TONAL WORKING MEMORY AND SINGING ABILITY RELATE TO INDIVIDUAL DIFFERENCES IN LONG-TERM MEMORY FOR MUSICAL PITCH

By

Evan Smith

Department of Psychology

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Faculty of Arts and Social Science

Huron University College

London, Canada

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CERTIFICATE OF EXAMINATION

Advisor: Dr. Stephen Van Hedger

Reader: Dr. Christine Tsang

The thesis by:

Evan Smith

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Date	Chair of Department

Abstract

Most individuals can tell when a familiar melody has been shifted in pitch by as little as one semitone – the smallest pitch difference found in Western music notation. These findings suggest that good absolute pitch memory is a widespread ability; however, the individual differences that relate to this form of pitch memory are understudied. The present study was designed to examine how individual differences in tonal working memory precision, singing ability, auditory imagery ability, and musical training may contribute to how individuals vary in their long-term memory for the absolute pitch of popular music recordings. Participants completed a tone adjustment task which has been previously used to measure tonal working memory. They were asked to judge whether popular recordings had been shifted in pitch or not as a measure of long-term absolute pitch memory. They were then asked to rate the vividness and ease with which they thought they could change auditory images. Finally, participants completed a singing accuracy task to measure accuracy in vocal production of pitches, which was followed by a short musical training questionnaire. The results indicated that participants with more precise tonal working memory ability and better singing accuracy had better long-term absolute memory for pitch. Tonal working memory precision was also the only variable that significantly predicted APM performance alongside the other measured variables. These results suggest that auditory working memory precision is likely connected to precise long-term representations of pitch in memory, however, considerations should be made about how long-term pitch memory is operationalized.

Keywords: long-term memory, working memory, musical training, singing ability, auditory perception, individual differences

Acknowledgements

I wish to express my deepest gratitude to my thesis advisor, Dr. Stephen Van Hedger, for his guidance and expertise throughout the project. I am extremely gracious that you allowed me to take on this project and for the time you took to read and provide advice on my writing. I also wish to thank my second reader, Dr. Christine Tsang, for her feedback and an engaging defence.

Table of Contents

Introduction

Absolute pitch (AP) is the ability to name or produce musical pitches in the absence of a reference pitch for guidance (e.g., Miyazaki, 1988). In addition to being able to ascribe labels to specific pitches, people who possess absolute pitch also have stable, long-term memory for pitch (Levitin, 1994), even in situations where their explicit pitch labels would not be beneficial (Van Hedger et al., 2016). Conversely, those with congenital amusia, a deficit in processing musical pitch, have an impaired ability to discriminate pitch in music (Peretz, 2008). It is also suggested that those with amusia have impaired memory for pitch compared to controls (Gosselin et al., 2009). Pitch is a fundamental component of music, and it is clear from both the cases of AP and amusia that there are remarkable differences in individuals' memory for pitch.

How does the everyday listener (i.e., those without AP or amusia) fare in terms of their memory for pitch? While less is known about how pitch memory is represented in everyday listeners, it was originally thought that individuals who do not possess AP would have poor memory for absolute pitches. Individuals without AP are thought to process pitch relatively, an ability in which individuals can identify the relations between pitches (also known as musical intervals; Levitin & Rogers, 2005). It has been suggested that there is a shift from absolute pitch processing to relative pitch processing as children develop, with few individuals retaining absolute pitch processing into adulthood (Takeuchi & Hulse, 1993). Relative pitch is overall an important part of how we perceive music; it is how we can recognize a familiar melody after it has been shifted in pitch (see McDermott and Oxenham, 2008 for a review). Relative pitch is also salient for musicians as learning intervals is an integral part of musical training.

Yet, an increasing body of work has challenged the notion that everyday listeners have poor memories for absolute pitches. Musically trained individuals were found to be able to reliably determine whether Bach preludes were played in the correct key; even determining differences as small as one semitone (Terhardt & Seewann,1983) This suggests that musically trained individuals may have stable, long-term representations for absolute pitches of familiar melodies. Terhardt and Seewann (1983) suggest that non-AP individuals may make decisions about key using multiple notes in a series (using relative pitch processing), this is in contrast with how AP possessors use their perception of individual notes without relying on relative processing of intervals to determine key. While Terhardt and Seewann (1983) present findings that support absolute pitch ability in non-AP possessors, the participants in the study were made up of only musically trained individuals, some of which possessed AP. As such, it is unclear whether the findings are generalizable to individuals who do not have extensive musical training or possess AP.

More recent research has expanded upon these findings and demonstrated that most individuals, regardless of formal musical training, have stable memory representations of absolute pitch. Levitin (1994) found that non-AP possessors were able to hum popular songs in the correct musical key (i.e., using the same collection of absolute pitches as the original recording) at rates that were significantly above chance, indicating that everyday listeners may possess an implicit accurate memory for pitch. Also using familiar musical recordings, Schellenberg and Trehub (2003) examined participant’s accuracy for determining whether popular television soundtracks had been shifted in pitch by one or two semitones (adjacent notes in the Western musical system). These individuals had minimal to no musical training. Conceptually similar to Levitin (1994), participants selected the correct version of the familiar recordings significantly more often than the “incorrect” pitch-shifted versions, and participants were unable to select the correct version of completely unfamiliar recordings, highlighting the critical role of familiarity. These results suggest that participants were relying on long-term representations of the pitch of familiar recordings, even if both studies assessed pitch memory in different ways (a vocal assessment in Levitin, 1994, and a perceptual assessment in Schellenberg and Trehub, 2003).

