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Timing-induced illusory percepts of pitch

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It has long been proposed that the brain integrates pitch and timing cues during auditory perception. If true, the pitch of a sound should influence its perceived timing, and the timing of a sound should similarly influence its perceived pitch. Previous research suggests that changes in the pitch of speech and music can induce illusory changes in their perceived tempo. We conducted two experiments to test the opposite effect: whether deviations from rhythmic timing can also influence the perceived pitch of a sound. In Experiment 1, participants heard an isochronous, repeating standard tone followed by a potentially mistimed, pitch-shifted probe tone, and were asked to discriminate between pitch increases and decreases. We observed a strong biasing effect of the probe's timing on its perceived pitch, such that later probes were more likely to be perceived as lower than the standard. Correct, bias-conforming responses to mistimed probes were also significantly faster than responses to probe tones played on the beat. In Experiment 2, we used an adaptive-difficulty version of Experiment 1 to investigate whether this timing-induced bias strengthens under conditions of low discriminability. We found that the biasing effects of probe timing were similarly strong regardless of how large the to-be-judged pitch difference was, and regardless of individual differences in pitch sensitivity. Alongside previous literature on pitch-induced illusory tempo changes, our present observation of timing-induced illusory pitch changes support the hypothesis that pitch and time are perceptually integrated. We discuss pitch–time integration within a Bayesian framework, as a possible result of a learned prior reflecting real-world correlations between changes in pitch and timing.

Keywords: illusion, perceptual bias, perceptual integration, pitch discrimination, rhythmic timing

Significance statement: Evidence from a pair of pitch discrimination experiments suggests that deviations from rhythmic timing can induce illusory changes in pitch. Specifically, early timing increases perceived pitch, while late timing decreases it. The existence of these effects supports the hypothesis that pitch and timing are integrated in auditory perception.

It has long been suggested that timing and pitch are integrated in auditory perception, such that changes along one dimension influence perceived changes along the other. In particular, Jones (1976) emphasized a principle of proportionality, in which changes in pitch (and loudness) are constrained in magnitude by the time over which they occur; meanwhile, changes in time can only be defined through reference to events that themselves have pitch and loudness. She proposed that the brain integrates the pitch, loudness, and timing of auditory signals into a trajectory through a combined representational space, the structure of which reflects the lawful relations between these three dimensions in the external world. Because of lawful relations like proportionality, movement along any one dimension constrains and biases expectations for movement along each other dimension. For example, early work by Cohen, Hansel, and Sylvester (1954) and more recent work by Henry and McAuley (2009, 2013) has demonstrated a bias to perceive changes in pitch as larger when spaced over a longer interval (often referred to as *tau* effects), and a bias to perceive the timing of notes as if pitch maintained a constant velocity over time (referred to as *kappa* effects).

Integration of Pitch and Timing

Although Jones (1976) focused on the proportionality of the magnitudes of changes in pitch and time, more recent evidence also supports a perceptual link in the *directionality* of changes in pitch and timing. Specifically, there appears to be a perceptual association between pitch increases and temporal acceleration. For example, listeners perceive ascending melodies to be faster (Boltz, 2011) and speeding up more (Collier & Hubbard, 1998) than descending ones, and applying a continuous pitch glide to a melody also induces illusory changes in tempo (Gordon & Ataucusi, 2021). This influence of pitch change on perceived timing extends beyond musical stimuli, as well. Illusions of tempo change have been observed in the perceived modulation rate of frequency-modulated (Herrmann, Henry, Grigutsch, & Obleser, 2013; Herrmann, Henry, Scharinger, & Obleser, 2014) and amplitude-modulated (Herrmann & Johnsrude, 2018) tones, with ascending tones perceived as increasing in modulation rate. In speech, it has also been found that listeners are best at recognizing changes in speaking rate and pitch when both features change in the same direction (Boltz, 2017).

Effects of absolute pitch on perceived timing have also been observed. For example, higher-pitched speech (Feldstein & Bond, 1981), melodies (Boltz, 2011), and scales (Collier & Hubbard, 1998) are perceived as faster than lower pitched ones. Additionally, when participants were asked to make early/late judgements about mistimed probes at the end of a rhythmic sequence, Pazdera and Trainor (2023) found that lower-pitched tones were consistently perceived as later than higher ones. Similarly, the P-centers of long, low-pitched tones tend to be later than those of long, high-pitched tones (Danielsen et al., 2019), and single intervals flanked by at least one low-pitched tone have been found to be overestimated (Lake, LaBar, & Meck, 2014; Pfeuty & Peretz, 2010). New findings from two of our own recent studies suggest that there may be an inverted U-shaped relation between absolute pitch and perceived tempo, in which perceived tempo rises with pitch at lower octaves, but reliably slows above A6 (1760 Hz); however, it remains uncertain whether this U-shaped effect originates from the same mechanism as higher–faster illusions (Pazdera & Trainor, 2024a, 2024b).

There has been considerably less investigation into whether timing also influences perceived pitch; however, if we believe that the brain integrates these two dimensions of sound into a shared representational space, then pitch and timing should bidirectionally influence one another (Boltz, 2017; Jones, 1976). Direct evidence for an effect of timing on perceived pitch is limited, but one collection of studies has observed a biasing effect of tempo changes on perceived pitch changes, such that slowing the tempo of orchestral and band recordings produced perceived decreases in pitch (Duke, Geringer, & Madsen, 1988; Geringer & Madsen, 1984; Madsen, Duke, & Geringer, 1984). Additional evidence that pitch and timing are at least implicitly associated, if not directly integrated, has been found in musical preference and imagery. When asked to adjust melodies to their preferred tempo, people tend to select faster tempos for higher-pitched music (Tamir-Ostrover & Eitan, 2015), and higher pitch correlates with faster imagined motion in adults (Eitan & Granot, 2006), though not children (Eitan & Tubul, 2010; Kohn & Eitan, 2009, 2016). Auditory Stroop effects have also been found, in which people associate high pitches with the word "fast" and low pitches with the word "slow" (Walker & Smith, 1984). Further study is needed, however, to conclusively support the perceptual integration of pitch and time.

The Present Study

In the present study, we conducted a pair of pitch discrimination experiments to further investigate whether pitch and timing are integrated in auditory perception. Specifically, we tested whether deviations from isochronous timing can induce perceived changes in pitch. In conjunction with previous findings that pitch influences perceived timing, such a reverse-influence of timing on perceived pitch would support the hypothesis that pitch and timing are perceptually integrated and bidirectionally bias one another (Boltz, 2017; Jones, 1976). Although we have previously reported an abbreviated analysis of sensitivity and bias in Experiment 1 of the present study in a conference proceedings (Pazdera & Trainor, 2023), the present manuscript serves to provide a complete analysis and interpretation of this experiment, as well as a follow-up study investigating whether there is a moderating effect of difficulty on timing-induced illusory changes in pitch.

