Pitch Memory and Exposure Effects

Moshe Shay Ben-Haim [*] Zohar Eitan [*]

Tel-Aviv University

Eran Chajut

The Open University of Israel

* The first and second authors contributed equally to this article.

Moshe Shay Ben Haim, School of Psychological Sciences, Tel Aviv University; Zohar Eitan, School of Music, Tel Aviv University; Eran Chajut, Department of Education and Psychology, The Open University of Israel.

This research was supported by an Israeli Science Foundation (ISF) F.I.R.S.T grant No. 1164/09 to the 2nd and 3rd authors. We thank Neta David, Shirit Cohen, and Alex Gotler for assistance with data collection and analysis, and Gitit Kave, Nurit Gronau and Miriam Furst-Yust for invaluable comments and suggestions.

Correspondence should be addressed to Zohar Eitan, School of Music, Tel Aviv University, Ramat Aviv, Israel, 69978. Email: Zeitan@post.tau.ac.il, +972-54-8100998, +972-9-7420726

Journal of Experimental Psychology: Human Perception and Performance, Vol 40(1), Feb 2014, 24-32. http://dx.doi.org/10.1037/a0033583

ABSTRACT

Recent studies indicate that the ability to represent absolute pitch values in long-term memory (LTM), long believed to be the possession of a small minority of trained musicians endowed with "absolute pitch" (AP), is in fact shared to some extent by a considerable proportion of the population. The current study examined whether this newly-discovered ability affects aspects of music and auditory cognition, particularly pitch learning and evaluation. Our starting points are two well-established premises: (1) frequency of occurrence has an influence on the way we process stimuli; (2) in Western music, some pitches and musical keys are much more frequent than others. Based on these premises, we hypothesize that if absolute pitch values are indeed represented in LTM, pitch frequency of occurrence in music would significantly affect cognitive processes, in particular pitch learning and evaluation. Two experiments were designed to test this hypothesis in participants with no AP, most with little or no musical training. Experiment 1 demonstrated a faster response and a learning advantage for frequent pitches over infrequent pitches in an identification task. In Experiment 2 participants evaluated infrequent pitches as more pleasing than frequent pitches when presented in isolation. These results suggest that absolute pitch representation in memory may play a substantial, hitherto unacknowledged role in auditory (and specifically musical) cognition.

Key words: Absolute pitch, absolute key, pitch memory, exposure effects, statistical learning

Introduction

Humans are extremely good in processing auditory pitch in working memory, often distinguishing pitches a few Hertz (Hz) apart when heard in close succession (Zwicker, Flottorp, & Stevens, 1957). Yet, the canonical consensus has been that for all but a tiny minority of individuals with absolute pitch (AP), there is no stable representation of absolute pitch values in long-term memory, but rather representations of pitch *relationships* (for reviews of AP research, see Deutsch, 1999; Levitin & Rogers, 2005; Purncutt & Levitin, 2001). For instance, even trained musicians, who would readily recognize relative pitch configurations such as intervals, chord types, and musical keys, would mostly fail to recognize or recall a single isolated pitch (e.g., 440 Hz A) without a reference tone.

Indeed, the notion that pitch *relationships* and patterns, rather than *absolute* pitch values, underlay music processing, is central to music theory and music cognition research, and to the practice of Western music. In music theory, basic concepts such as pitch intervals, chord structures, musical keys and modes, as well as pitch-class sets and tone rows in post-tonal theory, address pitch *relationships*, rather than absolute pitch identity (e.g., Christensen, 2008; Straus, 2004). Accordingly, for instance, two melodies would be considered essentially identical if the relationships among their constituent pitches are equivalent, even if these melodies have no pitches in common. Likewise, performers habitually transpose music from one key to another for practical purposes (e.g., fitting the vocal range of a particular singer), assuming that this procedure, which may alter every pitch in a melody while maintaining pitch relationships, has little or no impact on the overall musical experience.

However, accumulating evidence has indicated that long-term memory for pitch is more widespread than previously believed (e.g., Schellenberg & Trehub, 2003). Notwithstanding the undisputed role of pitch relationships in music perception, these findings suggest that absolute pitch representation may play a role in pitch processing. The current study presents two experiments that lend strong support to the presence of long-term pitch representation. More importantly, these experiments reveal the impact of implicit mental representation of absolute pitch on aspects of auditory processing (learning and evaluation) in the general, musically-untrained population.

Absolute Pitch (AP) has traditionally been defined as the ability to name the pitch (or pitch-class)[1] of a tone presented in isolation, or to produce a specified pitch without external reference (Levitin & Rogers, 2005). Thus defined, AP encompasses two components: pitch memory, the long-term representation of pitch (or pitch-class), and pitch labeling, which is the ability to *explicitly* associate perceived or produced pitch with a specific label or symbol (usually Western note-names and their corresponding musical notation). Pitch labeling is necessarily confined to people with musical training who have learned to associate pitch with conventional labels.

However, pitch memory has also been examined separately from pitch labeling, thus making it possible to investigate it within the general, musically untrained population. It appears that a sizeable proportion of the population, rather than just a minority of musicians, as hitherto believed (Rossing, 1990), is endowed with long-term pitch memory. Thus, for instance, musically untrained participants tend to reproduce familiar songs at or near the original pitch level (Halpern, 1989; Levitin, 1994). Similarly, mothers singing to their children tend to repeat their singing at the same pitch level (Bergeson & Trehub, 2002). When presented with familiar music, played both in the original key and in one or two semitone transpositions, adult participants without explicit AP (Terhardt & Seewann, 1983; Terhardt & Ward, 1982; Schellenberg, & Trehub, 2003) as well as 5-12 year old children (Trehub, Schellenberg, & Nakata, 2008; Schellenberg, & Trehub, 2008) distinguish the original key from its transpositions well beyond chance level. Similarly, Marvin and Newport (2011) exposed participants without explicit AP to short musical figures, and then used a recognition

---

[1] All pitches an octave (or its multiples) form each other belong to the same *pitch-class* (or share the same *pitch chroma* quality). For instance, the pitches A1 (55Hz), A2 (110Hz), A3 (220Hz), A4 (440Hz), etc., all belong to the pitch class denoted by the note-name "A-natural."

task to show that exposure led to successful distinction between the original figures and their minor third transpositions, thus demonstrating implicit learning abilities. Evidence for absolute pitch representation in the general population has been found not only for melodies or melodic figures, but also for single pitches. Thus, when non-musicians without explicit AP were asked to classify pitch-shifted versions of a familiar dial tone into normal, higher than normal, or lower than normal, they performed significantly above chance levels (Smith & Schmuckler, 2008).[2]

If LTM representation of absolute pitch is indeed widespread, as the above studies strongly suggest, then such representation should be of significance in auditory and music processing. Yet, how can such presumed effects be examined? Our starting points in investigating this issue are two generally accepted premises, from which we suggest to examine our novel hypothesis.