Non-AP possessors’ long-term memory for pitch is not exclusive to music; individuals who do not possess AP are able to identify the dial tone heard when picking up a landline phone (Smith & Schmuckler, 2008) and the censor tone (“bleep”) used in broadcast media (Van Hedger et al., 2016) among pitch shifted versions with decent (above-chance) accuracy. While non-AP possessors do not have the ability to explicitly assign labels to pitch, they do seem to have considerable long-term representations for the pitch of familiar stimuli. Long-term pitch memory ability does not appear to be directly related to musical training (Van Hedger et al., 2017) and has been found to follow a normal distribution in identifying the original pitch of songs with the majority of individuals being able to identify the original pitch of songs above chance (50%) with some performing much better or worse than chance (Schellenberg & Trehub, 2003), implying that this ability is widespread yet variable throughout the population.

Keeping in mind that long-term pitch memory was found to be normally distributed in the population, what factors might be associated with the individual differences seen in pitch memory? One recently explored possibility in the literature is singing accuracy. Recent research by Halpern and Pfordresher (2021) examined whether singing ability could partly account for individual differences in pitch memory. It was found that individuals who could accurately select the starting note of popular songs on a keyboard (used as a measure of long-term pitch memory) also tended to be more accurate singers. This suggests that individuals who are better singers may also have better long-term representations of pitch.

Singing ability has also been found to be correlated with the vividness of one's auditory imagery abilities, but not the ability to manipulate said auditory images (Halpern & Pfordresher, 2013). Auditory imagery refers to a type of perceptual memory which can be defined in terms of vividness and control (Halpern & Pfordresher, 2021). Vividness of auditory imagery is described as how clearly someone can imagine a sound in thought whereas control of auditory imagery is the ability to be able to change one imagined sound into another (Halpern & Pfordresher, 2021). While auditory imagery ability has generally not been found to be associated with long-term pitch memory (Van Hedger et al., 2017), this study used a different auditory imagery scale from that of the Halpern and Pfordresher (2013) research – the Clarity of Auditory Imagery Scale (CAIS; Willander & Baraldi, 2010). The CAIS exclusively measures the clarity of auditory images, whereas the Bucknell Auditory Imagery Scale used in the Halpern and Pfordresher (2013) study measures both vividness and ability to manipulate auditory imagery. It is possible that inconsistencies in the measures used to assess auditory imagery ability could be contributing to the lack of associations seen with auditory imagery abilities and long-term pitch memory. It is also possible that auditory imagery could potentially serve as a moderator for singing ability and pitch memory, ostensibly because individuals with stronger auditory imagery abilities would be able to better match external pitch targets in singing as well as use auditory imagery more effectively to identify the correct absolute pitches of familiar recordings.

Long-term pitch memory abilities have also been suggested to be related to auditory working memory ability (Van Hedger et al., 2017). In a sample of non-AP possessors, Van Hedger et al. (2017) found that performance on an implicit note memory task, which involves adjusting a starting note to match a target note and has been characterized as a measurement of auditory working memory (Van Hedger et al., 2015), was related to accurate long-term memory for the absolute pitch of popular songs.

While musical training has not been found to be directly associated with absolute pitch memory in research by both Van Hedger et al. (2017) and Halpern and Pfordresher (2021), it is still worth considering as musical training may improve singing accuracy and tonal working memory. Previous research has shown that musicians have enhanced tonal working memory abilities compared to non-musicians (Ding et al., 2018), suggesting that musical training may improve tonal working memory ability. Likewise, it would also be reasonable to expect musical training to improve singing accuracy. Prior research has indicated that musically trained individuals tend to be better at imitating pitch than non-musically trained individuals (Pfordresher & Demorest, 2021). Both tonal working memory and singing ability have been associated with absolute pitch memory in previous research (Van Hedger et al. 2017, Halpern and Pfordresher, 2021), so it may be expected that musical training could have an indirect effect (e.g., as a moderator) on APM ability through tonal working memory and singing ability.

The present research builds upon previous research by Halpern and Pfordresher (2021) and Van Hedger et al. (2017) to examine how general auditory abilities such as tonal working memory precision, singing ability, auditory imagery ability, and musical training factor into the current understanding of individual differences in long-term pitch memory in non-AP possessors. The current study is novel in that it incorporates all measures used in the two previous studies using a within-subjects design. The present study used the implicit note memory (INM) task used in the Van Hedger et al. (2017) research to measure auditory working memory precision. The INM task measures the accuracy in which participants can manipulate one note to match the pitch of another note. The Seattle Singing Accuracy Protocol (SSAP) and Bucknell Auditory Imagery Scale (BAIS) that were both used in the Halpern and Pfordresher (2021) study were also used in the present study. The SSAP measures singing accuracy and the ability to detect changes in auditory frequency (specifically, participants' difference thresholds for auditory frequency). A measure of musical training was also incorporated into the SSAP. The BAIS measures the vividness and ease with which participants can manipulate auditory imagery. The advantage to including all the measures in one study is that they can then be formally modelled together, providing a better understanding of how individual differences factor into long-term pitch memory.