In both experiments, participants listened to an isochronous, repeating standard tone followed by a (potentially) mistimed final tone that was shifted either up or down in pitch. Participants were tasked with determining the direction of the pitch change, and we analyzed whether the timing offset of the probe tone influenced its perceived pitch. We hypothesized that late probe tones would be more likely to be perceived as low-pitched than early ones, given previous evidence for associations between low pitch and slow timing (e.g., Boltz, 2011). We also hypothesized that pitch discrimination would be more sensitive for probe tones played on the beat than for mistimed probes, in line with the principles of Dynamic Attending Theory (Jones & Boltz, 1989; Large & Jones, 1999) and previous empirical evidence (e.g., Chang, Bosnyak, & Trainor, 2019; Henry & Herrmann, 2014; McAuley & Fromboluti, 2014).

Experiment 1

In Experiment 1, we tested whether the timing of a probe tone influences its perceived pitch. Participants listened to six isochronous standard tones and rated whether a final probe tone was higher or lower in pitch than the standard. The final tone could arrive early, on the beat, or late, and we evaluated whether these timing deviations biased participants' pitch discrimination responses.

Methods

Participants

We collected data for Experiment 1 between March and April 2022 under special COVID-19 safety protocols, as approved by the local research ethics board, including mask requirements for all participants and experimenters. Thirty undergraduate students (9 male, 21 female) from McMaster University participated in the study for course credit. Ages ranged from 18–22 years, with a mean age of 18.6 (SD = 1.1). Of these participants, we excluded five from analysis for failing to perform above chance, as evaluated by a binomial test.

Data Availability

We have made all data, code, and stimuli from both experiments publicly available on the Open Science Framework at `https://osf.io/hrj3t/`, as well as on GitHub at `https://github.com/jpazdera/IllusoryPitch`.

Materials

We used Python to create complex tones with a percussive amplitude envelope by summing four sine waves with random phase, including the fundamental frequency and the first three overtones with an amplitude fall-off of 6 dB/octave. The tones were 250 ms in duration and consisted of a 10 ms linear rise, followed by an exponential decay and 10 ms linear fade. We used Audacity's loudness normalization function, which is based on recommendation ITU-R BS.1770-4 (International Telecommunication Union, 2017), to balance all tones to the same loudness. To ensure precise inter-onset timing, we pre-generated all tone sequences using Python, and played them back as WAV files during the experiment.

Apparatus

Participants completed the study on a 2011 iMac, and we presented stimuli at 75 dBA via a pair of HD 201S Sennheiser headphones. We used the JavaScript library jsPsych (de Leeuw, 2015) to implement stimulus presentation and response collection. Although we conducted the study in person, we used the online platform Pavlovia (`https://pavlovia.org`) to host the experiment, which participants accessed via Google Chrome. The purpose of hosting the experiment on Pavlovia was to enable flexible switching between online and in-person testing in the event that COVID-19 restrictions changed during data collection. Ultimately, however, all participants completed the study in person. We performed all analyses using a combination of Python (version 3.10) and R (version 4.3).

Design

The study followed a 3 probe timing offset (15% Early, On-Beat, 15% Late) × 2 octave (3^{rd} or 5^{th}) × 2 pitch shift direction (Up or Down) within-subjects design. Third-octave standard tones were A3 (220 Hz) and fifth-octave standard tones were A5 (880 Hz), with the probe tone shifted by ±7.9 cents, equating to ±1 Hz and ±4 Hz, respectively.

Procedure

Participants completed a pitch discrimination task in which they heard six isochronous repetitions of a standard tone (A3 = 220 Hz or A5 = 880 Hz) followed by a final probe tone. The standard tone always played at an interonset interval of 500 ms, and the probe tone played either 425, 500, or 575 ms after the final repetition of the standard. Following the presentation of the probe, the participant responded via a key press (up or down arrow) whether the probe was higher or lower in pitch than the repeating standard. There was no time limit on their response, and participants were instructed to respond as accurately as possible. The next trial then began 1.5 s post-response.

Trials were administered in four blocks of 60, with each block consisting of 10 repetitions of each of the six combinations of probe timing offset and pitch shift direction, randomly ordered. In order to reduce the difficulty of the task, all trials within a block used standard tones of the same octave, and octave alternated between blocks in an ABAB pattern. The octave of the first block was randomized between participants. Four practice trials preceded the first block, all of which used a standard pitch of A4 (440 Hz), a probe tone that played 500 ms after the final repetition of the standard, and a pitch shift of ±6 Hz (three times larger in cents than the experimental trials). Feedback was provided on the practice trials only. Participants received self-paced breaks between blocks.

Data Analysis

Our primary analysis used a signal detection theory approach to evaluate sensitivity and bias in participants' pitch discrimination. To do so, we marked trials as hits when participants correctly identified a pitch increase, and we marked trials as false alarms when participants misidentified a pitch decrease as an increase. From this scoring, we calculated sensitivity as d' and bias as C (Stanislaw & Todorov, 1999), while correcting for hit rates and false alarm rates of 0 and 1 using the method proposed by Hautus (1995). Specifically, we added 0.5 to the numerator and 1 to the denominator when calculating all hit rates and false alarm rates. Under this labeling scheme, higher values of C indicate greater conservatism about rating the probe tone as higher in pitch than the standard. In other words, positive values of C indicate a bias to rate probes as low-pitched, and negative values of

C indicate a bias to rate probes as high-pitched. For each participant, we calculated d' and C separately for each of the six combinations of probe timing offset and octave. We then analyzed these values via a pair of 3 (offset) × 2 (octave) repeated measures ANOVAs—one for sensitivity and one for bias.

Next, we performed an exploratory analysis to determine whether the biasing effect of probe timing was stronger in individuals with lower sensitivity. Because our planned analysis found an approximately linear effect of timing on bias, we quantified the magnitude of each participant's bias by fitting a linear regression across the C values for their three probe timing conditions, pooling the data from both octaves. The slope of this line indicates the change in bias associated with every 1% delay of the probe tone. A steeper positive slope therefore indicates a stronger overall bias to rate later probe tones as lower in pitch than earlier probe tones, and we refer to this slope as an individual's *timing-induced bias*. We then pooled the data from all conditions to calculate each participant's overall d' sensitivity score, and tested the Pearson correlation between sensitivity and timing-induced bias.

Finally, we tested whether reaction times differed depending on probe timing offset and pitch shift direction. For this analysis, we included only correct responses, while excluding any response with a reaction time slower than 5 seconds (1.6% of correct responses). We then analyzed reaction times via a 3 (offset) × 2 (pitch shift direction) repeated measures ANOVA.

