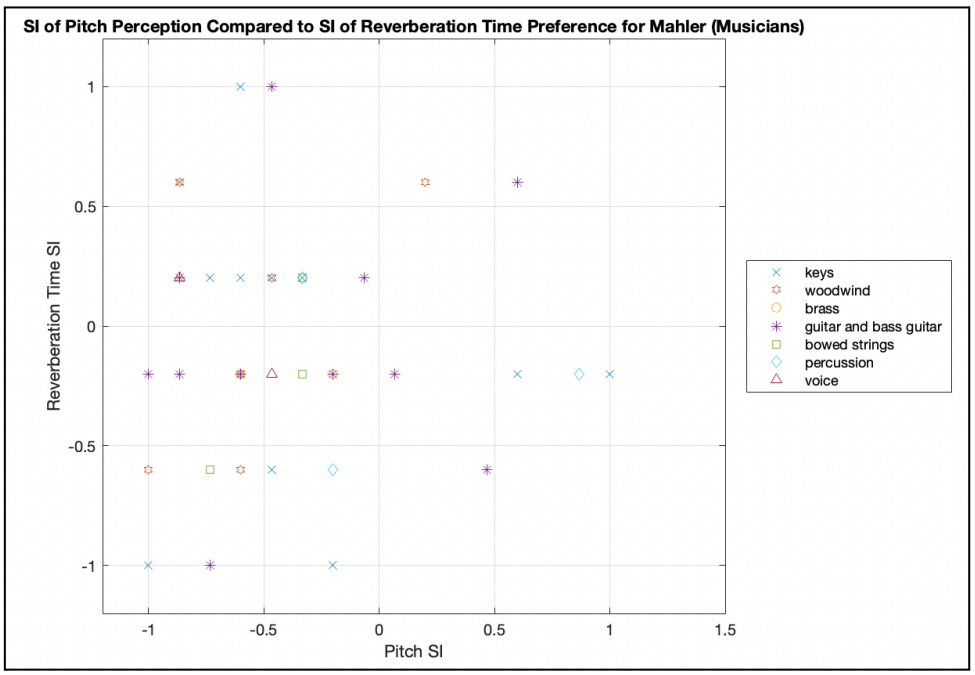

Figure 4 - Plot showing comparison of pitch perception SI and reverberation time preference SI for the Mahler music piece. This plot shows only the musicians' responses.

The plot in Figure 4 shows the relationship between pitch perception and reverberation time preference for all musically trained participants for the Mahler stimulus. The different types of musical instruments are indicated on the plot with different shapes and colours. From this plot it can be concluded that most musician participants prefer a shorter reverberation time for the Mahler music piece, however this does not seem to be related to pitch perception.

The pattern of results in the plot was very similar for the Beethoven stimulus amongst musicians.

3.2 Statistical Analysis

Several two-way ANOVA statistical tests were carried out using MATLAB on the experiment results and nothing was found to be statistically significant. The lowest p-value was for the effect of musical training which had a p-value of 0.23.

A t-test was used to analyse the effect of the two different music pieces on the SI_{RT}, the p-value was calculated to be 0.43 which indicates an insignificant result. According to both the ANOVA and the t-test, music piece did not have a significant effect of the SI_{RT}.

4 DISCUSSION

4.1 Pitch Perception

The results of the pitch perception test, displayed in Figure 1, show that the majority of the participants were fundamental listeners, with 55 participants having an SI between -1 and 0, and 25 having an SI between 0 and 1. The mean average SI across all 80 participants' responses was -0.2, this is the most common SI result across all participants, with 11 participants having an SI of -0.2.

This result is in line with past work that consistently indicates a bias towards fundamental listening across their results[1,3]. The online experiment received 80 responses, which is usually a large enough sample size to render a significant result and patterns in the data.

Overall, three participants had an SI of -1, indicating that they are consistent fundamental listeners. Only one participant had an SI of 1, indicating that they are a consistent spectral listener. All four of these participants are trained musicians with four to 10 years of experience. It is possible that receiving musical training made these participants more aware of pitch differences as no non-musicians had consistent responses for the pitch perception test. The musicians' consistency may indicate that they were certain of their responses, someone that was unsure may have variances in their responses however, using the forced choice test method it is not possible to determine this.