The first hypothesis is based on the findings by Van Hedger et al. (2017) and states that working memory precision will be positively associated with accuracy in absolute pitch memory for popular songs. A second prediction states that singing accuracy will be positively associated with absolute pitch memory for popular songs, which would represent a conceptual replication of Halpern and Pfordresher (2021). While musical training and auditory imagery abilities have not been found to be directly associated with long-term pitch memory in the past, it could be possible that these abilities may moderate the relationship between the other variables and memory for pitch. For example, musical training or auditory imagery ability may potentially predict performance on the SSAP or INM tasks, which in turn may be associated with absolute pitch memory, however, it is not expected that musical training or auditory imagery ability will directly predict absolute pitch memory performance.

Method

Participants

Forty-one participants (*M* = 19.54 years, *SD* = 2.59 years, range = 18-34 years, 28 females, 13 males) were recruited mainly from students at Western University and its affiliate Huron University College via course announcements, social media posts, and flyer advertisements on campus. Criteria for inclusion consisted of participants possessing normal hearing ability (self-reported). Criteria for exclusion included self-identifying as possessing absolute pitch. Participants were provided $14.00 CAD or 1% course credit (if they were taking an eligible psychology class) as compensation.

Materials

The implicit note memory (INM) task was coded in jsPsych 7 (de Leeuw, 2015) and was identical to that used in Van Hedger et al. (2018) apart from being programmed in jsPsych. The sine tones were presented at a volume of approximately 70 dB SPL and were 250 ms in duration. The task contained 4 target notes (F#4, G4, G#4 and A4) and eight starting notes. Four of the starting notes were higher in pitch than the target notes (A#4, B4, C5 and C#5) and four were lower in pitch than the starting notes (D4, D#4, E4 and F4). There were a total of 64 trials with every combination of target notes and starting notes included twice.

The APM task was coded in jsPsych 7 (de Leeuw, 2015). The task contained 28 excerpts from popular recordings which were confirmed to be highly recognizable through previous pilot testing (see Appendix for a list of recordings). Each recording was five seconds in duration and had a 500 ms linear fade-in and fade-out. The excerpts underwent a pitch shifting algorithm in Audacity in which three versions of each recording were generated (correct, incorrect +1 semitone, and incorrect –1 semitone). Correct stimuli were shifted up in pitch by 0.5 semitones and then down by 0.5 semitones. Incorrect +1 semitone stimuli were shifted up in pitch by 0.5 semitones twice. Incorrect -1 semitone stimuli were shifted down in pitch by 0.5 semitones twice. A “high-quality stretching” option was selected to preserve the length of each recording to 5 seconds. All stimuli were subjected to the pitch shifting algorithm twice, using 0.5 semitone shifting, to ensure that artifacts produced by the pitch shifting procedure could not be used to determine correctness of the excerpts.

The Bucknell Auditory Imagery Scale (BAIS) was programmed in Qualtrics (Qualtrics: Provo, UT). The questionnaire consisted of 25 items total and was divided into two subscales: vividness (BAIS-V) and control of auditory imagery (BAIS-C). The BAIS-V consisted of 14 items, whereas the BAIS-C consisted of 11 items. For the BAIS-V, participants rated how vividly they could think of an auditory image in their head for several scenarios (e.g., “For the next item, consider ordering something over the phone. [How vivid is] the voice of an elderly clerk assisting you?”). Ratings were made on a 7-point Likert-type scale (1: *No image present at all*, 7: *As vivid as the actual sound*). For the BAIS-C, participants were given pairs of scenarios that required them to change a sound in their mind’s ear and were subsequently asked how easily they were able to do so (e.g., "Consider attending a choir rehearsal. (a) The sound of an all-children’s choir singing the first verse à (b) The sound of an all-adults’ choir now sings the second verse of the song”). Like the BAIS-V, participants made their ease-of-change ratings on a 7-point Likert-type scale (1: *No image present at all*, 7: *Extremely easy to change the image*). The BAIS-V and BAIS-C were moderately correlated with one another ($r = .67$), as has been reported in prior research (Halpern, 2015), and both displayed good internal consistency (BAIS-V: $\alpha = .83$; BAIS-C: $\alpha = .75$).