Results

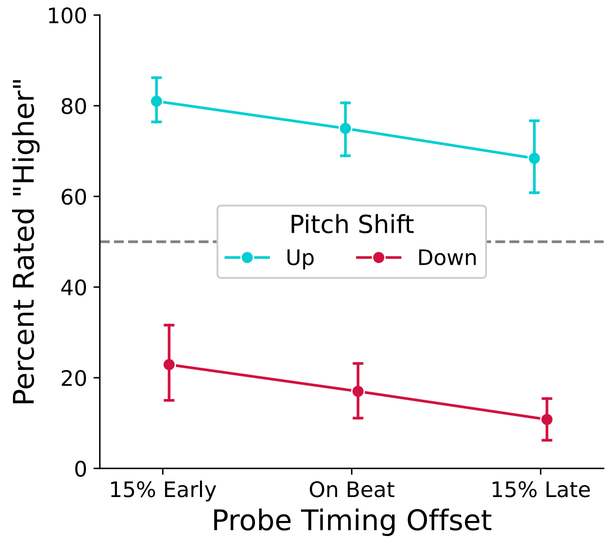
Sensitivity & Bias

Figure 1 illustrates the percent of probe tones participants rated as higher in pitch than the standard, as a function of probe timing offset and the true pitch shift direction. These data suggest that the earlier the probe tone played, the more likely participants were to rate it as higher in pitch. In order to separately analyze sensitivity and bias within these ratings, we labeled all trials where participants correctly identified pitch increases (upper line) as hits, and labeled all trials where participants incorrectly responded to pitch decreases (lower line) as false alarms. From these hit rates and false alarm rates, we obtained the sensitivity (d') and bias (C) of participants' pitch discrimination. Figure 2 illustrates sensitivity and bias as a function of the octave of the standard tone and the timing offset of the probe tone. Higher values of d' indicate greater discriminability of pitch increases and decreases, while higher values of C indicate a bias towards rating probe tones as lower in pitch than the standard.

We analyzed sensitivity via a 3 (offset) × 2 (octave) repeated measures ANOVA. Neither probe timing offset, $F(2, 48) = 0.26$, $p = .772$, $\omega_p^2 = -.010$, nor octave, $F(1, 24) = 0.74$, $p = .397$, $\omega_p^2 = .010$, significantly affected sensitivity, and offset and octave did not interact, $F(2, 48) \approx 0.00$, $p > .999$, $\omega_p^2 = -.014$. Participants were similarly sensitive to pitch changes at both octaves, and regardless of whether the probe tone played early, on the beat, or late.

Figure 1

Probability of Rating Probes as Higher Than the Standard



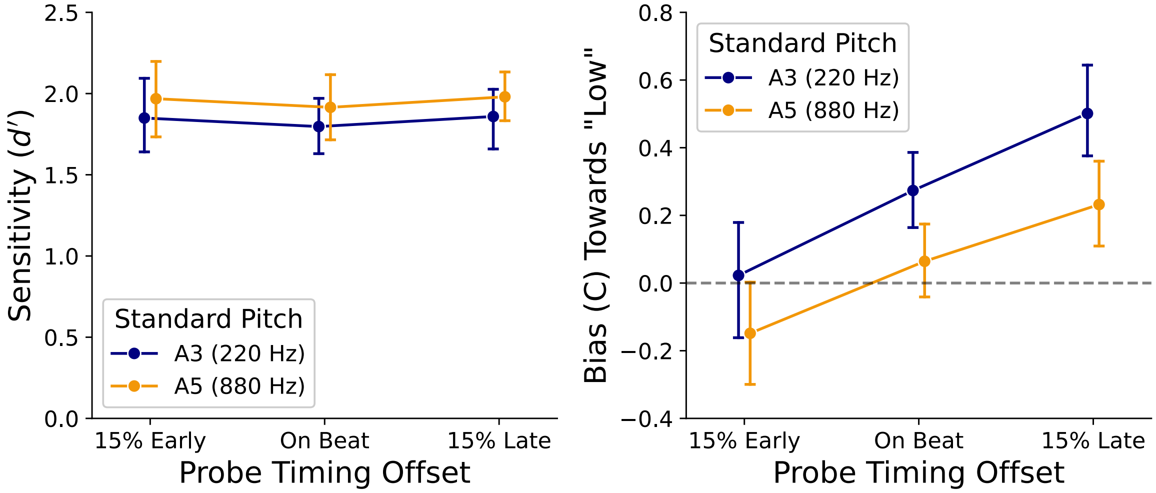
Note. Probability of rating probe tones as higher than the repeating standard tone in Experiment 1, depending on the probe tone's timing and true pitch shift direction. Error bars indicate within-subject 95% confidence intervals. In calculating d' and C for all subsequent analyses, we treated correctly-rated pitch increases as hits (upper line) and incorrectly-rated pitch decreases as false alarms (lower line). Hit rates and false alarm rates both decreased as the probe tone became later.

We next analyzed bias via a 3 (offset) × 2 (octave) repeated measures ANOVA, which indicated significant main effects of both probe timing offset, $F(2, 48) = 10.51$, $p < .001$, $\omega_p^2 = .290$, and octave, $F(1, 24) = 8.99$, $p = .006$, $\omega_p^2 = .133$. The interaction between timing offset and octave was not significant, $F(2, 48) = 0.42$, $p = .661$, $\omega_p^2 = -.008$. Post-hoc pairwise t-testing with Holm–Bonferroni correction indicated that the C values for all three probe timing offsets significantly differed from one another, with participants tending to rate later probe tones as lower in pitch, as hypothesized. This pattern was consistent between both octaves we tested; however, participants showed an unexpected main effect of octave such that they were more likely to rate probe tones as lower in pitch when the standard was A3 (220 Hz) than when it was A5 (880 Hz).

Finally, we explored whether the biasing effect of the probe's timing correlated with sensitivity. Figure 3 illustrates

Figure 2

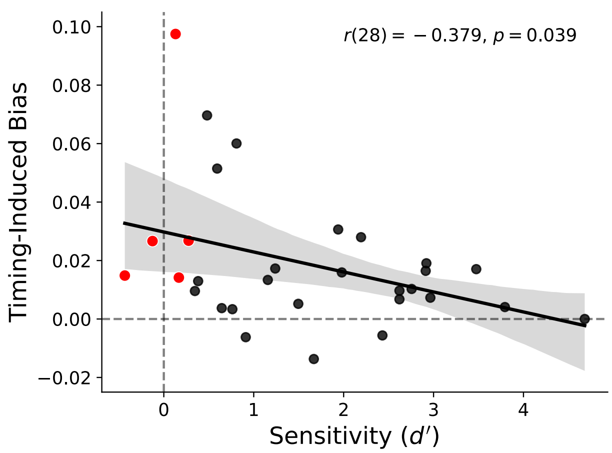
Sensitivity and Bias of Pitch Discrimination



Note. Sensitivity (d') and bias (C) of pitch discrimination in Experiment 1, as a function of the octave of the standard tone and the timing offset of the probe tone. Higher values of C indicate a greater bias towards labeling probe tones as lower in pitch than the standard. Error bars denote within-subject 95% confidence intervals. The timing of the probe tone biased participants' pitch perception at both octaves, such that later probes were perceived as lower, without a reduction in discriminability.

