The Journal of Science and Medicine
2022: Special Issue: Undergraduate Student Research
Student Articles: Corresponding Editor Mark Tommerdahl

Human auditory frequency discrimination and inter-stimulus interval

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The goal of this study was to determine how human performance in discriminating between similar frequencies in the auditory spectrum was influenced by modifying the interstimulus interval (ISI). The ISI is defined as the time elapsed from the end of the first stimulus and the beginning of the second stimulus. The relationship between ISI and auditory discrimination was explored using an auditory file comprised of 40 tests that each contained two tones with a frequency difference of 1%. For each test, 44 participants were asked to select the tone they perceived as being a higher frequency. The two frequencies used in each test were centered around one of five base frequencies, and the ISI used in each test was one of eight predetermined intervals. Results from previous auditory frequency discrimination studies regarding the just-noticeable difference (JND) and Weber's law were used in the selection of the frequency difference of 1% that was used in this experiment. This frequency difference was kept constant across all the tests in order to ensure that the ISI was the main factor influencing participant performance. Participant performance was greatest at an ISI of 1000 ms when results were averaged by frequency. Additionally, as the base frequency increased, average performance generally improved. The findings from this experiment promote further investigation into the effects of varying ISI on the integration of auditory information by the auditory cortex.

Introduction

Our ability to detect changes in tonal frequencies, termed frequency discrimination, is vital for recognizing the sources of auditory stimuli and identifying potentially dangerous situations [1]. In humans, the auditory cortex works in concert with the specialized sensory receptors in the cochlea to provide us with this useful information [2]. Typically, adults can perceive auditory frequencies from approximately 20 Hz to 20,000 Hz [3]. By studying the limitations of this system with regards to frequency discrimination, we can better understand the mechanisms by which different frequencies are identified.

The just-noticeable difference (JND) is a concept that has proven useful in psychophysics research and represents the amount a stimulus must be changed in order for a difference to be detectable by the subject. Weber's law uses the JND to describe the relationship between the actual and perceived differences in the intensities of a pair of stimuli [4]. Previous work has shown that trends in detecting differences in the intensities of both vibrotactile and auditory stimuli tend to follow Weber's law which states where I represents the stimulus intensity, ΔI represents the change in the stimulus intensity required for the just-noticeable difference, and K represents a constant known as the Weber fraction [4,5]).

Unlike stimulus intensity, the relationship between actual and perceived differences in the frequencies, or pitches, of a pair of stimuli does not seem to be constant across frequencies. Even though, in humans, low frequencies have correspondingly low JNDs, and the JND increases drastically as the reference frequency increases [6], studies in humans and primates exploring frequency discrimination have revealed significant deviations from Weber's law [7,8]. Instead, the JND for frequencies that the human ear is most sensitive to tends to be approximately 0.5% of the reference frequency[9].

The auditory inter-stimulus interval (ISI), which refers to the time elapsed between the beginning of the first auditory stimulus and the beginning of the second, has been shown to influence learning. Studies have shown that a longer ISI will increase a subject's ability to learn from the stimuli [10]. At an ISI above 300 ms, learning is likely to occur and performance will increase, however once the ISI increases above 1000 ms the performance is likely to decline. The majority of these studies have been conducted using tactile stimuli and have been conducted on rabbits or small rodents.

Less studied, however, is the effect of the ISI on the subject's ability to discern differences in pitch -- a proxy for the JND. To explore the relationship between these, this experiment was designed to determine the abilities of a group of healthy participants (N = 44) to discern which auditory tone between two is higher pitched at a variety of ISIs.

Methods

An audio file containing 40 frequency discrimination tests was created using a custom Python script. Each test contained two sequential tones with a frequency difference of 1% between the two tones. The tones in each test were centered around one of five predetermined base frequencies: 100, 1080, 2060, 3040, and 4020 Hz. For each base frequency, the inter-stimulus interval (ISI) was set to be one of eight predetermined values. The ISI's used were 250, 500, 750, 1000, 1250, 1500, 1750, and 2000 ms. The order of the base frequencies and ISIs used the order of each ISI with the frequencies were randomized in the audio file to prevent adaptive learning as the test went on.

All participants in this experiment were healthy young adults aged between 20 and 22 years old. Each participant played the audio file on their personal laptops and were instructed to use their own headphones to take the test in an environment where there are no outside audio distractions. During testing, subjects were presented with the tones and completed a Google Form through which they indicated which tone they perceived to be the highest frequency without replaying the test. The time between each test was kept constant at 5 seconds.