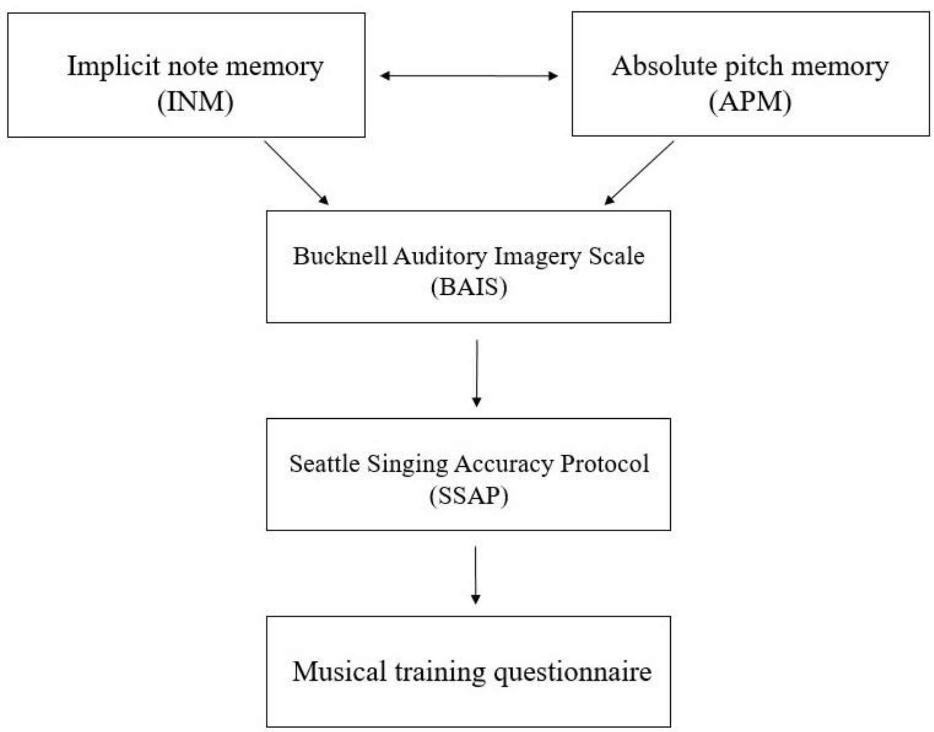
The Seattle Singing Accuracy Protocol (SSAP) was programmed in Matlab (MathWorks: Natick, MA). The task contains a series of trials in which participants must vocally reproduce single notes and short melodies. The task required imitation of recordings of sung notes and notes played on a piano. This was followed by a pitch discrimination task and a brief questionnaire on musical background as well as demographic information. The pitch discrimination task was based on prior work (Loui, 2008), and used an adaptive staircase procedure to determine an individual's difference threshold for auditory frequency. The standard tone was set at 500 Hz, and the initial comparison tone was set at 96 Hz. For every three answers that a participant got correct, the relative pitch difference between the comparison tone and the standard tone was cut in half. For every incorrect answer, the difference between the comparison tone and the standard tone was doubled. As such, the pitch discrimination task used a "three-up, one-down" adaptive staircase procedure. The script terminated when participants reached six reversals (i.e., going from a correct answer to an incorrect answer or vice versa). The questionnaire included questions such as participants' age and number of years of musical training. A Steinberg UR12 USB audio interface was used in addition to an Audio-Technica AT2020 stereo microphone for recording sound during the SSAP. Sony MDR-7506 stereo professional headphones were used in the INM, APM, and SSAP tasks.

Procedure

Figure 1 provides an overview of the experimental procedure. Upon providing informed consent, participants first completed the INM and APM tasks. The order of which task was presented first was alternated between participants. In the INM task, participants were asked to listen to a target tone followed by 1000 ms of masking noise. Participants were then instructed to adjust a starting note to match the target note by increasing or decreasing the frequency by clicking on up and down arrows displayed on the screen.

Figure 1

Overview of the experimental design



Note: The order in which participants completed the INM and APM was counterbalanced between participants. After completing both tasks, participants completed the BAIS, followed by the SSAP, and finally, a questionnaire about demographic information and musical training.

Each time the participant clicked on the up or down arrows, the pitch of the starting note was shifted by one-third of a semitone (i.e., 33.3 cents) up or down, respectively. The target note was presented only once. Once participants were satisfied with their response, they could hit the enter key to move onto the next trial. Participants were given two initial practice trials, which were not scored, to become familiar with the task. INM performance was operationalized as the mean absolute deviation from the target note, represented in terms of arrow clicks (e.g., a mean score of 5 would reflect that a participant was, on average, five clicks or 1.67 semitones away from the actual target note). Individual trials that were more than three standard deviations away from a participant's mean were discarded, similar to the procedure outlined in Van Hedger et al. (2017).