Figure 3

Individual Differences in d′ and Timing-Induced Bias



Note. Each data point represents one participant's sensitivity (d') and timing-induced bias scores in Experiment 1. Higher timing-induced bias scores indicate a stronger tendency to rate later tones as lower in pitch than the standard. Participants marked in red are those who were excluded from other analyses for failing to perform above-chance. The shaded region indicates the regression line and its 95% confidence interval. Individuals who were less sensitive to pitch changes tended to be more biased by the probe's timing offset.

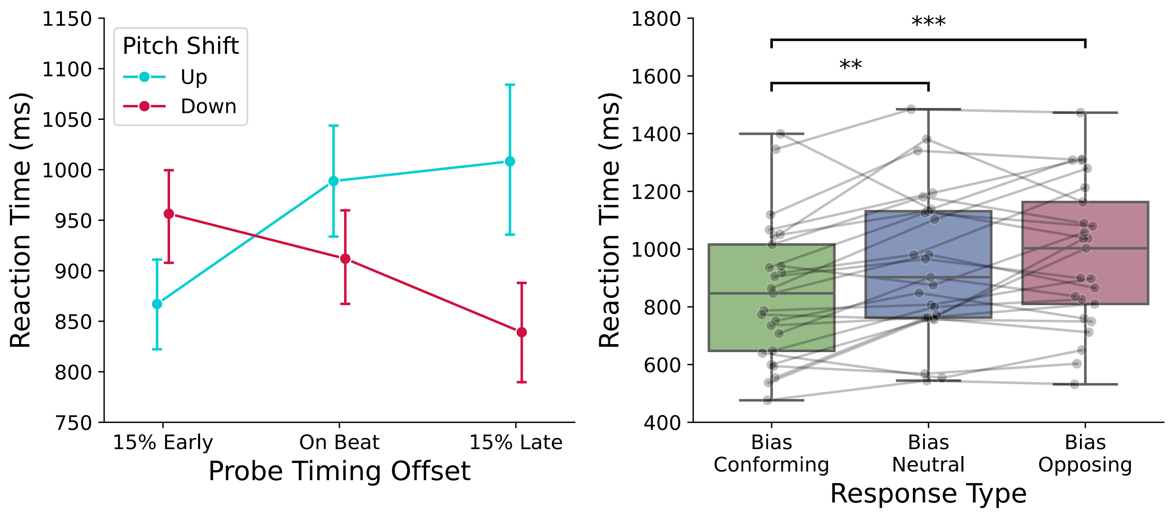
each participant's overall d' across all trials, paired with the magnitude of their bias to rate later probe tones as lower (formally, the linear slope of their bias across offset conditions, see Data Analysis). Participants who failed to perform above chance, and were therefore excluded from our main analyses, are marked in red. Notably, participants with low d' values tended to be highly biased by timing, especially those with $d' < 1$. When including all participants, we observed a moderate negative correlation between sensitivity and timing-induced bias, $r(28) = -.379, p = .039$. Among above-chance performers, this correlation remained moderate in size, but was non-significant, $r(23) = -.330, p = .107$.

Reaction Time

Figure 4A illustrates average reaction times for correct pitch discrimination responses, depending on the direction of the pitch shift and the timing offset of the probe tone. A 3 (probe timing offset) × 2 (pitch shift direction) repeated measures ANOVA identified a significant two-way interaction, $F(2, 48) = 13.38$, $p < .001$, $\omega_p^2 = .142$, while neither main effect was significant: probe timing offset, $F(2, 48) = 1.32$, $p = .276$, $\omega_p^2 = .003$, and pitch shift direction, $F(1, 24) = 1.78$, $p = .194$, $\omega_p^2 = .035$. In particular, Figure 4A suggests that participants responded correctly most quickly to early, high probes and late, low probes. Therefore, as a post-hoc test of the two-way interaction between timing offset and pitch direction, we recategorized correct responses as ei-

Figure 4

Reaction Times for Correct Responses



Note. Reaction times for correct responses in Experiment 1. **A)** Participants correctly rated pitch increases most quickly when the probe tone was early (blue line), but correctly rated pitch decreases most quickly when the probe was late (pink line). Error bars indicate within-subject 95% confidence intervals (Loftus & Masson, 1994). **B)** Categorizing responses as either bias-conforming (early/high or late/low), bias-neutral (all responses to on-beat probes), or bias-opposing (early/low or late/high) reveals faster reaction times for bias-conforming responses than for both other response categories. Individual data points indicate subject averages for each category.

ther bias-conforming (early/high and late/low probes), bias-opposing (early/low and late/high probes), or bias-neutral (any on-time probe). We next calculated each participant's average reaction time when making each of these three response types, as shown in Figure 4B. We then conducted dependent samples t-tests with Holm–Bonferroni correction between each of the three response types. As expected, reaction times for bias-conforming responses ($M = 850$ ms, $SD = 241$ ms) were significantly faster than reaction times for both bias-neutral ($M = 949$ ms, $SD = 255$ ms), $t(24) = -3.88$, $p_{adj} = .001$, and bias-opposing responses ($M = 980$ ms, $SD = 250$ ms), $t(24) = -4.42$, $p_{adj} < .001$. However, bias-opposing responses were not significantly slower than bias-neutral responses, $t(24) = 1.24$, $p_{adj} = .233$.

Discussion

In a pitch discrimination paradigm, we observed a biasing effect of a probe tone's timing on the perception of its pitch. As hypothesized, when a pitch-shifted probe tone played 15% early following six isochronous repetitions of a standard, participants showed a bias to rate the probe as higher in pitch than the standard; meanwhile, when the probe played 15% late, participants showed a bias to rate it as lower in pitch (Figure 2). Our results support the idea that pitch and timing are integrated during auditory perception (Jones, 1976). In conjunction with previous findings that higher pitches and ascending pitch sequences are perceived as faster (Boltz, 2011), earlier (Pazdera & Trainor, 2023), or speeding up (Herrmann et al., 2013), our results support a bidirectional influence in which timing can also influence perceived pitch.

To better understand the biasing effect of tone timing on pitch perception, we also analyzed participants' reaction times. We found that correct, bias-conforming responses to early and late probes (i.e., early/high and late/low) were approximately 100 ms faster on average than correct judgments of on-beat probes. In contrast, bias-opposing responses (i.e., early/low and late/high) were not significantly slower than responses to probe tones that played on the beat. We provide a detailed interpretation of this pattern of reaction times in the General Discussion.

