Bidirectional Interactions of Pitch and Time

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August 4, 2023

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Research into pitch perception and time perception has typically treated the two as independent processes. However, previous studies of music and speech perception have suggested that the brain integrates pitch and timing information in auditory perception. It has been well-established that the pitch of an auditory stimulus can influence a person's perception of its duration and tempo. In contrast, little research has addressed the question of whether timing also influences perceived pitch – an effect that should similarly arise if the brain integrates pitch and time into a unified percept. We conducted a pair of experiments using similar two-alternative forced choice tasks to establish the bidirectional nature of pitch-time interactions in auditory perception. Experiment 1 tested the effect of pitch height on perceived mistiming, whereas Experiment 2 tested the effect of timing offset on pitch discrimination. We observed a strong bias to rate higher-octave probe tones as earlier than lower-octave probes with identical timing, as well as a strong bias to rate tones that arrive early as higher in pitch than those that arrive late. Together, these results suggest that pitch and time exert a bidirectional influence on one another, providing evidence of integrated processing of pitch and timing information in auditory perception. Identifying the mechanisms behind this pitch-time interaction will be critical for unifying theories of pitch and rhythm processing.

Keywords: integration, perceptual bias, pitch, tempo, time perception

1. Introduction

The hypothesis that the human brain integrates auditory pitch and timing information into a unified percept is not a new idea. Decades ago, Cohen, Hansel, and Sylvester (1954) proposed that changes in pitch can be understood as a movement through pitch space over time, and that the perception of this movement is biased by lawful associations between time and space. This hypothesis was formalized by Jones (1976), who proposed that the brain represents music as movement through an integrated space of pitch, loudness, and time. In this integrated space, changes along any one dimension lawfully relate to changes in each other dimension. Therefore, information about pitch can inform predictions and expectations about timing, and vice versa. These concepts have continued to gain support in recent years (Boltz, 2017; Henry & McAuley, 2013).

The effects of pitch and pitch change on perceived tempo have been well documented. Typically, higher-pitched speech and music have been associated with faster perceived tempo (e.g., Boltz, 2011; Collier & Hubbard, 1998; Feldstein & Bond, 1981). Ascending pitch has also been associated with perceived acceleration (e.g., Herrmann, Henry, Grigutsch, & Obleser, 2013). However, recent evidence suggests that the relation between pitch and perceived tempo may not always be monotonic. Pazdera and Trainor (2022) observed inverted U-shaped effects of pitch on perceived tempo when participants were exposed to tones across a five-octave range.

In addition to effects on beat-based timing, pitch has also been found to affect single-interval timing and duration judgments. There is some evidence that intervals flanked by one or more high-pitched tones are underestimated in duration (Lake, LaBar, & Meck, 2014; Pfeuty & Peretz, 2010), whereas the duration of higher-pitched sounds are overestimated (e.g., Cohen et al., 1954).

The inverse question of whether timing can influence the perceived pitch of a sound has received less attention. Early evidence from Madsen and colleagues suggests that tempo changes can drive illusory changes in perceived pitch, such that speeding up is associated with ascending pitch and slowing down is associated with descending pitch (Duke, Geringer, & Madsen, 1988; Geringer & Madsen, 1984; Madsen, Duke & Geringer, 1984). However, we are not aware of any research on how changes in single-interval timing influence pitch perception.

If our brains integrate pitch and timing information into a unified percept, then we should expect pitch and time to exert a bidirectional influence on one another. We therefore conducted two experiments to investigate the bidirectional nature of pitch-time interactions. Both experiments employed similar two-alternative forced choice tasks. Whereas Experiment 1 tested the biasing effects of pitch height on the perceived mistiming of probes, Experiment 2 tested the biasing effects of probe timing on pitch discrimination.

2. Methods (Experiment 1)

In Experiment 1, we tested the effect of pitch on perceived timing. Participants completed a two-alternative forced choice task in which they listened to a pacing signal consisting of five isochronous beats, continued to track the beat through two silent intervals (see Manning & Schutz, 2013), and then judged whether a final probe played early or late relative to the next beat. In order to separate the effect of the probe's pitch from that of the pacing signal, we assigned participants to one of two task conditions. In the pitched-probe condition, only the pitch of the