In the APM task, participants were instructed to listen to 28 5-second excerpts from popular songs and judge whether they had been shifted in pitch. There was an equal number of correct and incorrect trials. Of the 14 incorrect trials, 7 had been shifted upwards in pitch by one semitone and 7 had been shifted downwards in pitch by one semitone. The ordering of these three trial types (correct, incorrect +1 semitone, incorrect -1 semitone) was completely randomized, and the specific assignment of songs to trial types was also randomized across participants. Upon listening to the excerpt, participants were asked to indicate via a button press on the screen whether the song sounded correct (yes/no). If participants selected "no", they were asked whether they thought the recording was shifted "too high" or "too low" in pitch. They were also asked to indicate how familiar the recording was to them (*not at all*, *a little*, *somewhat*, *quite a bit*, *extremely*). APM performance was operationalized in terms of proportion correct for the initial question of whether the recording sounded correct. The follow-up question, which asked participants to clarify if the recording sounded "too high" or "too low" if participants reported that the recording sounded incorrect, was considered exploratory and is not reported here. Finally, trials for which participants reported no prior familiarity with the recording were discarded from analysis, as this kind of APM requires at least some prior familiarity with the recording (cf. Schellenberg & Trehub, 2003).

After completion of both the INM and APM, participants completed the BAIS. There were four demographic questions regarding age, sex, years of education, and occupation that were part of the Qualtrics survey prior to the BAIS. These demographic questions were then followed by the BAIS-V and the BAIS-C, in this order. The BAIS-V and BAIS-C were operationalized through calculating mean scores for each subscale.

Participants indicated to the researcher when they were finished with the previous tasks and were then given instructions for the SSAP. Participants were told to follow the interactive instructions for the SSAP and to sing at a clear, comfortable level into the microphone. Participants first completed a warmup exercise to determine their comfortable vocal range. The warmup consisted of singing a familiar song chosen from a list and singing the syllable “doo” at a comfortable level for two seconds. For the main trials, participants first listened to single sung pitches one-at-a-time and were asked to sing the pitches back. They then heard single pitches played one-at-a-time on the piano and were asked to sing them back. Following the single-pitch trials, participants heard four-note sung melodies and were asked to sing them back. To conclude the singing portion of the task, they were then provided the lyrics to the song they chose in the warmup and were asked to sing it first using the lyrics and then again using the syllable “doo”. Performance on the SSAP was operationalized in terms of the proportion of accurately reproduced notes, with “accurate” responses falling within one semitone of the provided template. This method of scoring has been used in previous instances of the SSAP (Pfordresher & Demorest, 2021).

Participants then completed the perceptual discrimination task, indicating whether two presented pitches were the same or different, using the adaptive staircase procedure described in the previous section. Performance on the pitch discrimination task was operationalized as the relative pitch difference between the standard and comparison tone at the end of the task, measured in cents (with one cent equaling 1/100 of a semitone). Participants were lastly asked to answer questions regarding hearing and neurological impairments, musical training, and spoken languages. Questionnaire responses were treated as individual items in the analyses. Following this final questionnaire, participants were provided with a debriefing letter, which explained the purpose of the study, and were also provided with compensation for participating in the study.