As shown in **Figure 1**, participant performance increased as the base frequency increased. This was expected, and similar results have been found by previous studies [6]. Previous work suggests that a 0.5% frequency difference is the JND – or the frequency difference that would be discernible by a normal hearing subject 50% of the time. The fraction of participants who were successful in the frequency discrimination was above 0.50 for all base frequency conditions. This was also expected as the tests were purposely created with a 1% frequency difference – double the previously found JND. This aspect of the experimental design was intended to ensure that the ISI was the main contributing factor to changes in participant performance.

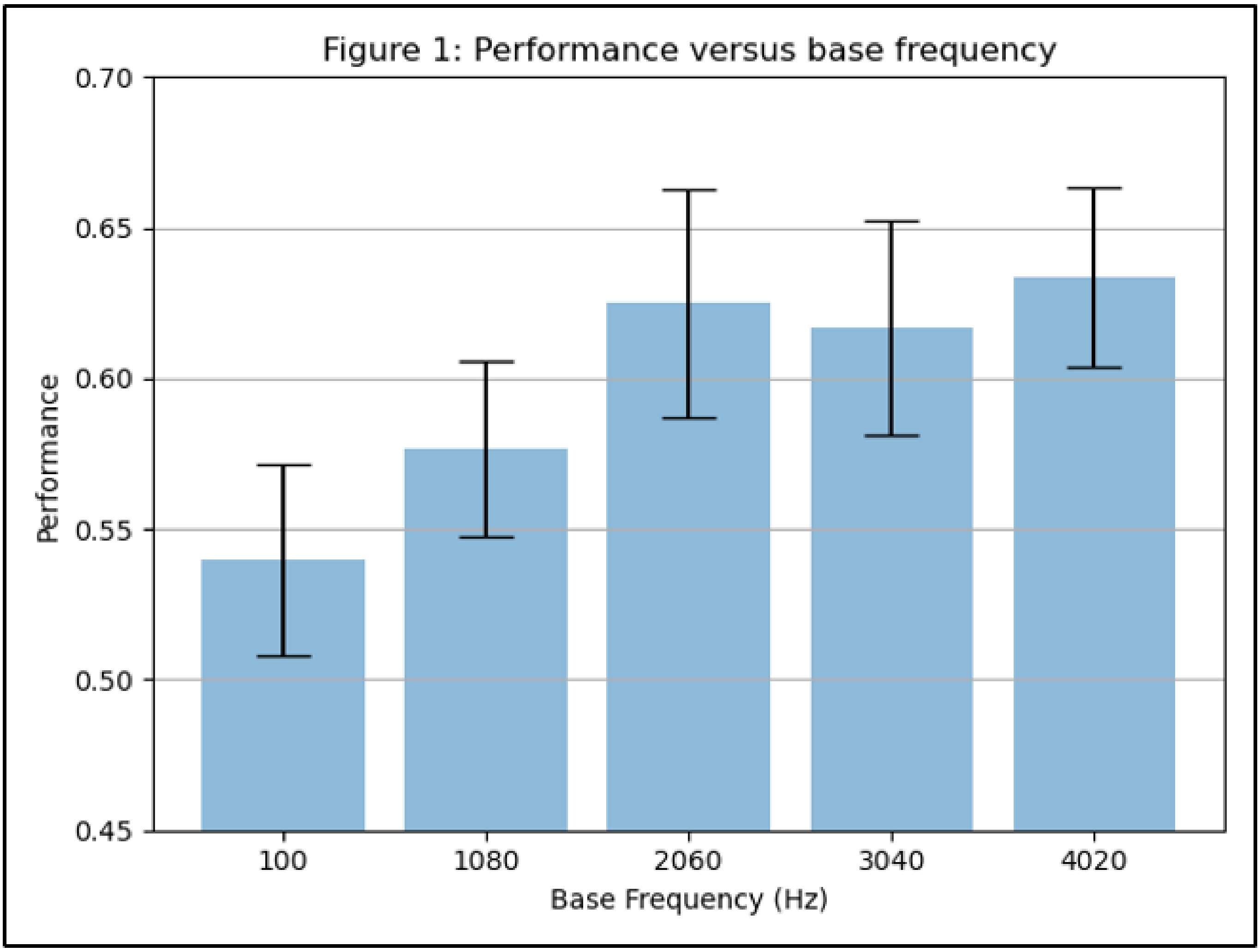

Figure 1. *The fraction of the total participants that answered the tests correctly at each base frequency, averaged across all ISIs.* Whiskers indicate standard error at each base frequency.