First, in Western tonal music some musical keys (and correspondingly, some pitches and pitch-classes) are extremely more frequent than others. Frequency of occurrence has been calculated for musical keys in both classical and popular music, demonstrating in both repertories a strikingly uneven distribution (individual differences between composers notwithstanding) and overall preference for specific keys, such as D, G, and C major. Consequently, listeners are exposed to some pitches, pitch-classes, and keys more often than they are exposed to others (Simpson & Huron, 1994; Purwins et al., 2003, for pitch-class and key distributions in classical music, and Figure 1 for our survey of contemporary popular music).

Second, it is well established that a variety of perceptual and cognitive tasks are sensitive to the rates in which the stimuli are presented. Effects of exposure frequency have been found

---

[2] . Notably, long-term memory representation has been found, in addition to pitch, for other surface musical features, such as tempo and timbre (Levitin, 2002; Trainor, Wu, & Tsang, 2004), thus further contesting the notion that musical memory relies exclusively on structural features such as tonal and metrical relationships.

in tasks of selective attention (Burt, 2002; Melara & Algom, 2003), recognition, particularly word recognition (Norris, 2006; Malmberg & Nelson, 2003), and evaluation of a wide gamut of stimuli, from proper names to artwork (Colman, Best, & Austen, 1986). In music cognition and perception, frequency of exposure has proved to be associated with several basic processes, as diverse as key identification (Krumhansl, 1990; Temperley, 2007) and emotional response (Huron, 2006). Furthermore, studies suggest that statistical learning of pitch may be associated with fundamental aspects of pitch perception and production, such as the selection of pitch intervals used in music, the perception of consonance and dissonance, and perhaps even pitch extraction itself (Schwartz & Purves, 2004; Schwartz, Howe, & Purves, 2003). However, since until recently the canonical consensus has regarded only relative pitch information as relevant for pitch processing, the role of frequency of exposure to *absolute* pitch or key in music processing has never been examined. Here we firstly examine how lifetime frequency of exposure to absolute pitch may affect pitch processing in the general population.

Given the evidence for long-term pitch memory, we expect that the frequency of occurrence of pitch (and pitch-class) would affect basic aspects of perception and cognition of music, such that frequent and infrequent pitches would be processed differently. Evidence in support of this hypothesis would suggest that absolute pitch representation in LTM is not only widespread, but that it also affects auditory processing in important ways. We conducted two experiments that tested aspects of this hypothesis, predicting that responses would reflect the extent of previous exposure to frequent and infrequent pitches. Experiment 1 demonstrated a speeded learning advantage for frequent pitches over infrequent ones in a pitch identification task. In Experiment 2, participants asked to evaluate the pleasantness of isolated pitches evaluated *infrequent* pitches as more pleasing than frequent ones.

Experiment 1: Occurrence frequency effects in pitch identification and learning

Experiment 1 examined the hypothesis that processing of frequent pitch would be superior to processing of infrequent pitch, using a pitch identification task. Specifically, we predicted that responses to frequent pitch would be faster and more accurate than responses to infrequent pitch, and that improvement in reaction time to frequent pitch would be greater than improvement in reaction time to infrequent pitch.

Method

Participants: One-hundred and seventy-four participants (133 females, 41 males, mean age = 27) were sampled, including 138 Open University undergraduates and 36 active musicians. Open University students participated in the study in partial fulfillment of course requirement. These participants were classified into three groups differing in their musical background: the no-experience group included 84 students with no musical experience whatsoever, and the minor-experience group included 54 students with little musical training (maximum three years, mean 1.2 years), who have not been engaged in music studies or music performance in recent years. The 36 active musicians constituted the professional group, and included advanced music students of the Buchman-Mehta School of Music at Tel Aviv University, with at least 7 years of formal musical training (mean = 10.3 years). All participants reported having normal hearing. Six untrained participants who exhibited random performance levels (less than 30% correct responses at one or more conditions) were excluded from the final analysis.

Stimuli: Four musical tones in the range of a perfect 5th, which established scale degrees 1, 2, 3, and 5 of a major key (e.g., C4, D4, E4, and G4 in C major). Each participant was assigned with pitches in one of six major keys, three of them frequent: C (C4, D4, E4, G4), D (D4, E4, F#4, A4), G (G4, A4, B4, D4), and three infrequent: Db (Db4, Eb4, F4, Ab4), F# (F#4, G#4, A#4, C#4), and Ab (Ab4, Bb4, C4, Eb4). Each of the four tones in a key was associated (pitch height order) with a number on the computer keyboard, from 1 to 4. The stimuli were MIDI concert piano sounds, each of 1s duration, generated by a Steinberg's Virtual Studio Technology Instrument (VSTi)-Edirol HQ Orchestral v.1.03. Stimuli were presented at a fixed volume by a Pentium(R) 4 2.8GH computer through standard computer video-chat headphones. Stimulus presentation and time measurement were controlled by a DirectRT Precision Timing Software (Version 2008.1.0.11).

Procedure: Pitches in the six keys were randomly assigned to participants. Participants were first introduced to the pitches by listening to each pitch twice while the corresponding number appeared on the screen. They were then asked to listen to these pitches freely over eight trials and were instructed to activate each pitch by pressing the corresponding number key. These trials were followed by two training sessions, consisting of 96 trials each, and a test phase, consisting of 120 trials. In both training and test phases, participants were asked to listen to the tone and then press the corresponding key as rapidly and as accurately as possible. Corrective feedback was provided when participants pressed the wrong key ("Error! This was sound number…"). When participants took more than 3000 ms to respond, they received feedback that they should try to respond faster (in the form of a written comment on the screen).

Data analysis: The reaction time (RT) analysis was performed on correct responses. Responses longer than 3000 ms or shorter than 180 ms were excluded from the analysis. Since pitch height is known to affect aspects of pitch perception, we also examined the effect of this variable, comparing data for lower (C, Db, D) and higher (F#, G, Ab) musical keys; pitch height proved to be non-significant for both accuracy ($p > 0.7$) and RT ($p > 0.2$), and is hence excluded from further analysis.