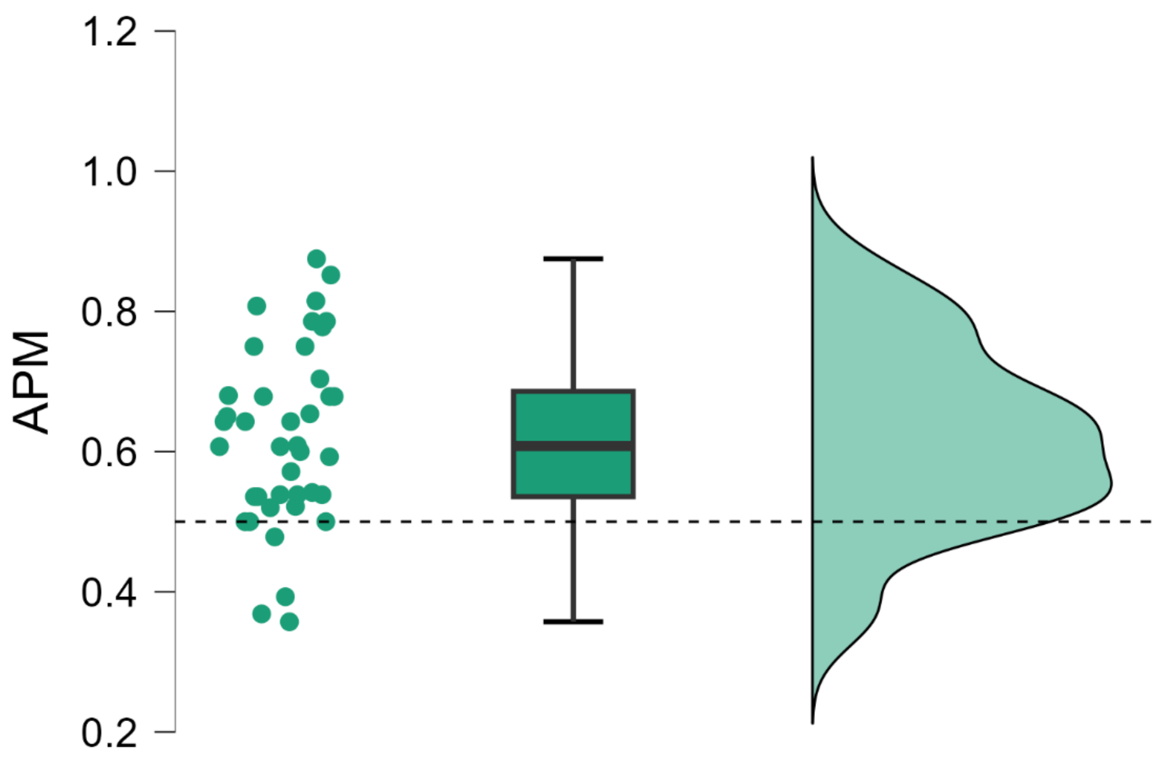
Results

Accuracy for determining whether popular recordings had been shifted in pitch in the APM task was first tested using a one sample t-test against a chance estimate (50%). Participants accurately judged the tuning of 62.0% of the recordings ($SD = 12.8\%$), which was significantly above chance $t(39) = 5.924$, $p < .001$, $d = 0.937$. Figure 2 displays a visualization of performance on the APM task.

Given the *a priori* hypotheses regarding the directional relationships between both the APM and INM (negative), as well as for the APM and SSAP (positive), one-tailed Pearson correlation coefficients were calculated to assess associations. Performance on the APM task was negatively correlated with performance on the INM task $r(39) = -.393$, $p = .006$ (see Figure 3), suggesting that participants who performed better on the APM task also had better tonal working memory performance on the INM task (as a lower score represents better performance on the INM task). There was a marginally significant positive correlation between APM task performance and singing accuracy *r*(39) = .251, *p* = .059, indicating that participants who were more accurate singers had better performance on the APM task, although the strength of the association was weaker.

Figure 2

Individual data points, boxplot, and distribution of performance on the absolute pitch memory (APM) task



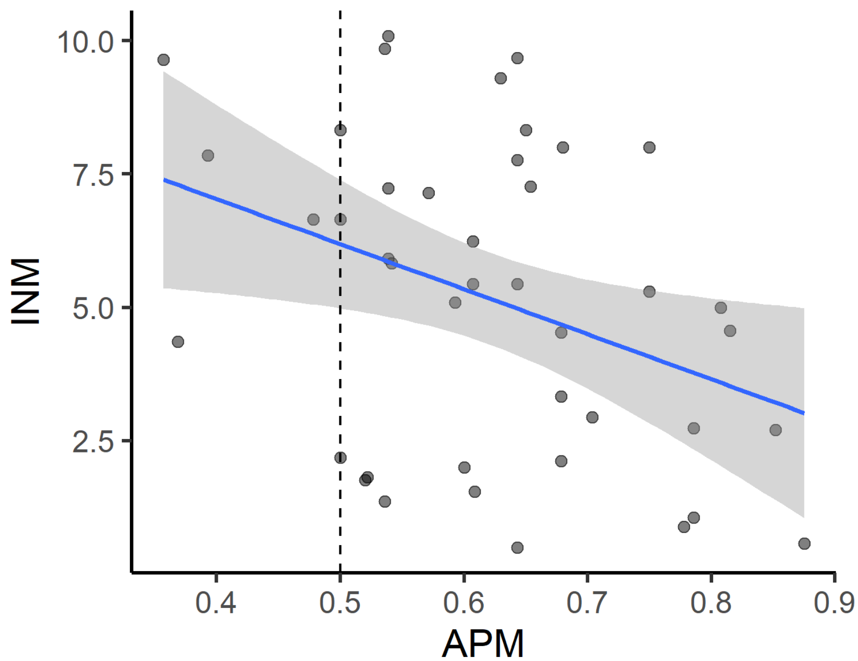
Note: The dashed line represents chance performance (50%). APM = absolute pitch memory task.

Tonal working memory performance on the INM task was significantly negatively correlated with singing accuracy *r*(39) = -.441, *p* = .004, meaning participants with better (lower) scores on the INM task tended to be more accurate singers. INM performance was correlated with the adaptive staircase pitch discrimination task $r(39) = .427$, $p = .006$. Participants who performed better on the INM task tended to be better at discriminating whether pitches were higher or lower in relation to other pitches. Musical training was significantly correlated with INM performance $r(39) = -.406$, $p = .009$. Participants with more years of musical training for an instrument (including voice) had more precise tonal working memory ability. Musical training was also correlated with singing accuracy $r(39) = .332$, $p = .037$. Participants with more years of musical training tended to have more accurate performance on the SSAP. Pitch discrimination ability was not significantly correlated with years of musical training $r(39) = -.232$, $p = .150$. Ratings of the vividness of auditory imagery on the BAIS-V items were not significantly correlated with years of musical training $r(39) = -.062$, $p = .704$ nor was it correlated with any of the other measured variables. Ratings of control of auditory imagery on the BAIS-C items were also not significantly correlated with years of musical training $r(39) = .141$, $p = .386$, however BAIS-C scores were significantly correlated with INM task performance $r(39) = -.384$, $p = .015$.