By averaging the performance of the participants across all frequencies and analyzing them at the individual ISIs, the ISI with the greatest performance was found to be 1000 ms. The average performance at 1000 ms was 0.67 as shown in **Figure 2**. Average performance increased steadily with ISI for ISI values less than 1000 ms. Past 1000 ms, performance decreased and plateaued for ISI values greater than 1500 ms. The results indicate that, for tests with shorter ISIs, the tones were too close together to allow for a reliable distinction between the two frequencies, but the mechanism for this tendency is not clear. It is possible that for the longer ISIs, the time elapsed between the tones was so long that the memory of the first sound was lost by the time the second sound occurred negatively impacting participant performance. These two phenomena inhibit strong performance at ISI values that are too high or too low and make performance the greatest at a central ISI value of 1000 ms. Using two-sided t-tests for statistical significance, it was found that there was a statistically significant ($p < 0.2$) difference between the performance at 1000 ms and the performance at every other interval, except for 1250 ms (**Figure 2**). Since data was only taken at specific intervals, performance may be optimized at an ISI that falls somewhere between 1000 ms and 1250 ms. These results coincide with results from previous work that have shown performance of a similar auditory disctimination task was maximized for ISIs between 1 and 3 seconds [11].

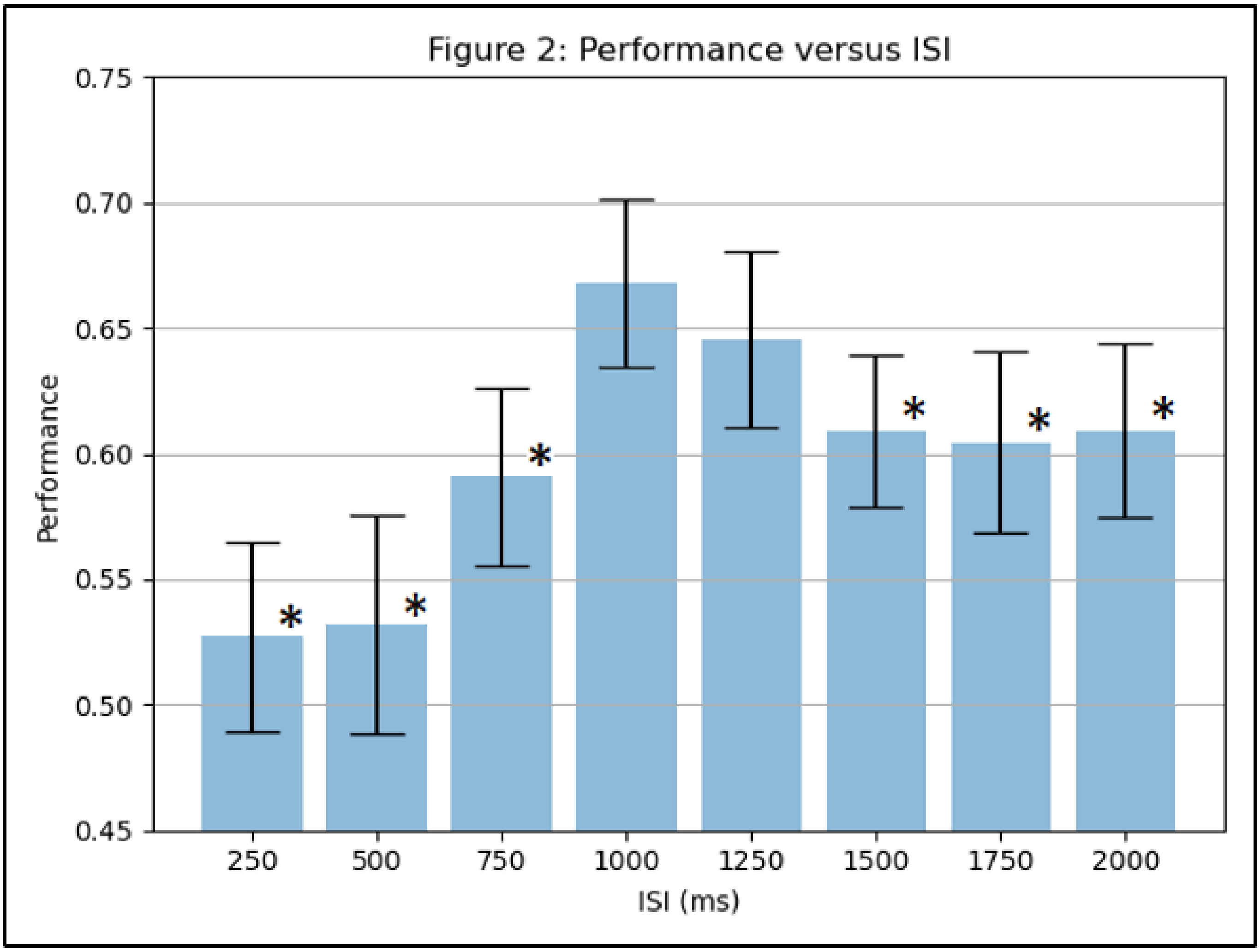

Figure 2. *The fraction of participants that answered the tests correctly at each ISI, averaged across all base frequencies without normalization.* Whiskers indicate standard error at each ISI. Two-sided t-tests for statistical significance between the average performance at each ISI and the average performance at ISI=1000 ms generated p-values of 0.003, 0.011, 0.124, 0.624, 0.124, 0.168, 0.108 for ISI values of 250 ms, 500 ms, 750 ms, 1250 ms, 1500 ms, 1750 ms, and 2000 ms respectively. Bars with p-values less than 0.2 are designated by an asterisk.

When the performances were broken down by frequency, there was no clear pattern for best performing ISI. For example, at 100 Hz, the ISI of 2000 ms had the best performance, while at other frequencies like 1260 Hz, the interval of 1250 ms had the best performance (**Figure 3**). There was no correlation between base frequency and best performing ISI.