Results and Discussion

Accuracy and RT in the test phase were analyzed by two-way analyses of variance (ANOVA), with key frequency (frequent/infrequent) and musical training (none/minor/pro) as between-subject variables. Consistent with our hypothesis, mean RTs were significantly shorter for frequent (890 ms) as compared to infrequent keys (952 ms), $F(1,168) = 4.28$, $MSE = 31953$, $p = 0.04$ (see Figure 2A). Although an expected main effect of musical training was present, $F(2,168) = 88.58$, $p < 0.0001$, the interaction between frequency and musical training was not significant, $F < 1$, suggesting that frequency facilitated performance regardless of musical experience. Mean RTs for individual frequent keys were C=866, D=884, and G=922, and the corresponding RTs for infrequent keys were Db=941, F#=963, and Ab=950. Thus, RTs for frequent keys were lower than RTs for adjacent infrequent keys. To avoid post-error slowing effects, resulting from error feedback (e.g., Koehn et al., 2008; Notebaert et al., 2009; Sanders, 1998), an analysis of RTs in trials following correct reactions was also conducted; feedback had no negative impact on results, $F(1,168) = 4.66$, $MSE = 32700$, $p = 0.032$. The error rate on frequent keys was 19% and the error rate on infrequent keys was 22%; these rates did not differ significantly, $F < 1$ (see Figure 2B). Importantly, however, error rates indicate that the occurrence frequency effect in RTs was *not* a result of a speed-accuracy trade-off. Although a significant main effect of musical training on error rates was found, $F(2,168) = 42.29$, $MSE = 0.018$, $p < 0.0001$), there was no significant interaction between occurrence frequency and musical training in terms of accuracy, $F < 1$.

Relative pitch effects. To evaluate the effect of relative pitch on performance, we compared RT and accuracy for the 4 tones presented to each participant (1, 2, 3, and 5) across all keys (see Table 1). Scale degree position had a substantial effect on both RTs, $F(3,504) = 86.69$, $p < 0.0001$, and error rates, $F(3,504) = 46.20$, $p < 0.0001$. Tukey post-hoc analysis indicated that performance was best (shortest RTs, lowest error rates) for the 1st and 5th scale-degrees, worse for the 2nd scale-degree, and worst for the 3rd degree, $p \leq 0.009$. For error rates, a significant interaction between scale degree and musical training also emerged, $F(6,504) = 5.20$, $p < 0.0001$, so that scale degree did not affect error rates for professional musicians, $p > 0.9$.

The above analysis highlights the contribution of both relative and absolute pitch to task performance. For instance, pitches D4 and Ab4 (G#4) were both presented twice: once as 1st degrees in the keys of D and Ab, and once as 2nd degrees in the keys of C and F#. Even though participants responded to the same absolute pitches in both cases, change in scale-degree position had a significant impact on RTs. Thus, for both pitches, performance was considerably faster when the decision referred to the 1st scale-degree (845ms for D, 869ms for

Ab) as compared to the 2nd scale-degree (939ms for D, 1049ms for Ab), $t(57) = 2.59$, $p = 0.012$. Notwithstanding these relative pitch effects, occurrence frequency effects were comparable across scale-degree positions, as the interaction between scale-degree and key frequency was not significant, $F < 1$.

Learning rate analysis. To assess improvement in performance, we plotted mean RTs throughout the entire experiment (including the training sessions) in blocks of 12 trials. As can be seen in Figure 3 (left-hand panel), performance improved for both frequent and infrequent keys. The rate of improvement, however, was significantly superior for frequent keys. Although starting at a comparable performance level, participants that allotted frequent keys gradually formed an increasing gap in performance through the progression of the experiment. The progressive difference in RT performance across the two groups is plotted in Figure 3, right-hand panel. A Pearson linear analysis of the progressive difference in acceleration across successive 12-trial blocks indicated that the difference in performance is doubled by a factor of 2.27 every 12 trials, $r = 0.655$, $p < 0.001$.

Accuracy also increased across blocks, but progressive differences in accuracy between frequent and infrequent keys did not reach statistical significance, $r = 0.16$, $p = 0.44$. Note, however, that this pattern of results indicates that the improvement in RT does not reflect a speed-accuracy tradeoff.

Experiment 2a: Occurrence frequency effects in pitch evaluation

Experiment 1 demonstrated a speeded learning advantage for keys frequent in the musical repertory, suggesting that long-term memory for absolute pitch influences participants' performance in a speeded pitch identification task. Experiment 2 examines the effects of pitch memory on another fundamental cognitive ability: affective evaluation. We hypothesize that the evaluation of frequent pitches would differ from the evaluation of infrequent pitches. Whether frequent pitches would be rated as more or less pleasant than infrequent ones is an open question, since data attesting to the relationship between exposure frequency and evaluation is not unequivocal. On the one hand, the *mere exposure effect,* in which exposure rate is positively associated with evaluation (Zajonc, 1968), has been established in diverse domains, including music perception (Hunter & Schellenberg, 2011; Schellenberg, Peretz, & Vieillard, 2008; Szpunar, Schellenberg, & Pliner, 2004). On the other hand, overexposure has been shown to lead to *a decrease* in liking, both for music (Hunter & Schellenberg, 2011; Schellenberg et al., 2008; Szpunar et al., 2004; Tan et al., 2006) and for other stimuli (see Bornstein, 1989, for a review and meta-analysis of relevant research). Nevertheless, a significant difference in pleasantness ratings in either direction between frequent and infrequent pitches would suggest that long-term memory of pitch plays an important role in pitch evaluation.

Method

Participants: Thirty Open University undergraduates (23 females, 7 males; mean age = 27) took part in the experiment. All participants attested to having no explicit absolute pitch abilities, and have had little or no musical background (mean years of musical training = 0.7). None of the participants had participated in Experiment 1. Participants took part in the experiment in partial fulfillment of course requirements.

Stimuli: The stimuli consisted of MIDI sounds simulating three musical instruments: piano, flute, and violin. They were generated by a Steinberg's Virtual Studio Technology Instrument (VSTi)-Edirol HQ Orchestral v.1.03. Twenty four 1-second pitches in the range of C4 to B5 (2 octaves) were presented in each instrumental timbre, comprising a total of 72 experimental trials. Stimuli were presented at a fixed volume by a Pentium(R) 4 2.8GH computer. To minimize the effects of relative pitch (Mull, 1925; Hartman, 1954), a 10-second interval was inserted between each two test pitches. The interval was filled by 24 MIDI tones (C4-B5) of a different timbre (“timpani”), each lasting 300 ms. These tones were played in a random order, and were followed by white noise. Auditory fillers were intended to minimize relative pitch effects that could be generated by the previous test tone.

Procedure: Participants listened to each pitch separately, and were requested to rate the pitch for pleasantness on a scale of 1 ("not pleasant") to 9 ("very pleasant"). Each of the 72 pitches was presented once. Stimuli were intermixed randomly within the experimental session with a different randomization used for each participant. Each 1 second test pitch was followed by a 10 second filler interval.