A multiple regression analysis was conducted predicting APM performance from tonal working memory precision (INM), singing accuracy (SSAP), pitch discrimination ability, vividness of auditory imagery (BAIS-V), control of auditory imagery (BAIS-C), and number of years of musical training. Additionally, based on the hypothesis of the study, the INM and SSAP were allowed to interact with both musical training and auditory imagery (BAIS-V and BAIS-C) (i.e., to assess whether the relative strength of associations changed as a function of musical training or auditory imagery). Overall, the regression was not significant $F(13, 39) = 1.05$, $p = .438$, and there was no evidence that either musical training or auditory imagery interacted with the INM or SSAP (all ps > .155).

Figure 3

Correlation between absolute pitch memory and tonal working memory



Note: There was a significant correlation between absolute pitch memory (APM) and implicit note memory (INM) task performance, $r(39) = -.393$, $p = .006$, suggesting that participants with better tonal working memory also had better long-term memory for pitch. The dashed vertical line represents chance performance on the APM task. The ribbon around the trend line represents the 95% confidence interval.

Discussion

The present study aimed to investigate how tonal working memory, singing accuracy, auditory imagery ability, and musical training may play a role in non-AP individuals' long-term absolute pitch memory. It was predicted that tonal working memory precision would be associated with accuracy of absolute pitch memory for popular songs, as reported in Van Hedger et al. (2017). It was also hypothesized that singing accuracy would be positively associated with accuracy of absolute pitch memory for popular songs, as reported in Halpern and Pfordresher (2021). Musical training and auditory imagery abilities were not expected to be directly associated with absolute pitch memory but were thought to perhaps play a moderating role in the relationship between tonal working memory precision and absolute pitch memory accuracy, and in the relationship between singing accuracy and absolute pitch memory accuracy. The first hypothesis was supported by the finding that tonal working memory accuracy on the INM task was significantly correlated with APM performance. Individuals who had more precise tonal working memory tended to also have more accurate absolute pitch memory for popular songs. There was marginal support for the second hypothesis with SSAP performance being marginally correlated with APM performance. There was no evidence of a moderating effect of auditory imagery ability or musical training.

The finding that better INM performance was associated with more accurate absolute pitch memory for popular recordings conceptually replicates prior work done by Van Hedger et al. (2017) with the effect size in the present study (r = -.39) being similar to that found in their research (r = -.43 in Experiment 1 and r = -.31 in Experiment 2). One possible explanation for the relationship between INM performance and APM ability that is highlighted by Van Hedger et al. (2017) is that both tasks may rely on precision in working memory. Prior research has looked at working memory in terms of two potentially dissociable concepts: precision, the quality of working memory, and capacity, the number of items that may be maintained in working memory (Zhang & Luck, 2011). Van Hedger et al. (2017) states that the INM task is more involved in the precision of working memory and that judging whether the pitch of popular recordings, as done in the APM task, is also likely to rely on precision in (long-term) memory. It is possible that short-term memory and long-term memory could have similar limits in terms of precision, which may be why performance on the APM task, a measure of long-term representations of pitch, was correlated with and predicted by performance on the INM task. Previous research has examined the fidelity of long-term memory and working memory in the visual domain and has indicated that fidelity of long-term memory was comparable to that of working memory (Brady et al., 2013). This suggests that long-term memory and working memory may have a shared limit in terms of precision. This finding has however been challenged by a replication of the Brady et al. (2013) study which found that working memory representations of colour information were more precise than that in long-term memory, suggesting that there may not be a general limit on both working memory and long-term memory (Biderman et al., 2018). While it is uncertain whether both working memory and long-term memory rely on the same limit on precision, the findings of the present study suggest that there is a connection between both types of memory as individuals who have high precision in long-term memory also tend to have high precision of tonal working memory.

In terms of the relationship between APM accuracy and SSAP performance, the results are similar to those found in Halpern and Pfordresher (2022) with the effect size of the present study (r = .25) being nominally weaker than their findings (r = .30). The stronger correlation between INM performance and SSAP accuracy perhaps indicates there may be a shared process that occurs within pitch reproduction, regardless of whether the task involves vocal reproduction or not. The finding that INM performance is correlated with APM accuracy indicates that pitch reproduction tasks play an important role in explaining differences in APM performance. The stronger relationship between INM performance and APM performance as opposed to APM and SSAP performance may be explained by the fact that the APM task used in the present study was a perceptual task and did not involve any elements of production. The APM task used by Halpern and Pfordresher (2022) involved selecting the starting pitch of popular songs on a keyboard, which means participants had to not only remember the correct pitch of the original song, but also reproduce that pitch. The APM task in the present study was strictly perceptual in nature, which may explain why the correlation between APM and SSAP performance in the present study was weaker than in Halpern and Pfordresher (2022). Future work should further examine whether correlations of performance on production tasks and pitch memory tasks are dependent on the extent to which the task involves production or perceptual responses. This is further discussed for future directions later.

Contrary to the initial prediction that musical training may moderate the relationship between APM and the other measures of auditory and musical individual differences, the present results did not find any indication of this. Although musical training was correlated with INM and SSAP performance, musical training did not significantly change the association strength between either the INM or SSAP and APM performance, which would have emerged in the multiple regression model as a significant interaction term. This suggests that musical training is likely not predictive of APM accuracy. Prior research by Van Hedger et al. (2017) also did not find a relationship between musical training and APM ability and to my knowledge, no other research has explored whether musical training may have a moderating effect on the relationship between auditory tasks, such as the INM, and APM ability. It is clear that the ability to reproduce pitch is related to APM performance, however this association does not appear to be significantly connected to musical training.