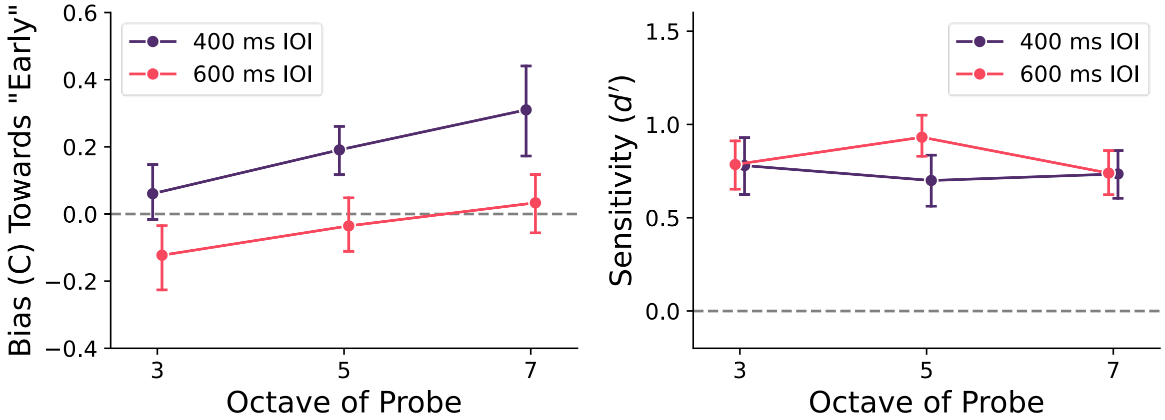

Figure 1. Pitch biases perceived mistiming. Bias (left) and sensitivity (right) of timing offset discrimination in Experiment 1, as a function of tempo and the pitch of the probe tone. Positive values of *C* indicate a bias towards rating probe tones as earlier. Error bars denote within-subject 95% confidence intervals. Participants rated higher-octave probe tones as earlier than lower-octave probes.

probe varied across trials. In the pitched-context condition, only the pitch of the pacing signal varied. We also tested participants at two tempos, to assess whether the effect of pitch on perceived timing differs between faster and slower contexts.

2.1. Participants

Fifty-five undergraduate students (4 male, 50 female, 1 nonbinary) from McMaster University completed the experiment for course credit. We randomly assigned 25 participants (22 female) to the pitched-probe condition and 30 (28 female) to the pitched-context condition. Ages ranged from 17–21 years (M = 18.2, SD = 0.7). An additional thirteen participants completed the experiment but were excluded from analysis due to either failing both attempts at the headphone test (N = 6) or completing the task with a negative d' (N = 7). We conducted the experiment online between October 2021 and January 2022 due to COVID-19 restrictions.

2.2. Materials

Our stimuli consisted of both complex tones and clicks. We generated all complex tones in Python by summing three sinusoidal waves with random phase, including the fundamental frequency (F0) and the first two overtones (F1 and F2), with an amplitude fall-off of 6 dB/octave. The tones were 250 ms in duration and followed a percussive amplitude envelope, consisting of a 10 ms linear rise followed by a 240 ms exponential decay. Clicks were generated using Audacity, and were 50 ms in duration. We then used Audacity to normalize the loudness of all sounds to −14 LUFS to approximate the loudness of other web-based content. To ensure precise interonset interval (IOI) timing, we pre-generated all tone and click sequences as WAV files. We implemented stimulus presentation and response collection in JavaScript using the jsPsych library (de Leeuw, 2015), and hosted our experiment via the web-based platform Pavlovia (https://pavlovia.org). We have made all data, code, and materials from both experiments publicly available on the Open Science Framework at https://osf.io/3ahxe/.

2.3. Procedure

Experiment 1 used a 2 task (pitched probe or pitched context) × 3 octave (3rd, 5th, or 7th) × 2 tempo (400 or 600 ms IOI) mixed design. Octave and tempo varied within subjects, whereas the task varied between subjects. On each trial, participants in the pitched-probe condition heard an isochronous series of clicks and judged the timing offset of a subsequent probe tone. Participants in the pitched-context condition instead heard an isochronous, repeating tone and judged the timing offset of a subsequent click. Within each condition, we presented probes at seven unique timing offsets relative to the beat (on-beat, 10% early/late, 20% early/late, or 30%, early/late). We repeated each combination of octave, tempo, and offset eight times (once per block), and presented a different pitch class (C, D, D#, F, F#, G#, A, or B) from that octave on each repetition. Practice trials instead used the tones F4, G4, F6, and G6, and always used a 500 ms IOI with a probe offset of 30%.

Participants were instructed to wear headphones during the experiment, and the session began with six trials of a headphone test based on that of Woods, Siegal, Traer, and McDermott (2017). Participants were notified if they failed to answer at least four trials correctly. In this case, they were informed that they may not be able to answer correctly without headphones and were asked to attempt the test again.