Results and Discussion

Participants rated frequent pitches (mean = 6.02) less favorably than they rated infrequent pitches (6.25), t(29) = 3.7, $p < 0.001$, d = 0.68. Though instrumental timbre strongly affected ratings, with piano being the most favorable and violin the least favorable, the preference for infrequent pitches was consistent for all three instrumental timbers. For the violin sounds, the mean rating of frequent pitches was 4.67, and of infrequent pitches -- 4.96; t(29) = 2.31, p = 0.029. For flute, the mean rating of frequent pitches was 6.36, and of infrequent pitches -- 6.59; t(29) = 2.45, p = 0.02. For piano, the mean rating of frequent pitches was 7.05, and of infrequent pitches -- 7.20; t(29) = 1.82, p = 0.079. Figure 4 presents performance across instruments.

Table 2 plots the mean ratings for each of the 12 pitch classes according to their respective frequency of occurrence (Simpson & Huron, 1994). While frequency tended to correlate with ratings, the correlation was only marginally significant, r = 0.38, p = 0.068. Note that the *positive* direction of the correlation is due to the use of an *inverted* frequency measure (Simpson & Huron, 1994), such that pitches with higher inverse log frequency are actually less frequent. No correlation was found between pitch height and mean ratings, r = -0.30, p = 0.15.

The results of Experiment 2a suggest that participants evaluate frequent pitches as less pleasant than infrequent pitches. Higher ratings of less frequent pitches might seem surprising, and yet these findings are consistent with Berlyne's (1970) inverted U model. Since participants were presented with very simple stimuli, they may have favored the least familiar because these were more arousing. However, ratings in Experiment 2a were fairly noisy, and the correlation between frequency and ratings was only marginally significant. We suspect that these noisy results reflect sensitivity to order of presentation, as well effects of load or fatigue, as participants had to respond to repeated pitches, each presented in three different timbres, following each other in close succession.

Pitch context – relative pitch effects -- may have also influenced the results of Experiment 1, as each participant in that experiment heard several pitches within a specific key in close succession. Indeed, our analysis of relative pitch effects in Experiment 1 indicated that in addition to the effect of occurrence frequency, relationships among pitches have a significant impact on task performance.

Experiment 2b aims to examine the effects of absolute pitch memory on evaluation, while isolating stimuli from any pitch context. In this experiment, each participant rated pleasantness of one *single* pitch. Thus, data was collected from a large number of participants, each rating a different pitch. Results consistent with those of Experiment 2a would suggest that listeners represent properties of a single, context-free pitch in LTM, and that this latent representation affects pitch evaluation.

Experiment 2b: Context-free effects of occurrence frequency in pitch evaluation

Method

Participants: Two-hundred and forty-five participants (194 females, 51 males; mean age = 27) were sampled. All participants attested to having no explicit absolute pitch abilities, and have had little or no musical background (mean years of musical training = 1.7). None of the participants took part in Experiments 1 or 2a. All participants were Open University undergraduates who received partial course credit for their participation.

Stimuli: The stimuli consisted of MIDI concert piano sounds in the range of C4 (approx. 292 Hz) - B4 (494 Hz), encompassing all the 12 chromatic pitches in an octave. Sounds were generated by a Steinberg's Virtual Studio Technology Instrument (VSTi)-Edirol HQ

Orchestral v.1.03, and were presented at a fixed volume by a Pentium(R) 4 2.8GH computer. Each sound was heard for 1 second.

Procedure: Each participant was asked to rate a single pitch on a 1 (“considerably dislike”) to 9 (“considerably like”) scale. Participants were randomly assigned to one of the 12 pitches.

Results and Discussion

Ratings for frequent pitches (mean = 5.61) were significantly lower than ratings for infrequent pitches (mean = 6.32), t(238) = 2.47, p = 0.014, as shown in Figure 5. This difference indicates that the preference for infrequent over frequent pitches (d = 0.32) is reliable.

Comparing the average ratings of each frequent pitch with those of its adjacent infrequent pitch reveals that the difference is consistent across all pitches in our sample, as can be seen in Table 3. Thus, frequent pitches received lower pleasantness ratings relative to adjacent infrequent pitches. Furthermore, frequency was significantly correlated with ratings of pleasantness, r = 0.58, p = 0.049 (see Figure 6). Note that Simpson and Huron (1994) used an inverted value of frequency, so that higher values indicate less rather than more frequent pitches. Our analysis showed that frequency explained 33% of the variance in ratings. Though there was also a tendency for pitch height to correlate with ratings, r = 0.40, this tendency did not reach statistical significance, p = 0.19.

The results of Experiment 2b demonstrate that evaluation of isolated, context-free pitches is inversely associated with lifetime exposure to pitch-classes. This pattern of performance suggests that pitch (or pitch-class) is represented in LTM. This finding is particularly noteworthy since stimuli in Experiment 2b were completely free of any immediate pitch context, and thus devoid of veridical auditory memory associations.

General Discussion

Two experiments demonstrated that lifetime exposure to musical pitches affects important aspects of pitch processing: frequent pitches are learned more efficiently than infrequent pitches in an identification task (Experiment 1), and are rated as less pleasing than infrequent pitches in an evaluation task (Experiments 2a, 2b).

Our data are in line with previous studies according to which AP information is implicitly encoded and stored by the majority of the population (Schellenberg, & Trehub, 2003; Smith, & Schmuckler, 2008; Trehub et al., 2008). However, the implications of our findings are novel in several ways. First, the current results indicate that encoding of absolute pitch information in the general population does not necessarily depend on veridical memory of specific stimuli, such as a frequently heard song or dial tone. Instead, it may rely on representation of pitch or pitch-class categories that are dissociated from a specific, familiar auditory stimulus. Consequentially, the effects of long-term pitch memory may generalize to diverse musical and auditory contexts, and apply to stimuli that the listener has not heard before.

Second, Experiment 1 extends previous findings, which have revealed RT advantage for processing frequent, white-key pitches. Such advantage has been documented in trained musicians, either those who had AP (Miyazaki, 1989, 1990; Takeuchi & Hulse, 1991) or those with no AP (Marvin & Brinkman, 2000). Yet, our study shows that participants with little or no musical background demonstrate similar sensitivity to pitch frequency. Thus, unlike previous findings, the current results cannot be attributed to professional music training, they cannot reflect reliance on explicit association of verbal labeling with musical pitches, and they cannot stem from a naming bias of black-key pitches, defined in terms of their white-key neighbors (a “white” pitch name + sharp/flat, e.g., C-sharp). Rather, the occurrence frequency effect seen here suggests that pitch memory is subject to implicit statistical learning over a lifetime of exposure to musical pitch.