The timing-induced bias we identified was not accompanied by a decrease in sensitivity to pitch changes; indeed sensitivity was quite consistent across early, on-beat, and late probe tones, in contrast with our hypothesis that d' would be highest for on-beat probes. One possible explanation for the lack of a dynamic attending-style advantage for on-beat perception (Chang et al., 2019; Henry & Herrmann, 2014; Jones & Boltz, 1989; Large & Jones, 1999; McAuley & Fromboluti, 2014) is that an on-beat sensitivity advantage might require a design in which the majority of probes fall on the beat. In the current design, the probe only played at the "expected" time on one third of trials. Although the average probe timing was on the beat, participants may have learned to spread their attention across the full presentation window due to the high variability in the probe's timing (Large & Jones, 1999). Alternatively, as each trial was only about three seconds in length, trials may have been too short for dynamic attending to emerge. For comparison, previous dynamic attending advantages for pitch perception identified by Chang et al. (2019) were found in sequences lasting 50 seconds.

In addition to time biasing perceived pitch change, participants also unexpectedly showed a bias to rate probe tones as lower than the standard when the standard was A3 (220 Hz), but they were relatively unbiased on average when the standard was A5 (880 Hz; see Figure 2). It is possible that our results relate to the pitch class polarization phenomenon identified by Prpic et al. (2016), in which musicians tended to underestimate the pitch class of lower-octave tones and overestimate the pitch of higher-octave tones. However, given substantial differences between our pitch discrimination task and their pitch class identification task, further investigation would be necessary to support a definitive link between our findings.

Lastly, we identified a possible negative correlation between sensitivity and timing-induced bias, such that participants with low sensitivity tended to be more strongly biased by the probe tone's timing (Figure 3), but only when we included participants who failed to perform above-chance in the analysis. We designed Experiment 2 to investigate two potential explanations for such a correlation. One possibility is that people may rely on temporal cues as supplemental information when they are uncertain about a pitch change. In this case, we should be able to observe a within-subject effect of task difficulty on timing-induced bias. By varying the size of the pitch shift between trials in Experiment 2, we tested whether individuals would increasingly rely on timing information as pitch changes diminished. Alternatively, individuals with greater pitch sensitivity may simultaneously be better able to differentiate pitch changes from timing changes, allowing them to resist the bias. In Experiment 2, we measured participants' just-noticeable differences for pitch change, and used this measure to calibrate the task difficulty on an individual basis. If greater pitch sensitivity is associated with improved separability of pitch and timing information, then participants with smaller just-noticeable differences should also tend to show weaker timing-induced bias in Experiment 2.

Experiment 2

In Experiment 2, we followed up on our exploratory finding that individuals with lower sensitivity to pitch change also tended to show stronger timing-related bias. To do so, we created an adaptive-difficulty version of our pitch discrimination task. We first determined each participant's 70.7% just-noticeable pitch difference (JND) via a staircase procedure in which they rated which of two tones was higher in pitch. After obtaining their JND, we presented them with a task similar to Experiment 1, except that the probe tone shifted by a number of cents either equal to their JND (easier condition), or half that number (harder condition). If timing-related bias is stronger in individuals with weaker pitch sensitivity, then we would expect the effect of probe timing offset to positively correlate with JND (as higher JNDs indicate lower sensitivity). Alternatively, or in addition, if timing-related bias increases with task difficulty, then we would expect a stronger effect of probe timing offset in the harder $\frac{1}{2}$JND pitch shift condition than in the easier condition.

Methods

Participants

We collected data for Experiment 2 between February and April 2023, under the same COVID-19 safety protocols as Experiment 1. Twenty-eight undergraduate students (17 female, 11 male) from McMaster University participated for course credit. Ages ranged from 18-22 years (M = 18.8, SD = 1.2). We excluded one participant from analysis for failing to perform above chance, as determined via a binomial test.

An additional 13 (12 female, 1 male) undergraduate students aged 18-20 years (M = 18.4, SD = 0.6) completed an alternative version of the task in which all trials were presented at their JND, and these participants were included only in our analysis of whether JND predicts timing-induced bias.

Materials

Tones were constructed via the same procedure as Experiment 1, with the exception that loudness normalization across octaves was not required due to all tones being within 100 cents of A4 (440 Hz).

Apparatus

Participants completed the study on a Windows 10 computer with an Asus Z87-C motherboard, and we presented stimuli at 78 dBA via a set of Escape HP-3868 headphones. We implemented stimulus presentation in Python (version 3.8) using the PsychoPy library (Peirce et al., 2019), and performed all analyses using Python (version 3.10) and R (version 4.3).

Design

The main pitch discrimination task followed a 3 probe timing offset (15% Early, On-Beat, or 15% Late) × 2 difficulty (Easy or Hard) × 2 pitch shift direction (Up or Down) fully within-subjects design. The easier difficulty condition used pitch changes equal to the participant's JND, whereas the harder difficulty condition used pitch changes equal to one half the participant's JND. Pilot testing suggested that with practice, participants became quite good at differentiating pitch changes at their JND, and we found that setting the more difficult condition to be below their initial JND produced desirable levels of performance.

Procedure

The session began with a difficulty calibration task, in which we determined the participant's 70.7% just-noticeable difference for pitch discrimination via an interleaved staircase procedure. On each trial of the calibration task, participants heard a 440 Hz tone followed by a tone slightly higher or lower in pitch than the first, with a 500 ms interonset interval between them. Participants then answered via a key press (1 or 2) whether the first or second tone was higher. A 1.5 s delay followed their response before the next trial began. We used four interleaved staircases in a 2 pitch direction (second tone higher or second tone lower) × 2 initial pitch shift size (1 cent or 25 cents) design. On each trial, we selected one staircase at random to generate the stimuli for that trial. We used a two-down, one-up procedure such that two consecutive correct answers on trials generated by the same staircase increased the difficulty of the next trial generated by that staircase, reducing the number of cents by which the tones differed (to a minimum of 0); meanwhile, a single incorrect answer reduced the difficulty of the next trial generated by that staircase, increasing the number of cents by which the tones differed (to a maximum of 100). Initially, difficulty changed by 8 cents at a time, and this step size halved after every two reversals in difficulty on a per-staircase basis, to a minimum step size of 1 cent. Each staircase ended after eight reversals in difficulty. After all four staircases had ended, we calculated the participant's JND as the average pitch shift size of the last four reversals from each staircase.