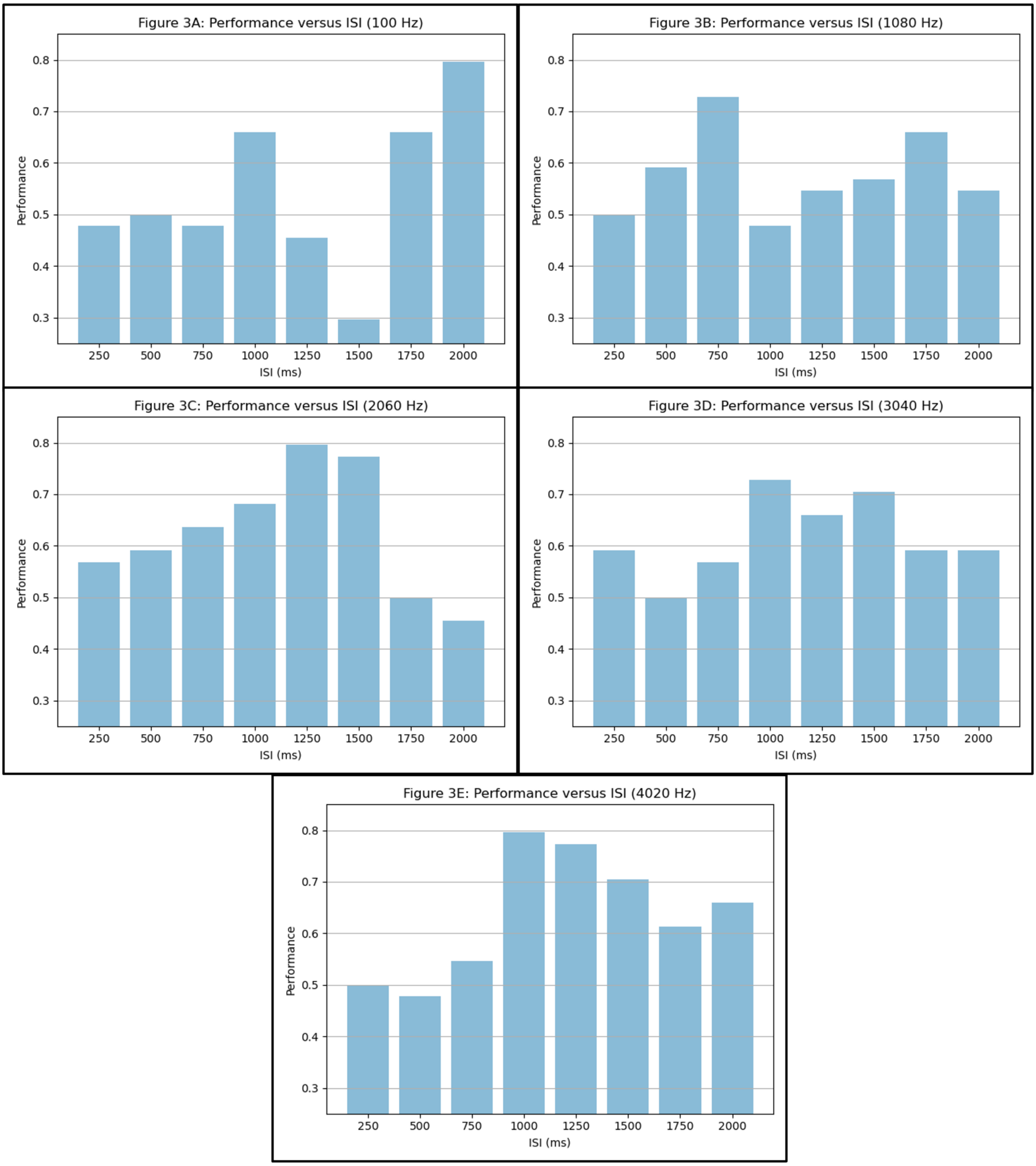

Figure 3. *The fraction of participants that answered the tests correctly at each ISI, arranged by base frequency.* 4A, 4B, 4C, 4D and 4E display the performance at each ISI at 100 Hz, 1080 Hz, 2060 Hz, 3040 Hz, and 4020 Hz respectively.

Additionally, when the average performance was analyzed at each frequency, and further broken down by ISIs, there was also no correlation between ISI and best performing frequency (**Figure 4**). However, overall some frequencies had better performances. For example, both 1000 ms and 1250 ms had performances better than 0.8 while some like 100 ms only had maximum performances of approximately 0.6.