Third, and perhaps most importantly, our results suggest that long-term pitch representation is not only widespread, but that it also affects fundamental aspects of auditory cognition, such as identification and evaluation.

We propose, then, that previous investigations of how we categorize, remember, learn, and evaluate music, and particularly how we process pitch-related aspects of melody, harmony, and voice-leading, might have overlooked a potentially substantial factor. By focusing almost exclusively on pitch *relationships*, research has ignored stored absolute pitch or absolute key knowledge, except when specifically addressing this knowledge in individuals with explicit AP. Note that our work calls into question the canonical notion of *transpositional equivalence*, according to which a piece of music remains essentially the same even if transposed to another key, as transpositions do not alter pitch relationships. In contrast to the transpositional equivalence assumption, taken for granted in much music theory and music cognition research, our results suggest that transposing a musical piece from G to F-sharp major, for instance, or choosing to compose a new song in B major instead of C major, may in fact affect perception and cognition in important ways.

Although the present study strongly suggests that long-term pitch memory may be an important factor in music processing, it raises many unresolved questions. First, it is unclear whether the effects that were found here for simple stimuli would generalize to more complex musical contexts. Future research must ask, for example, whether actual music in common keys, such as G major, would be easier to recognize or recall than the same music in less frequent keys, such as F-sharp major, as implied by the results of Experiment 1. Further investigation is also required to determine whether differences in evaluating frequent and infrequent pitches in isolation would be seen when more complex musical stimuli, such as melodies or chords, are processed, as implied by the results of Experiment 2.

Moreover, we do not know to what extent implicit long-term memory for pitch, as revealed here and in earlier studies, and explicit AP – the ability to name an isolated pitch, or to produce a specified pitch without any external references (Levitin & Rogers, 2005) – are based upon similar mechanisms. Authors such as Deutsch (2002) and Levitin and Rogers (2005) have proposed a two-component model of explicit AP: a pitch memory component, to be found in the population at large, and a pitch labeling component, to be found only in musically-trained individuals with explicit AP. Levitin and Rogers (2005: 32) write that "*the long-term memory representation for well-known songs might combine both absolute and relative pitch cues, suggesting a hybrid model and supporting the notion of accurate and stable 'pitch memory' distinct from labeling."* Our findings provide strong support for the existence of a stable pitch memory in the general population, showing that implicit processing of absolute pitch information affects auditory cognition. Furthermore, these findings are consistent with the hypothesis that non-musicians lacking the "labeling" component of explicit AP may still implicitly encode the same pitch-class categories that AP possessors explicitly label. Long-term memory for pitch thus appears to be more like memory in other sensory domains (e.g., color) than hitherto believed, since it may be experienced in terms of specific categories (see also Levitin & Rogers, 1995, for a discussion of this issue). Future work will have to further explore the relationships between explicit AP, as defined above, and the diverse phenomena demonstrating long-term pitch memory in the general population (for a different model of AP, also relevant to this issue, see Ross, Gore, & Marks, 2005).

Lastly, the effects of implicit pitch memory on other aspects of music processing have yet to be explored. For instance, further investigation is required to determine whether pitch-class frequency of occurrence affects basic aspects of pitch perception, such as detection or discrimination. It is also unclear how implicit absolute pitch memory interacts with well-established effects of *relative* pitch processing, such as the cognitive hierarchy of scale-degrees in major and minor keys (Krumhansl, 1990; Temperley, 2007). We also do not know how AP information affects the way music associates with emotion or with other extra-musical features. For instance, would frequent and infrequent musical keys have different perceived "characters" (e.g., “vigorous” vs. “mysterious,” respectively), as often claimed by 18th and 19th century musicians (Vernon, 1942; Steblin, 1983)? Until recently, such issues would have probably been regarded as irrelevant by most music researchers. We believe that our results may reopen such intriguing questions.

References

Bergeson, T., & Trehub, S. (2002). Absolute pitch and tempo in mothers' songs to infants. *Psychological Science, 13*(1), 72-75.

Berlyne, D. (1970). Novelty, complexity, and hedonic value. *Perception & Psychophysics, 8*(5A), 279-286.

Bornstein, R.F. (1989). Exposure and affect: overview and meta-analysis of research, 1968–1987. *Psychological Bulletin*, *106*, 265–289.

Burt, J. (2002). Why do non-color words interfere with color naming? (2011). *Journal of Experimental Psychology-Human Perception and Performance, 28*(5), 1019-1038.

Christensen, T. (2008). *The Cambridge History of Western Music Theory*. Cambridge, UK: Cambridge University Press.

Colman, A., Best, W., & Austen, A. (1986). Familiarity and liking - direct tests of the preference-feedback hypothesis rid A-3322-2008. *Psychological Reports, 58*(3), 931-938.

Deutsch, D. (1999). The processing of pitch combinations. In D. Deutsch (Ed.) *The Psychology of Music*. 2nd Edition. San Diego: Academic Press.

Dowling, W.J. (1978). Scale and contour: Two components of a theory of memory for melodies. *Psychological Review,* 85, 341–354.

Dowling, W. J. (1994). Melodic Contour in Hearing and Remembering Melodies. In Rita Aiello & John Sloboda (Eds.), *Musical Perceptions*. (pp.173-189). New York, NY: Oxford University Press.

Halpern, A. (1989). Memory for the absolute pitch of familiar songs rid B-7099-2009. *Memory & Cognition, 17*(5), 572-581.

Hartman, E. B. (1954). The influence of practice and pitch distance between tones on the absolute identification of pitch. *American journal of psychology*, *67*, 1-14.

Hunter, P. G., & Schellenberg, E. G. (2011). Interactive effects of personality and frequency of exposure on liking for music. *Personality and Individual Differences*, 50, 175–179.

Huron, D. (2006). *Sweet Anticipation: Music and the Psychology of Expectation.* Cambridge, MA: MIT Press.

Koehn, J. D., Dickinson, J., & Goodman, D. (2008). Cognitive demands of error processing. *Psychological Reports*, *102*(2), 532-538.

Krumhansl, C. L. (1990). *Cognitive Foundations of Musical Pitch.* Oxford: Oxford University Press.

Levitin, D. (1994). Absolute memory for musical pitch - evidence from the production of learned melodies. *Perception & Psychophysics, 56,* 414-423.

Levitin, D. J. (2002). Memory for musical attributes. In Levitin, D. J. (Ed.), *Foundations of Cognitive Psychology: Core Readings* (295–310). Boston, Mass: MIT Press

Levitin, D., & Rogers, S. (2005). Absolute pitch: Perception, coding, and controversies. *Trends in Cognitive Sciences*, *9*(1), 26-33.