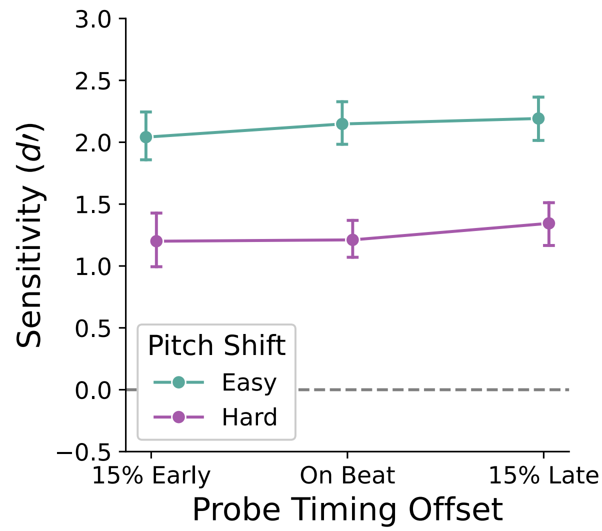
We next used the JND obtained from the calibration task to generate probe tones that were a number of cents above and below the standard tone (A4) equal to that threshold, as well as probe tones that were above and below the standard tone by one half the JND. Participants then completed a pitch discrimination task that followed the same procedure as Experiment 1, with the exception that the standard tones were always A4 and the size of the pitch difference between the standard and probe (JND or $\frac{1}{2}$JND) varied across trials. Trials were again organized into four blocks of 60 separated by breaks, with each combination of probe timing offset, difficulty (pitch shift size), and pitch shift direction presented five times per block in a fully randomized order. Four practice trials with a pitch shift size of four times the JND preceded the first block. Feedback was given on the practice trials only.

Data Analysis

We calculated participants' sensitivity and bias in each condition in the form of d' and C, respectively, using the same methods as Experiment 1 (Hautus, 1995; Stanislaw & Todorov, 1999). To confirm that our difficulty manipulation affected sensitivity as intended, we first analyzed d' via a 2 (difficulty) × 3 (probe timing offset) repeated measures ANOVA. Next, to assess whether difficulty affected the strength of the later–lower timing bias on pitch perception, we quantified timing-induced bias in a similar manner to Experiment 1. Specifically, for each participant and each difficulty, we fit linear models across the C values for the three probe timing offset conditions. As before, the slope of this line quantifies the expected change in bias with each 1% delay in the timing of the probe tone, which we refer to as the *timing-induced bias*. We then compared the timing-induced bias values from the two shift size conditions using a paired-samples t-test. To determine whether individuals with more sensitive pitch perception were less biased by timing, we calculated the Pearson correlation between participants' JNDs and their timing-induced bias, specifically for trials presented at their JND (the easy condition).

Figure 5

Pitch Discriminability by Difficulty Level



Note. Pitch discrimination performance in Experiment 2, based on the size of the pitch shift and the timing of the probe tone. Error bars indicate within-subject 95% confidence intervals. Increasing the difficulty of the task by reducing the size of the pitch shift successfully reduced d' evenly across probe timing conditions.

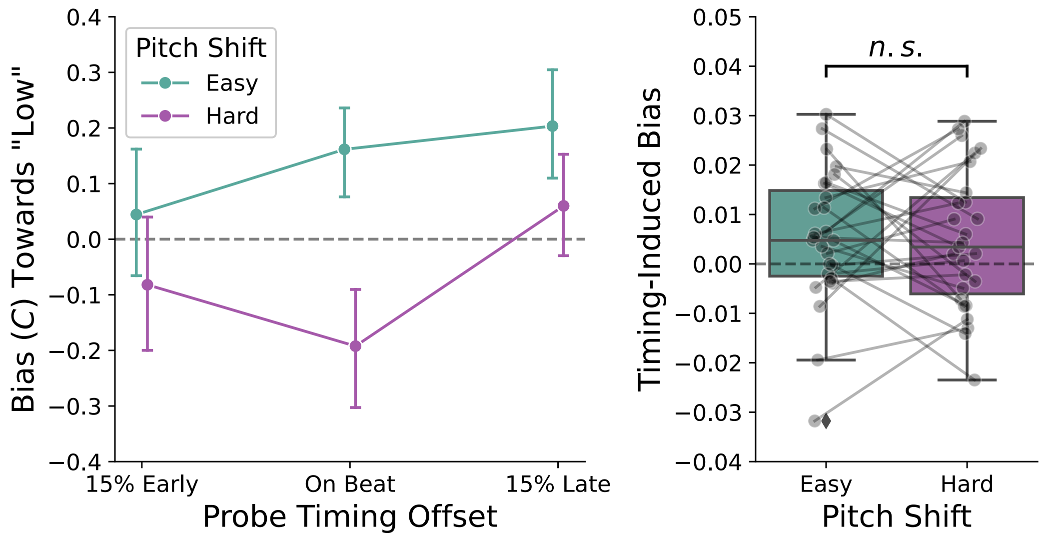
Results

Sensitivity & Bias

We first assessed whether our difficulty manipulation produced lower levels of sensitivity on trials where the pitch

Figure 6

Timing-Induced Bias by Difficulty Level



Note. Bias in pitch discrimination as a function of the probe tone's timing and the size of the pitch shift in Experiment 2. **A)** Average bias (C) towards rating probe tones as lower than the standard in each condition. Error bars indicate within-subject 95% confidence intervals. Late tones were more likely to be rated as low-pitched than early and on-beat tones. **B)** Data points indicate the linear effect of probe timing offset on bias for each participant and each difficulty condition. Reducing the size of the pitch shift did not strengthen timing-induced bias.

shift size was $\frac{1}{2}$JND than on trials where it was equal to their JND. Figure 5 illustrates d' for each combination of difficulty and probe timing offset. A 2 (difficulty) x 3 (probe timing offset) repeated measures ANOVA identified a large, significant main effect of difficulty on d', $F(1, 26) = 49.97$, $p < .001$, $\omega_p^2 = .469$, a non-significant main effect of of probe timing offset, $F(2, 52) = 1.59$, $p = .214$, $\omega_p^2 = .005$, and a non-significant interaction, $F(2, 52) = 0.18$, $p = .836$, $\omega_p^2 = -.010$. Smaller pitch shifts were significantly less discriminable than larger pitch shifts, confirming that our difficulty manipulation was successful. Furthermore, consistent with Experiment 1, participants were similarly sensitive to pitch changes regardless of whether the probe played early, late, or on the beat.