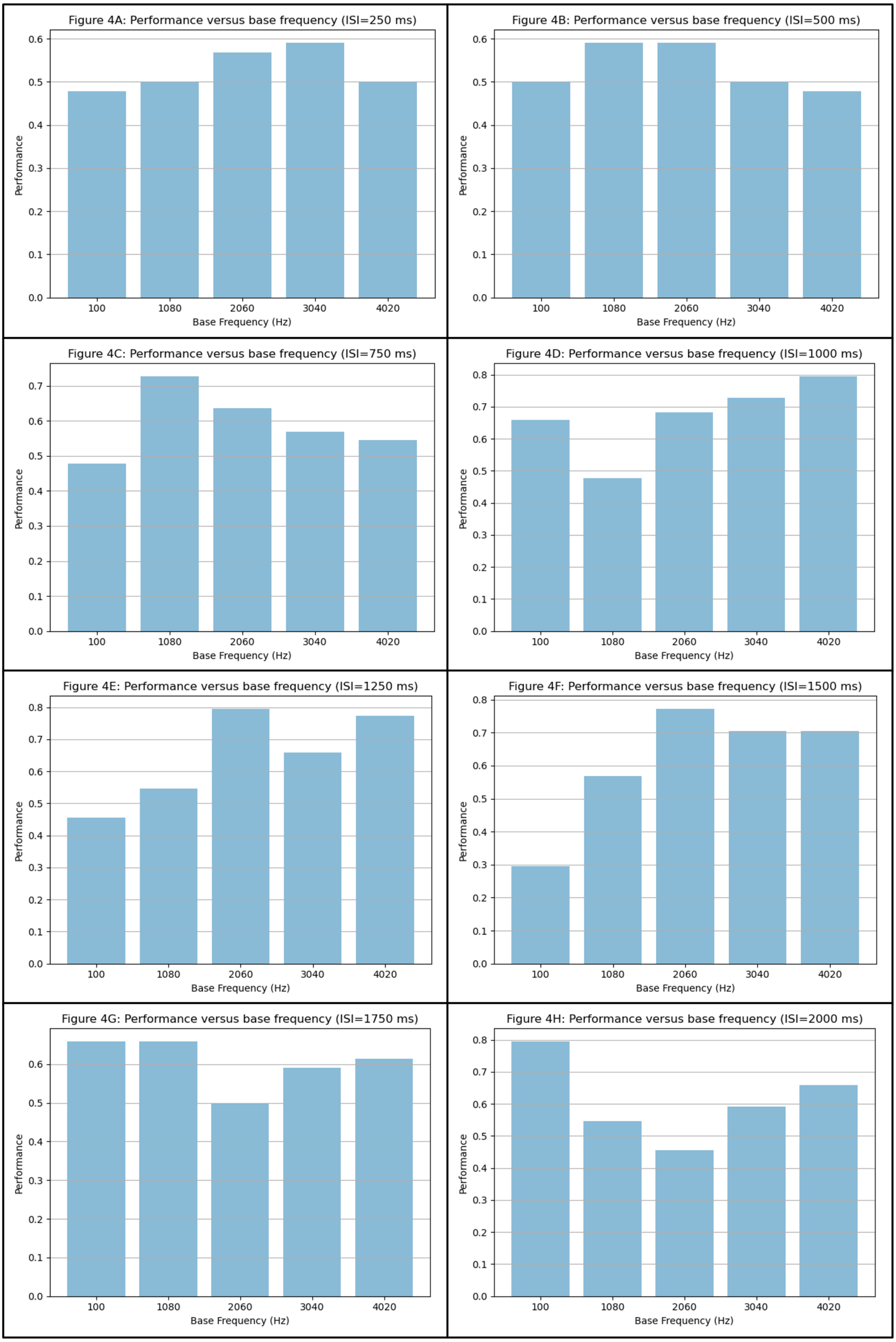
Figure 4A: Performance versus base frequency (ISI=250 ms)
Performance
0.0 0.1 0.2 0.3 0.4 0.5 0.6
100 1080 2060 3040 4020
Base Frequency (Hz)
Figure 4B: Performance versus base frequency (ISI=500 ms)
Performance
0.0 0.1 0.2 0.3 0.4 0.5 0.6
100 1080 2060 3040 4020
Base Frequency (Hz)
Figure 4C: Performance versus base frequency (ISI=750 ms)
Performance
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
100 1080 2060 3040 4020
Base Frequency (Hz)
Figure 4D: Performance versus base frequency (ISI=1000 ms)
Performance
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
100 1080 2060 3040 4020
Base Frequency (Hz)
Figure 4E: Performance versus base frequency (ISI=1250 ms)
Performance
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
100 1080 2060 3040 4020
Base Frequency (Hz)
Figure 4F: Performance versus base frequency (ISI=1500 ms)
Performance
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
100 1080 2060 3040 4020
Base Frequency (Hz)
Figure 4G: Performance versus base frequency (ISI=1750 ms)
Performance
0.0 0.1 0.2 0.3 0.4 0.5 0.6
100 1080 2060 3040 4020
Base Frequency (Hz)
Figure 4H: Performance versus base frequency (ISI=2000 ms)
Performance
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
100 1080 2060 3040 4020
Base Frequency (Hz)

Figure 4. *The fraction of participants that answered the tests correctly at each base frequency, arranged by ISI.* 5A, 5B, 5C, 5D, 5E, 5F, 5G, and 5H display the performance at each base frequency at ISI values of 250 ms, 500 ms, 750 ms, 1000 ms, 1250 ms, 1500 ms, 1750 ms, and 2000 ms respectively.

The final question in the Google Form for the experiment asked the participants to rate their perceived performance on a scale from 1 to 5, with 1 representing "extremely poor" while 5 represented "extremely well." Over 80% of the participants believed their performance should be rated a 2 or lower, indicating that most believed they performed poorly on the tests (**Figure 5**). With this rating we would expect the results to indicate that these participants answered less than 50% of the questions correct. However, when comparing their perceived performance with the actual percent of questions they got correct, the majority of the participants answered more than 50% of the questions correctly (**Figure 5**). Several of the participants who believed their performance rated a 1 or a 2 answered more than 70% of the tests correctly. These results show the opposite of the Dunning-Kruger effect – i.e. high performers underestimate their performance. [12]