Malmberg, K., & Nelson, T. (2003). The word frequency effect for recognition memory and the elevated-attention hypothesis. *Memory & Cognition, 31*(1), 35-43.

Marvin, E. W., &. Newport, E. (2011). *The Absolute Pitch Continuum: Evidence of Incipient AP in Musical Amateurs*. Paper presented at the Conference of the Society for Music Perception and Cognition (SMPC), Rochester, NY.

Marvin, E., & Brinkman, A. (2000). The effect of key color and timbre on absolute pitch recognition in musical contexts. *Music Perception, 18*(2), 111-137.

Melara, R., & Algom, D. (2003). Driven by information: A tectonic theory of stroop effects. *Psychological Review, 110*(3), 422-471.

Miyazaki, K. (1989). Absolute pitch identification - effects of timber and pitch region. *Music Perception, 7*(1), 1-14.

Miyazaki, K. (1990). The speed of musical pitch identification by absolute-pitch possessors. *Music Perception, 8*(2), 177-188.Norris, D. (2006). The bayesian reader: Explaining word recognition as an optimal bayesian decision process. *Psychological Review, 113*(2), 327-357.

Mull, H. K. (1925). The acquisition of absolute pitch. *American journal of psychology, 36*, 469-493.

Notebaert, W., Houtman, F., Van Opstal, F., Gevers, W., Fias, W., & Verguts, T. (2009). Post-error slowing: An orienting account. *Cognition, 111*(2), 275-279.

Parncutt, R. & Levitin, D. J. (2001*). Absolute Pitch*. In S. Sadie [Ed.], *New Grove Dictionary of Music and Musicians*. New York: St. Martins Press.

Purwins, H., Graepel, T., Blankertz, B., & Obermayer, K. (2003). Correspondence analysis for visualizing interplay of pitch class, key, and composer. In Mazzola, G., Noll, T., and Luis-Puebla, E., editors, *Perspectives in Mathematical and Computational Music Theory*, Osnabrück Series on Music and Computation (pp. 432–454). Osnabrück: Electronic Publishing.

Ross, D. A., Gore, J. C., & Marks, L. E. (2005). Absolute pitch: Music and beyond. *Epilepsy and Behavior*, 7, 578-601.

Rossing, T. D. (1990). *The science of sound*. USA: Addison-Wesley.

Sanders A. F. (1998). *Elements of Human Performance: Reaction Processes and Attention in Human Skill*. Mahwah, NJ: Lawrence Erlbaum .

Schellenberg, E. G., Peretz, I., & Vieillard, S. (2008). Liking for happy- and sad-sounding music: Effects of exposure. *Cognition and Emotion*, 22, 218–237.

Schellenberg, E., & Trehub, S. (2003). Good pitch memory is widespread. *Psychological Science, 14*(3), 262-266.

Schellenberg, E. G., & Trehub, S. E. (2008). Is there an asian advantage for pitch memory? *Music Perception*, 25(3), 241-252.

Schwartz, D., Howe, C., & Purves, D. (2003). The statistical structure of human speech sounds predicts musical universals. *Journal of Neuroscience, 23*(18), 7160-7168.

Schwartz, D., & Purves, D. (2004). Pitch is determined by naturally occurring periodic sounds. *Hearing Research, 194*(1-2), 31-46.

Simpson, J., & Huron, D. (1994). Absolute pitch as a learned phenomenon - evidence consistent with the Hick-Hyman law. *Music Perception, 12*(2), 267-270.

Smith, N. A., & Schmuckler, M. A. (2008). Dial A440 for absolute pitch: Absolute pitch memory by non-absolute pitch possessors. *Journal of the Acoustical Society of America, 123*(4), EL77-EL84. doi: 10.1121/1.2896106.

Szpunar, K. K., Schellenberg, E. G., & Pliner, P. (2004). Liking and memory for musical stimuli as a function of exposure. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 30, 370–381.

Steblin, R. (1983). *A history of key characteristics in the eighteenth and early nineteenth centuries*. Ann Arbor: UMI Research Press.

Straus, J. N. (2004). *Introduction to Post-Tonal Theory* (3rd Edition). Englewood Cliffs, N. J.: Prentice-Hall.

Tan, S. L., Spackman, M. P., & Peaslee, C. L. (2006). The Effects of Repeated Exposure on Liking and Judgments of Musical Unity of Intact and Patchwork Compositions, *Music Perception*, 23, 407-421.

Takeuchi, A., & Hulse, S. (1991). Absolute-pitch judgments of black-key and white-key pitches. *Music Perception, 9*(1), 27-46.

Temperley, D. (2007). *Music and Probability*. Cambridge, Massachusetts: MIT Press.

Terhardt, E., & Seewann, M. (1983). Aural key identification and its relationship to absolute pitch. *Music Perception, 1*(1), 63-83.

Terhardt, E., & Ward, W. (1982). Recognition of musical key - exploratory-study. *Journal of the Acoustical Society of America, 72*(1), 26-33

Trainor, L. J., Wu, L., & and Tsang, C. D. (2004). Long-term memory for music: Infants remember tempo and timbre. Developmental Science, 7(3), 289–296.

Trehub, S. E., Schellenberg, E. G., & Nakata, T. (2008). Cross-cultural perspectives on pitch memory. *Journal of Experimental Child Psychology, 100*(1), 40-52.

Vernon, P.E. (1942). The Individuality of Keys. *Musical Times*, 83, 105-107, 138-39.

Ward, W. D. (1999). Absolute pitch. In D. Deutsch (Ed.), *The psychology of music* (2nd ed., pp. 265-298). San Diego: Academic Press.

Zajonc, R. (1968). Attitudinal effects of mere exposure. *Journal of Personality and Social Psychology*, *9*(2P2), 1-27.

Zwicker, E., Flottorp, G., & Stevens, S. S. (1957). Critical bandwidth in loudness summation. *Journal of the Acoustical Society of America*, 29, 548-557.