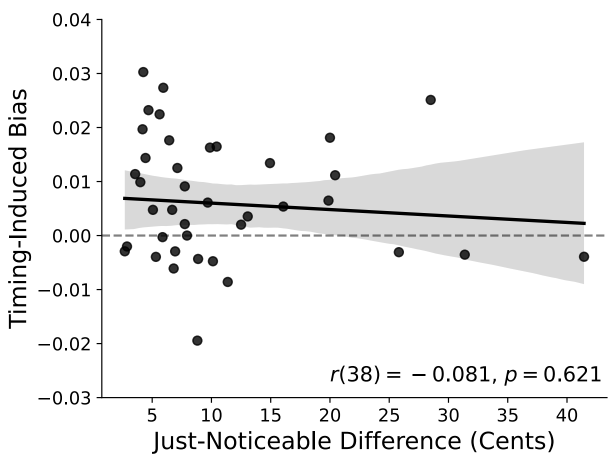
Having confirmed that our difficulty manipulation impacted pitch discriminability, we next tested whether difficulty affected participants' tendency to rate later probes as lower. Figure 6A illustrates C as a function of difficulty and the probe's timing offset. A 2 (difficulty) x 3 (probe timing offset) repeated measures ANOVA identified significant main effects of difficulty, $F(1, 26) = 9.88$, $p = .004$, $\omega_p^2 = .152$, and probe timing offset, $F(2, 52) = 4.67$, $p = .014$, $\omega_p^2 = .067$, as well as a significant two-way interaction, $F(2, 52) = 3.72$, $p = .031$, $\omega_p^2 = .032$. The main effect of difficulty was such that participants showed an overall bias to rate larger pitch shifts as a decrease and smaller pitch shifts as an increase. With respect to the effect of the probe's timing, post-hoc pairwise t-tests with Holm–Bonferroni correction found that late probes were rated as significantly lower than early and on-beat probes. To determine whether the two-way interaction matched our hypothesis that timing-induced bias would be stronger when the pitch shift was smaller, we compared timing-induced bias between pitch shift sizes using a dependent samples t-test. According to our hypothesis, timing induced bias should be more positive in the JND condition than the $\frac{1}{2}$JND condition; however, this was not the case, $t(26) = 0.18$, $p = .860$. Rather, the two-way interaction can be accounted for by the difference in C being significantly larger between difficulty conditions when the probe played on the beat than when it played late, $t(26) = 2.57$, $p = .016$.

Just-Noticeable Differences & Timing-Induced Bias

Figure 7 illustrates each participant's 70.7% just-noticeable pitch difference alongside the timing-induced bias they exhibited on pitch discrimination trials presented at their JND. A positive correlation would indicate that the biasing effects of probe timing were stronger among participants with less sensitive pitch perception (consistent with Figure 3 from Experiment 1), after accounting for task difficulty. Instead, we observed a weak and non-significant negative correlation, $r(38) = -.081$, $p = .621$, suggesting that timing

Figure 7

Individual Differences in JND and Timing-Induced Bias



Note. Data points indicate each participant's just-noticeable pitch difference in cents, paired with their timing induced bias in Experiment 2. Higher just-noticeable differences indicate less sensitive pitch perception, while greater timing-induced bias indicates an stronger tendency to rate later tones as lower. The shaded region indicates the regression line and its 95% confidence interval. Participants in Experiment 2 were similarly biased by the probe tone's timing regardless of their pitch sensitivity.

biased participants' pitch perception similarly regardless of their sensitivity to pitch differences.

Discussion

In Experiment 2 we investigated whether the biasing effects of timing on pitch perception vary in strength according to task difficulty and/or individual pitch sensitivity. We conducted an adaptive-difficulty pitch discrimination task calibrated to each person's just noticeable pitch difference. Although we replicated the bias to perceive later probe tones as lower in pitch, we did not find evidence that this bias strengthens when pitch changes are made less discriminable by reducing the size of the change. Timing-induced bias was similarly strong when the pitch change was equal to the participant's JND as when it was half that size (Figure 6). We also did not find evidence that the strength of the bias correlated with JND (Figure 7). Participants were similarly influenced by the timing of the probe regardless of the precision of their pitch perception. Therefore, neither of these factors appear to account for the sensitivity–bias correlation in Experiment 1.

General Discussion

Across two pitch discrimination experiments we observed a biasing effect of early versus late tone timing on perceived pitch. Later timing resulted in lower perceived pitch without an impact on discriminability (Figures 1–2 and 5–6). The strength of this illusion was not found to depend on task difficulty (the size of the pitch difference between standard and probe tones; Figure 6), nor individual differences in sensitivity to pitch changes (measured as just-noticeable difference; Figure 7). Alongside previous findings that ascending pitch produces illusions of speeding up (e.g., Boltz, 2011; Collier & Hubbard, 1998; Herrmann et al., 2013), our results provide evidence that pitch and timing bidirectionally influence one another in auditory perception. This bidirectional influence is consistent with accounts that suggest pitch and timing are perceptually integrated (Boltz, 2017; Jones, 1976).

This type of cue integration has often been framed as a Bayesian inference problem (Kersten, Mamassian, & Yuille, 2004; Knill & Richards, 1996; Knill & Pouget, 2004; Vilares & Kording, 2011; Vincent, 2015), and we can apply a similar explanation here. The fundamental idea behind Bayesian models of perception is that the brain needs to infer the state of the surrounding environment based only on noisy sensory information, in conjunction with learned priors regarding the statistical structure of the world. Due to the stochastic nature of neural activity, there are many different states of the world that can produce any given pattern of sensory activation; therefore, incorporating prior knowledge about world structure helps narrow down which of these possible world states generated any given pattern of sensory activity. Optimal Bayesian inference has previously been used to explain illusions in perceived visual (Weiss, Simoncelli, & Adelson, 2002) and tactile (Goldreich & Tong, 2013) motion, and Bayesian/predictive coding accounts of music perception have also emerged within the last decade (Cannon, 2021; Koelsch, Vuust, & Friston, 2019; Vuust & Witek, 2014).

Auditory Cue Integration as Bayesian Inference

What Jones (1976) described as a "lawful natural relationship" between changes in pitch and time is precisely the type of world structure that might be incorporated into a perceptual prior. Her hypothesis of expected proportionality between changes in pitch and time can be understood as a prior on the velocity of pitch motion (see also Henry & McAuley, 2009, 2013). In nature, larger changes in pitch are statistically more likely to take place over a longer period of time, and so movement along one auditory dimension (pitch or time) does carry information about movement in the other. Bayesian statistics provides a formal mathematical description of *how much* information each dimension provides about the other (Friedman, Ludvig, Legge, & Vuong, 2013; Genewein, Hez, Razzaghpanah, & Braun, 2015), but the fundamental ideas align closely with Jones (1976). Lawful relations in nature between changes in pitch and time make it possible to partially infer the magnitudes of pitch changes based on elapsed time, and to partially infer the interval between two sounds from the magnitude of pitch change between them. Therefore, when the brain reconstructs the state of the external world based on a combination of incoming noisy sensory data and prior expectations, it is statistically optimal to bias perception towards those priors.

In the context of the present study, we observed a biasing effect of the *direction* of temporal change (rather than magnitude) on the direction of perceived pitch change. This effect might similarly be explained by a prior expectation for a positive correlation between directional changes in pitch and timing. In our task, the probe tone's change in timing is much larger than the change in pitch. The timing change is therefore much easier to detect and, in cases when the probe arrives late, can even be known before the tone plays. Therefore, we can assume the brain is able to infer the directional change in timing faster than the directional change in pitch. This inference allows prior knowledge of correlations between timing changes and pitch changes to inform the ongoing inference about the pitch change. For example, if speeding up is correlated with increasing pitch in nature, then a tone that plays early is more likely *a priori* to have increased in pitch, rather than decreased. Boltz (2011, 2017) has previously argued that there is reason to expect such a real-world correlation to exist, as both higher pitch and faster tempo are higher-energy states. For example objects tend to generate higher-pitched sounds as they speed up, and pitch and tempo might similarly be expected to covary in speech alongside changes in arousal (e.g., Black, 1961). Broze and Huron (2013) have also noted that lower instruments tend to be larger and have slower attack times, constraining how quickly they can be played relative to similar instruments of higher pitch and smaller size. However, a full cross-cultural investigation of pitch–tempo correlations in speech and music will be necessary to conclusively demonstrate a lawful relationship in directionality.