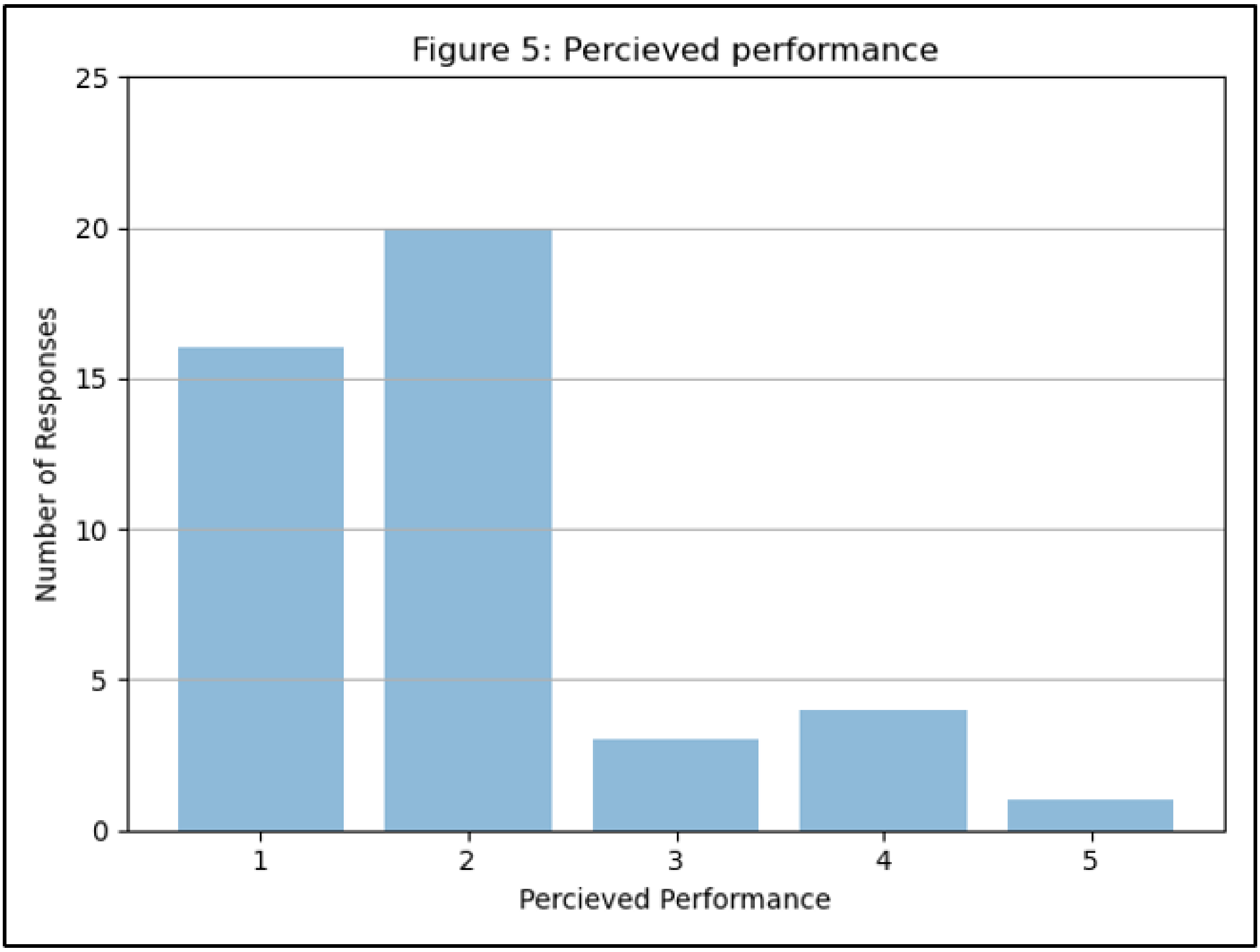

Figure 5. *Participants' self-evaluation after testing.* A lower performance score corresponds to poorer perceived performance while a higher score corresponds to a stronger perceived performance.

Figure 6 also displays which participants' responses indicated they have musical backgrounds. These participants generally had higher perceived performances as well as higher actual performances. In fact, one of these participants answered 100% of the tests correctly and correspondingly rated their performance as a 5. The previous auditory training that comes with a musical background likely allowed these particular participants to more reliably differentiate between close frequencies [13]. It is possible that since those with training in auditory frequencies and pitches had a better performance, increased exposure to and practice with the auditory tests would improve performance results as well as increase perceived performance score.