List of Figures

Figure 1

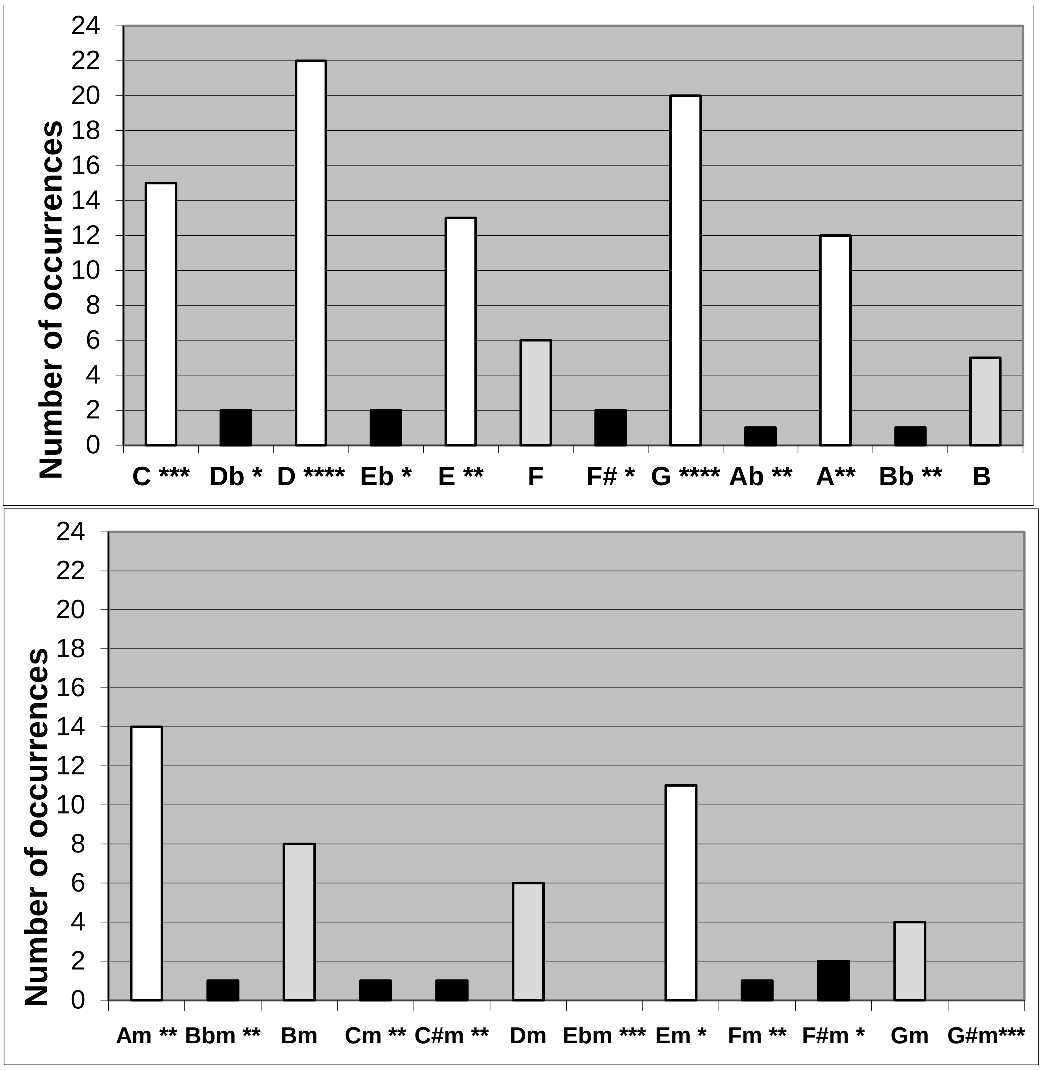

Figure 1: The distribution of Major (top panel, A) and Minor (Bottom panel, B) musical keys in 135 internationally popular hits played by a trendy radio station in Israel (Galgalatz, 91.8 FM); modulations ranging at least a whole chorus or verse were counted as an additional key, leading to overall 150 keys in the sample. The overall sample deviated from a random distribution, $X^2=80.45$ for major and $X^2=58.44$ for minor keys, $p<0.001$. For the individual keys in the sample, white bars represent keys that were significantly more frequent than a random distribution of the binomial test, black bars represent significantly rare keys, and grey bars represent keys that did not differ significantly from a random distribution in the sample. Asterisks denote significant levels of the binomial test, as compared to an even distribution of major or minor keys: *$p<0.05$; **$p<0.025$; ***$p<0.01$; **** $p<0.001$.

Figure 2

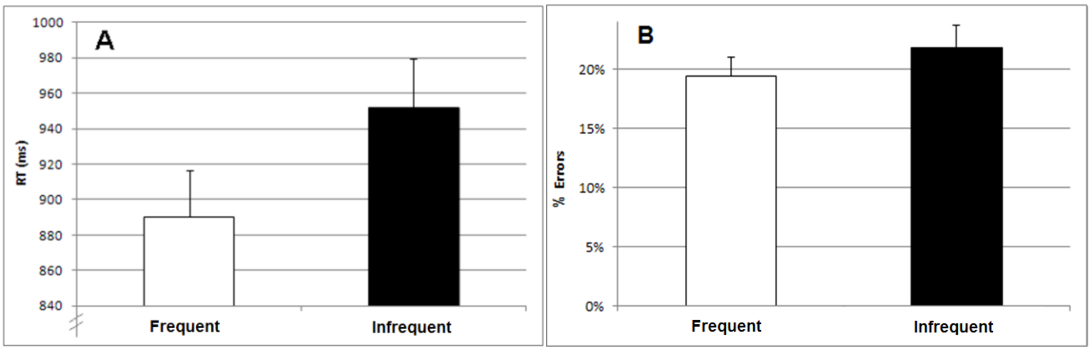

Figure 2: (A) Mean reaction times (in milliseconds) for frequent and infrequent keys. (B) Mean error rates for frequent and infrequent keys. Bars represent one standard deviation around the mean.

Figure 3

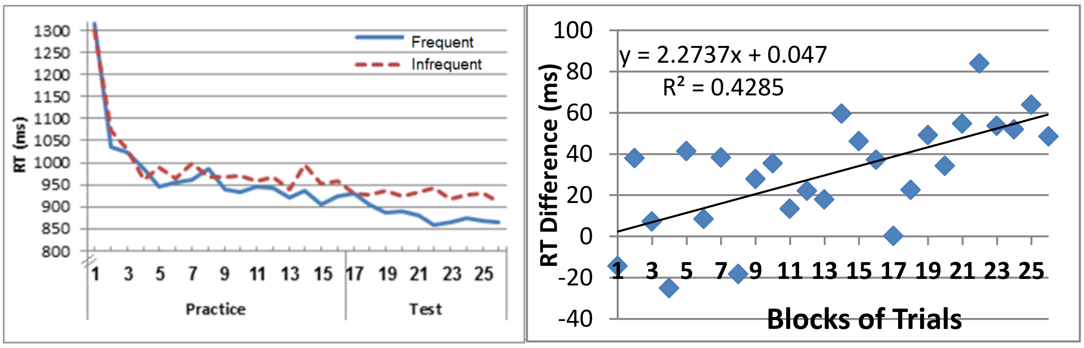

Figure 3: Improvements in RTs across the entire experiment, computed for blocks of 12 trials. The left-hand panel plots the mean RTs for frequent and infrequent keys. The right-hand panel plots the difference in RTs between performance for frequent and infrequent keys. The progression of this difference is represented by a linear equation.