Faster Bias-Conforming Responses

We have established that a Bayesian prior for pitch increasing during acceleration and decreasing during deceleration might explain the biases observed in the present study. But what of our reaction time results? We found that bias-conforming responses to early and late probes were about 100 ms faster than responses to on-beat probes. Bias-opposing responses were slightly slower on average than responses to on-beat probes, but not significantly so (Figure 4). We believe this pattern of results can also be explained within the Bayesian framework discussed above, if reliance on the prior allows for faster inference of off-beat pitch changes by acting as an extra cue to the pitch change. All responses to on-beat probes and all correct bias-opposing responses must have been generated based on a slower analysis of the pitch-related sensory activation (or by random guessing). For on-beat probes, this is the case because there is no change in timing to use as a supplemental cue (although a small change in timing could still be incorrectly inferred). For correct bias-opposing responses this is the case because reliance on the prior only biases inference towards an incorrect response. In contrast, correct bias-conforming responses may have either been based on this slower analysis of the pitch-related sensory activity, or through a faster inference process informed by the tone's timing. In this way, correct bias-opposing and bias-neutral responses may be generated by similar processes, while bias-conforming responses sometimes follow a faster, more biased process (for additional discussion of how Bayesian inference may translate to a decision process, see Dunovan, Tremel, & Wheeler, 2014).

Alternatively, fast responses may derive from heightened attention rather than heuristic processing. As we did not restrict response times in our study, we cannot distinguish whether faster responses originated from heuristic processing or differences in attention. In future work, it may be insightful to vary the amount of time participants are given to respond, as one could assess whether timing-induced bias is stronger when participants are forced to rely more heavily on prior expectations to make speeded responses. Attention might also be manipulated through the use of a distractor task (e.g., Herrmann & Johnsrude, 2018).

Difficulty and Perceptual Sensitivity

A Bayesian account might also explain why our selected difficulty manipulation in Experiment 2 (varying the size of the pitch change) did not change the extent to which timing influenced perceived pitch. In multi-cue Bayesian inference, the relative weighting of the cues is proportional to the precision of the estimates that can be made from them (Friedman et al., 2013). The pitch of the probe tone was equally clear in our easy and difficult conditions—the pitch change was just smaller, making it harder to make a discrimination response given a fixed level of sensory precision. From a signal detection theory framework, discriminability in the form of d' is the number of standard deviations between the means of the distributions for the two categories of stimulus. Therefore, one could manipulate discriminability either by moving the two distributions closer together as we did in Experiment 2, or by degrading the stimuli to increase the standard deviation of the distributions. Future research should test whether timing-induced bias increases when pitch changes are degraded rather than made smaller, for example through spectral smearing (Baer & Moore, 1993), as this should theoretically reduce the weighting of spectral information relative to temporal in a Bayesian integration process.

For the same reason, we might expect individuals with less precise pitch perception to down-weight pitch-related sensory information and up-weight temporal information. In Experiment 1, we did observe a negative correlation between d' and timing-induced bias that conforms to this prediction (Figure 3); however, we found a near-zero correlation between just-noticeable difference and timing-induced bias during Experiment 2, when difficulty was calibrated at an individual level (Figure 7). One reason we might not see a negative correlation between pitch sensitivity and timing-induced bias is if pitch sensitivity correlates positively with temporal sensitivity, such that individuals with poor pitch sensitivity also have poor temporal sensitivity (e.g., Sares, Foster, Allen, & Hyde, 2018). Alternatively, it is possible that timing-induced bias may only significantly increase when pitch sensitivity becomes too poor to perform above chance. As bias tended to be high in participants who failed to perform above chance in Experiment 1 (Figure 3), it is possible that the correlation was driven by some participants explicitly using timing as a cue due to the task being too difficult for them to detect any pitch changes at all. In situations where participants can only detect one feature of a stimulus changing, they may conceivably resort to making judgments based on that feature, even if it is not the feature to which they were instructed to attend (Feldstein & Bond, 1981). The individualized difficulty calibration in Experiment 2 may have alleviated this issue and eliminated any correlation between sensitivity and timing-induced bias.

Rhythmic Deviation or Foreperiod Effect?

Although we used deviation from a rhythmic context to manipulate perceived pitch in the present study, it is possible that timing-induced bias depends on the time elapsed since the end (or beginning) of the previous note, rather than on a note's phase within the rhythmic context. This alternative explanation could be tested using a pitch discrimination task in which a single standard tone plays on each trial, followed by a variable delay (i.e., foreperiod) before the onset of the probe tone. Two recent studies by Herbst and Obleser (2017, 2019) implemented a design similar to this without testing the effects of foreperiod duration on bias, as reaction time and accuracy have typically been the focus of foreperiod analyses. We believe our present results support the addition of tests for foreperiod effects on bias in future studies of pitch discrimination. If shorter foreperiods in the absence of a rhythmic context result in higher perceived pitch, our present results might be better explained not by a learned prior on pitch-timing correlations, but rather by an effect in which residual neural activity from one tone exerts a decaying pitch bias on the perception of the next. However, given our previous findings that pitch influences perceived mistiming in the same direction that mistiming influences perceived pitch (Pazdera & Trainor, 2023), we believe that a learned correlation is more likely.

Conclusion

The present study demonstrates that a tone's timing within a rhythmic context can alter the perception of its pitch. These timing-induced illusory pitch changes—alongside previous evidence for pitch-induced illusory tempo changes—support the long-standing hypothesis that the brain integrates pitch and timing during auditory perception.

Declarations

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Conflicts of interest

The authors have no conflicting financial or non-financial interests to disclose.

Ethics approval

This study was performed in line with the principles of the Declaration of Helsinki. Approval for the present research was granted by the McMaster Research Ethics Board (No. 2609).

Consent to participate

All participants provided informed consent prior to their participation in our study.

Open practices statement

All data, code, and stimuli from our experiments are publicly available on the Open Science Framework at `https://osf.io/hrj3t/`, as well as on GitHub at `https://github.com/jpazdera/IllusoryPitch`.

Author Contributions

Conceptualization: JKP, LJT
Data curation: JKP, OR
Formal analysis: JKP, OR
Funding acquisition: LJT
Investigation: JKP, OR
Methodology: JKP, LJT
Project administration: JKP, LJT
Resources: LJT
Software: JKP

Supervision: LJT
Visualization: JKP, OR
Writing – original draft: JKP
Writing – review & editing: JKP, OR, LJT

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