Some individuals' pitch perception changed when they were presented with the same pair of test tones but with the order of complex tones reversed. Tests six and nine in the online experiment were the same pair of tones, but the repeat test presented the pair in reverse order. This repeat of tests caused the most variance in results out of the three repeated pairs. The interval between the missing fundamental frequencies in this pair is 5.4Hz which is the smallest interval out of all pairs of missing fundamental tones in the experiment, the mean average interval between missing fundamentals is 27Hz. With a relatively small interval between the missing fundamental frequencies of the tones, it is understandable that this repeat is where the most variance in results occurred. As there was no option for participants to indicate if they were unsure, it is not possible to know if there was a higher number of uncertain responses for these tests rather than definite changes in perception. It may be beneficial in future work on pitch perception, using an online test, to include a comments box for participants to provide more detail on their response.

It was found, when analysing the data for each test in the experiment, that musicians' responses were less effected by test repeats and inversing the order of the pairs. Where there were changes due to inversing the order of the pair, this was for tests six and nine that were previously discussed. From the data collected by the online experiment, it seems musicians' perception of missing fundamental tones is less influenced by changes in order and repeats of tests than non-musicians'. Previous research undertaken on the perception of missing fundamental complex tones supports this, concluding that musically trained participants' responses are less likely to be influenced by order effect[3], suggesting that this pattern in the results from this experiment is accurate and repeatable.

Some participants recorded in the Google Form that they had received many years of musical training, far beyond learning an instrument in school. One of these was Participant 7 who included in the form that they are a music teacher and have been a flautist for over 34 years and a pianist for over 10 years, playing a handful of other instruments at a basic level due to their career. It would be expected that Participant 7, with over 34 years of experience playing the flute, would be a spectral listener. Participant 7's SI was 0.2, indicating that they are a spectral listener. An SI of 0.2 suggests that their responses varied throughout the experiment, perceiving pitch differently for different pairs of complex tones but with a bias towards spectral listening. Through close analysis of the data, it could be seen that Participant 7 was not influenced at all by order effect and so it can be assumed that the SI result is an accurate representation of their perception of complex pitch.

An ANOVA test was carried out on the results of the pitch perception test. The results of this test indicate that musical training is not statistically significant on pitch perception, with a p-value of 0.23.

While musical training has shown to have some effect on pitch perception results for this research, the trends in the data are weak and cannot give decisive conclusions of the effect of musical training on pitch perception. The order of the tones in each pair and musical training was found to have a p-value of 0.07. This is not statistically significant however with more musically trained participants, a trend could be found and the statistical analyses may find a statistically significant result for this comparison as a p value of 0.07 is close to 0.05. This is possibly due to the number of musicians in the data set, with only 45 musicians participating in the experiment, significant trends may have been more difficult to obtain than if the data set was larger.

4.2 Comparison of Pitch Perception and Reverberation Time Preference

The results of the online listening experiment, shown in Figures 2 and 3, indicate that there is not a relationship between pitch perception of missing fundamental complex tones and preference of concert hall reverberation time.

There are some interesting points in the data, however they do not seem to be the result of pitch perception as a pattern cannot be seen in the results across participants with the same or similar SI for pitch.

Participant 28 has a pitch SI of -1 which indicates that they consistently perceived each pair of complex pitch tones based on the missing fundamental. The results of the reverberation time preference part of the experiment show that Participant 28 consistently preferred a longer reverberation time for the Beethoven stimuli and consistently preferred a shorter reverberation time for the Mahler stimuli, resulting in an SI_{RT} of 1 and -1 for each music piece respectively. Participant 28 is the only participant for this experiment that gave consistent answers for both the pitch perception part of the experiment and the reverberation time preference part of the experiment. However, it seems unlikely that their consistent preferences of reverberation time are a result of their perception of complex pitch. The other participants with a pitch SI of -1 have an SI_{RT} that is less than zero for both music pieces, which indicates they prefer a shorter reverberation time for all stimuli. From this it may be concluded that consistent fundamental listeners prefer a shorter reverberation time, however more fundamental listener participants would be needed to investigate this thoroughly.