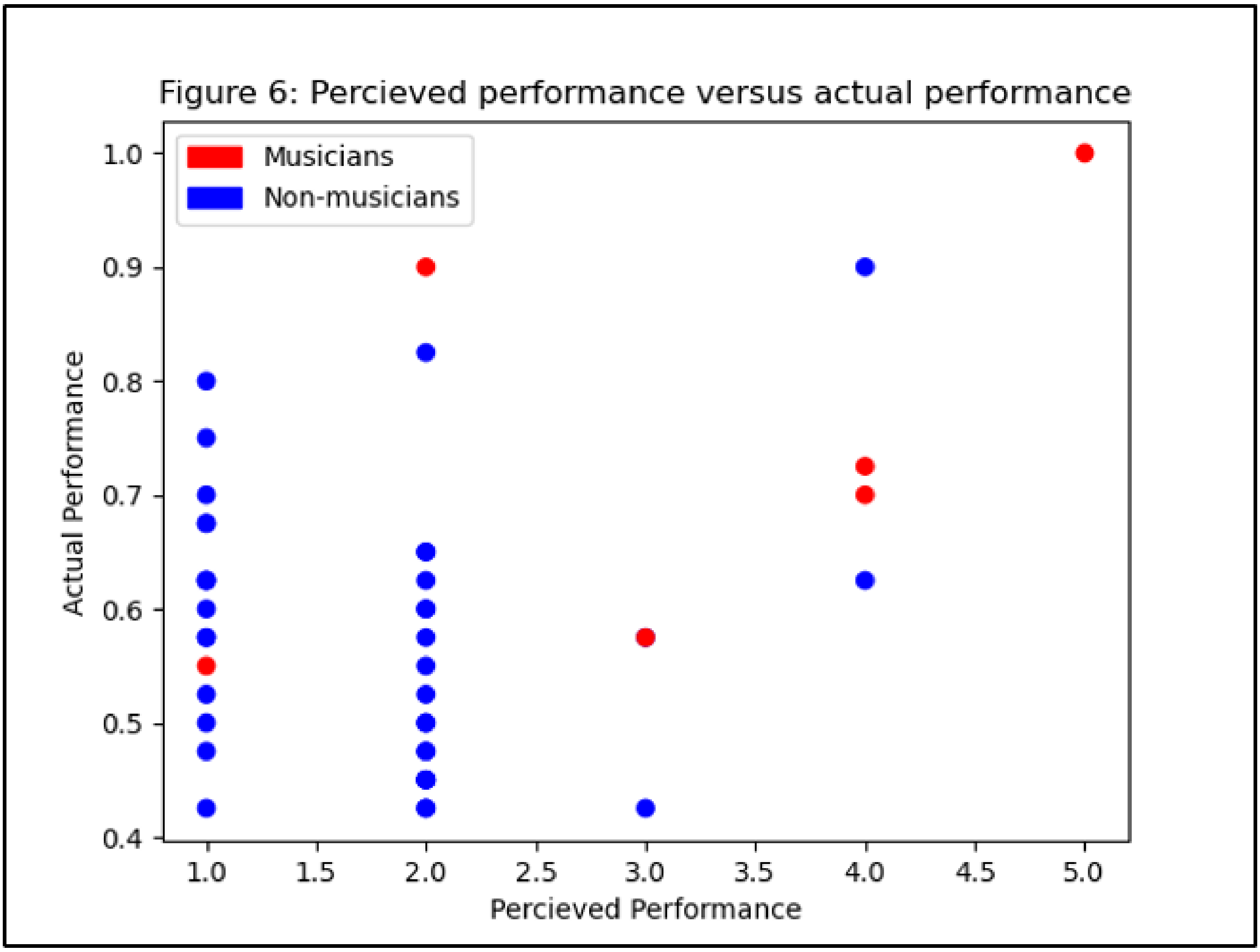

Figure 6. *Participants' average performance plotted against their self evaluation score.* Participants shown in red responded that they practice a musical instrument for greater than 3 hours weekly.

To improve on this experiment for the future, a wider array of tests can be administered. This experiment was limited in the number of base frequencies and ISIs it explored, but future investigators could conduct the same experiment with more ISI or base frequencies in order to test whether the results in the current study are replicable. Similarly, future work could test ISI values close to 1000 ms to try and pinpoint the exact optimal ISI.

Additionally, this experiment was sent out to the participants, so their testing environment and the headphones they used could not be controlled. In order to ensure the results remain consistent and are not influenced by outside factors, future experiments should be conducted in controlled environments. These participants were also all young, healthy individuals who were all 19-22 years old. It cannot be determined from this experiment whether the same ISI results would hold for other age groups.

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