Auditory imagery ability was also not found to be related to APM performance. Ratings of the vividness of auditory images were not correlated with any of the other individual difference measures nor was it predictive of APM performance. While the ratings of the ease in which one could control and change auditory images was not related to APM performance, it was correlated with INM performance. This may be explained by the idea that both tasks are conceptually measuring working memory performance, with the INM being considered a measure of tonal working memory (Van Hedger et al., 2017) and the BAIS-C being a self-report measure of the ease in which individuals can manipulate auditory images in thought (Halpern & Pfordresher, 2022). It would make sense that participants who perform better on a tonal working memory task may report more ease in manipulating auditory images. However, control of auditory imagery did not interact with any of the other measured variables in explaining APM performance.

The present study is not without limitations. The study is limited in generalizability due to the overall homogeneity of the sample. With the sample consisting of mainly university students, it is uncertain if the present results would generalize to a population with more variance in levels of education. In using a university sample, the present study was unable to examine the effects of age. Although previous research has suggested that pitch memory is an ability that remains stable into adulthood (Jakubowski et al., 2016), future research could include a more diverse sample to ensure generalizability of the results. Another potential limitation could be in using a self-report measure to assess auditory imagery. Future studies could use a more objective measure such as the pitch imagery task used in Greenspon and Pfordresher (2019) in addition to the BAIS to further test the concept of auditory imagery in relation to long-term memory for pitch.

As stated earlier, future work should examine whether performance on pitch reproduction tasks and pitch memory tasks are dependent on the extent to which the pitch memory task involves production or perceptual responses. The pitch memory task used in the present study relied on perception, as participants made judgements on the pitch of popular recordings but were not required to hum or reproduce the pitches of these songs (cf. Levitin, 1994). Other studies such as Levitin (1994) operationalized pitch memory using a production task in which participants hummed popular songs from memory and sung pitches were compared to that of the original songs. Future research could expand on the present study by examining whether the correlation strength between performance on the INM task and APM and SSAP performance and APM are dependent on the congruency of pitch memory task. It would be reasonable to expect that SSAP performance would be more strongly correlated to a long-term pitch memory task that involved vocal production like that used in Levitin (1994) as both tasks would rely on one's ability to reproduce pitches accurately. While INM performance was correlated with performance on the perceptual APM task used in the present study, the INM also involves aspects of pitch production, however not in a vocal sense. By examining the role of production in pitch memory tasks, insight may be provided into the relationship that was found between INM and SSAP performance to better understand the mechanisms involved in vocal pitch reproduction and other forms of pitch reproduction such as that implemented in the INM task.

To summarize, the present study served as an exploratory analysis of how individual differences in tonal working memory precision, singing accuracy, auditory imagery ability, and musical training factor into the variance observed in long-term pitch memory abilities in the average listener using a within-subjects design. The present results indicate that tonal working memory was most significantly correlated with pitch memory ability, however, the relative strength of this association (particularly compared to the weaker association between the SSAP and pitch memory) may be influenced by the way in which pitch memory was operationalized in the study. Further research should seek to elaborate on the role of perceptual versus production-based pitch memory tasks in terms of how individual differences contribute to long-term pitch memory.

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Appendix

Title	Artist
Single Ladies	Beyonce
Umbrella	Rhianna
Shake It off	Taylor Swift
Toxic	Britney Spears
Rolling in the Deep	Adele
Firework	Katy Perry
Blinding Lights	The Weeknd
Hey Ya	Outkast
Hips Don’t Lie	Shakira
Bringing Sexy Back	Justin Timberlake
Call Me Maybe	Carly Rae Jepsen
Uptown Funk	Bruno Mars
Poker Face	Lady Gaga
Starships	Nicki Minaj
Royals	Lorde
Party in the USA	Miley Cyrus
Bad Guy	Billie Eilish
Get Lucky	Daft Punk
Happy	Pharrell Williams
Despacito	Luis Fonsi
Gangnam Style	Psy
Take On Me	a-ha
Sweet Child O Mine	Guns ‘N Roses
Imagine	John Lennon
We Are The Champions	Queen
Smells Like Teen Spirit	Nirvana
Somebody That I Used to Know	Gotye
American Pie	Don McLean

28 excerpts of popular songs were used in the APM task.

Curriculum Vitae

Name:

Evan Smith

Place and Year of Birth:

London, Canada, 2001

Secondary School Diploma:

Senior Matriculation, St. Thomas Aquinas Catholic Secondary School, London, Canada

Experience:

Huron Auditory Perception Lab – Undergraduate Research Assistant

Awards:

Dean’s Honors List	2020/2021
Dean’s Honors List	2021-2022
Dr. Joanne and Peter Mac Pherson Psychology Scholarship	2021-2022