The plot in Figures 2 and 3 indicates that participants with a pitch SI between 0.5 and 1 prefer a longer reverberation time overall. It was expected that spectral listeners would prefer a shorter reverberation time, however with so few participants with a pitch SI greater than 0.7, it is not possible to draw a significant conclusion from this data set. To investigate this with more certainty, it would be necessary to receive reverberation time preference data from more spectral listeners.

Over half of the participants prefer longer reverberation time for both music stimuli. 46 participants prefer a longer reverberation time for the Beethoven piece and 42 participants prefer a longer reverberation time for the Mahler piece. While more participants prefer a shorter reverberation time for the Mahler stimuli than the Beethoven stimuli, a longer reverberation time is most popular overall. The majority of participants are fundamental listeners, however it is not likely that this is related to the majority of participants also preferring a longer reverberation time. Most spectral listeners also prefer a longer reverberation time to a shorter reverberation time, and so this further enforces that reverberation time preference is likely not influenced by pitch perception.

An ANVOVA test was undertaken to investigate what other factors may influence reverberation time preference if pitch perception is not one of them. The following variables were analysed alongside SI of reverberation time preference:

- Order of reverberation time in each pair of stimuli.
- The different music pieces.
- Age.
- Musical training, including the type of instrument played and how long each participant has received musical training for.

All the above variables were also analysed through comparing different variables to each other and nothing produced a statistically significant result. This indicates that reverberation time preference is influenced by something else entirely.

This experiment was done on untrained listeners as this would most accurately simulate a real-life experience of visiting a concert hall and subjectively judging the sound. Some participants, on completion of the online experiment, communicated that they were unsure what they were listening for in the second part of the experiment. This may have affected results by participants judging their preference based on something other than the reverberation time. Initially, in the pilot run of the experiment, participants were asked to do a practise question to familiarise themselves with how a difference in reverberation time sounds, however it was decided that untrained participants would be most effective for this research. Altering the reverberation time of a signal alters other parameters such as clarity and envelopment so it was considered inaccurate to describe the changes in the signal as just a change of reverberation time. Simply asking the participants to indicate their preference when presented with a pair of stimuli with little information on what has changed, produces a result that is purely based on preference. While the results collected are individual preference of reverberation time, the results may have been different if all participants were certain of what the change was that they were listening for.

There may be a relationship between pitch perception and concert hall reverberation time preference that would be identifiable with a larger and more diverse sample size. However, with 80 participants, it was not possible to identify a relationship between pitch perception and individual reverberation time preference. It is not possible to conclude from these results what may significantly influence reverberation time preference.

5 CONCLUSION

Research was carried out to investigate if there is a relationship between pitch perception and individual reverberation time preference. The result of the research indicates that there is not a relationship between pitch perception and reverberation time preference. The results of the two parts of the online experiment were analysed to investigate the effects of different variables on pitch perception and preference of reverberation time separately.

Although a significant relationship was not found, the outcome of this research may lead to further, more extensive research into the relationship between pitch perception and individual reverberation time preference where a significant trend may be present in the data. The results of this research are also interesting for the topic of individual preference of reverberation time. Reverberation time is a key factor when establishing the perceived quality of a concert hall and so it would be beneficial to

research further what can influence the preference of a longer or shorter reverberation time in such spaces.

For future work on the relationship between pitch perception and reverberation time preference, it would be beneficial to carry out a large scale online listening test. Using an online experiment worked well for this research, no complicated setup was required to get the data that was needed from participants, and an online experiment was able to get many responses, far more than an offline experiment.

The results of the research described in this report indicate that something other than what was investigated may influence an individual's preference of reverberation time. While music piece has some effect on preference, it is not significant and no other factors that were investigated in this experiment were significant either. It is possible that reverberation time preference is influenced by an individual's past experiences and what they have been made to believe is best. Further work on this topic could produce interesting and significant results.

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