Figure 4

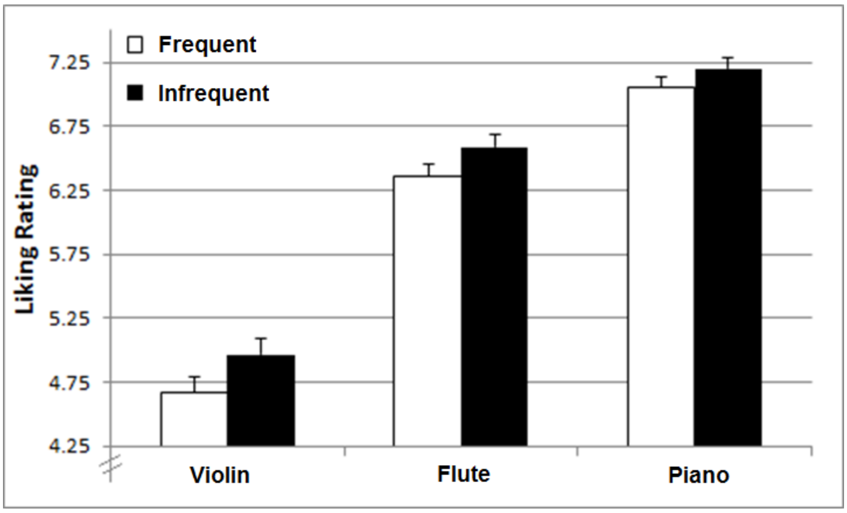

Figure 4: Average ratings for frequent and infrequent pitches in the different musical instruments. Bars denote one standard deviation around the mean.

Figure 5

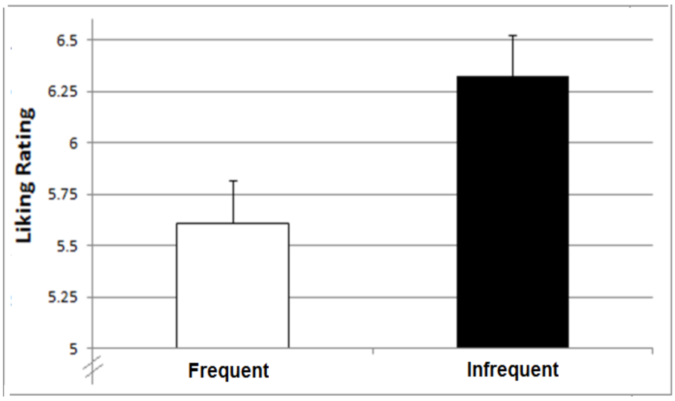

Figure 5: Average ratings for frequent and infrequent pitches. Bars denote one standard deviation around the mean.

Figure 6

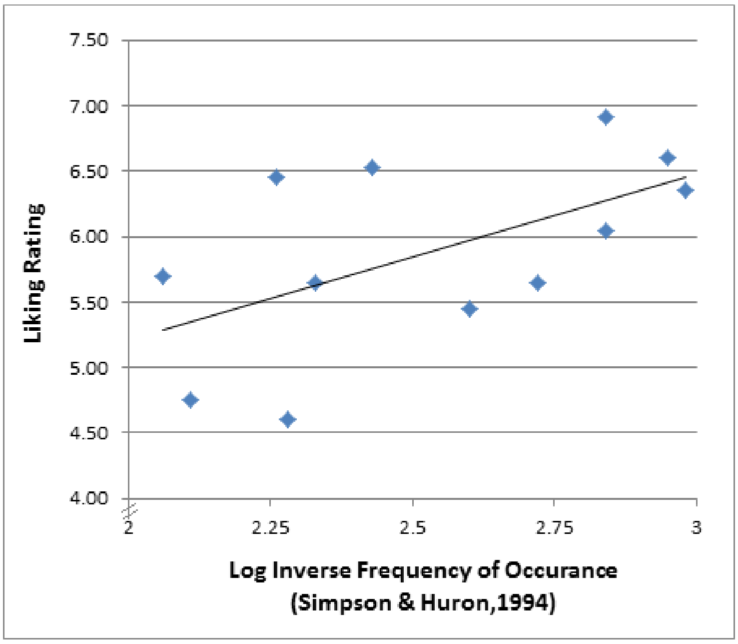

Figure 6: Ratings of each of the 12 pitches plotted against pitch frequency estimate. Estimates are based on Simpson and Huron (1994), and computed as the logarithm base 2 of the multiplicative inverse of the probability of the stimulus.

List of Tables

Table1

Table1

Mean reaction times and error rates for the four scale degrees in each key

	Reaction Times				Errors			
	Scale Degree				Scale Degree			
Key	**1**	**2**	**3**	**5**	**1**	**2**	**3**	**5**
C	783	939	982	800	12%	26%	27%	11%
Db	945	1000	1037	834	23%	18%	31%	12%
D	845	944	994	808	16%	26%	29%	13%
F#	851	1049	1090	908	13%	29%	31%	17%
G	860	980	1004	871	14%	21%	23%	14%
Ab	869	1024	1063	901	13%	29%	30%	17%
Mean frequent	829	955	993	826	14%	24%	27%	13%
Mean Infrequent	889	1024	1063	881	16%	25%	30%	15%
Total	859	989	1028	854	15%	25%	29%	14%

Table2

Table 2

Mean ratings of the 12 pitch-classes across 2 octaves and 3 instrumental timbres in Experiment 2a

Pitch	Log inverse Frequency	Mean ratings
C	2.33	6.01
Db	2.98	6.73
D	2.06	6.21
Eb	2.84	6.19
E	2.28	6.03
F	2.6	6.06
F#	2.72	6.14
G	2.11	6.12
Ab	2.95	6.13
A	2.26	5.89
Bb	2.84	6.07
B	2.43	5.87

Table3

Table 3

Mean ratings of the 12 pitch classes along with frequency estimates

Pitch	**Log Inverse Frequency of Occurrence**	**Rating**
C	**2.33**	**5.65**
Db	**2.98**	**6.35**
D	**2.06**	**5.70**
Eb	**2.84**	**6.05**
E	**2.28**	**4.60**
F	**2.6**	**5.45**
F#	**2.72**	**5.65**
G	**2.11**	**4.75**
Ab	**2.95**	**6.60**
A	**2.26**	**6.45**
Bb	**2.84**	**6.91**
B	**2.43**	**6.52**