Participants next received instructions for the main task. Each trial consisted of a pacing signal followed by a probe. The pacing signal consisted of five isochronous repetitions of a click or tone. Two silent beats followed the pacing signal, and the probe played near the third beat after the signal ended. We instructed participants to keep track of the beat

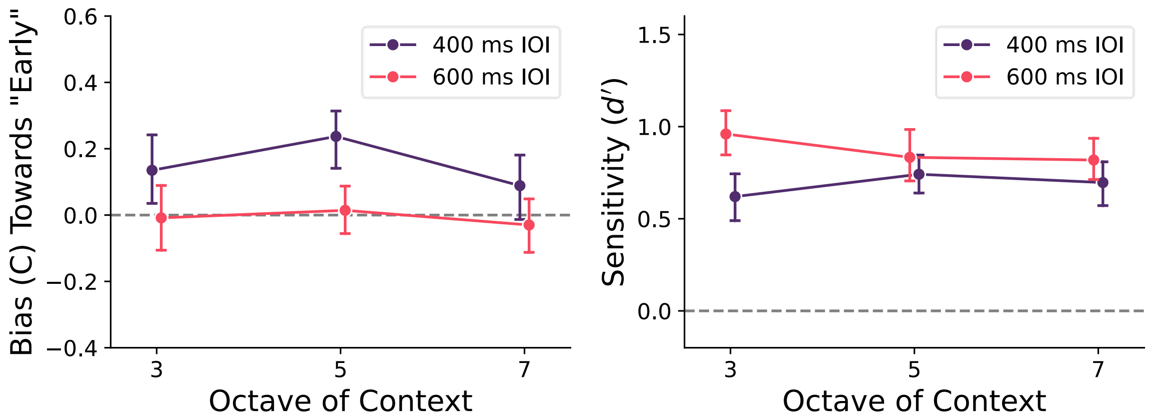

Figure 2. Effect of preceding context on perceived mistiming. Bias (left) and sensitivity (right) of timing offset discrimination in Experiment 1, as a function of tempo and the pitch of the preceding context. Positive values of *C* indicate a bias to rate probe clicks as earlier. Error bars denote within-subject 95% confidence intervals.

through the silent period in order to determine whether the probe began earlier or later than the next beat should have occurred. Participants were free to choose how to maintain the beat, and provided their trial responses via a key press. There was no time limit to make a response, and the next trial began 1.5 s after the participant responded.

The session consisted of eight practice trials and 336 experimental trials, organized into eight blocks of 42, with self-paced breaks between blocks. Each combination of octave, tempo, and offset appeared once per block. We fully randomized octave and offset within each block, but alternated the tempo every seven trials to limit the difficulty of the task. We provided feedback on practice trials only.

3. Results (Experiment 1)

Our primary measures of interest were the bias (*C*) and sensitivity (d') of participants' offset discrimination judgments. We calculated these measures for each participant at each octave and tempo by considering trials as hits if the participant correctly identified a late probe as late, and false alarms if the participant misidentified an early probe as late. We excluded trials with on-beat probes from analysis, as no correct answer was possible. To prevent hit rates and false alarm rates of 0 and 1, we followed the correction method of Hautus (1995), adding 0.5 to the count of each cell of the contingency table. Under our chosen scoring framework, higher values of *C* correspond to greater conservatism about rating tones as late (i.e., a bias to rate tones as early).

3.1. Pitch of the probe

Figure 1 illustrates bias and sensitivity as a function the probe tone's octave and the tempo of the pacing signal in the pitched-probe condition. We analyzed bias via a 3 octave × 2 tempo repeated measures ANOVA. We observed a large, significant main effect of octave, $F(2, 48) = 6.07$, $p = .004$, $\omega_p^2 = .154$, such that higher-octave probe tones were rated as earlier than lower-octave probes. The main effect of tempo was also significant, with a large effect size, $F(1, 24) = 16.62$, $p < .001$, $\omega_p^2 = .267$. Participants were relatively unbiased in their responses to probe tones that followed a metronome with a 600 ms IOI, but tended to rate probe tones as early when they followed a metronome with a 400 ms IOI. The interaction between octave and tempo was nonsignificant, $F(2, 48) = 0.78$, $p = .466$, $\omega_p^2 = -.003$, suggesting that the probe tone's pitch had a similar effect on its perceived timing regardless of tempo.

We next analyzed sensitivity in the pitched-probe condition via a 3 octave × 2 tempo repeated measures ANOVA. Both the main effect of octave, $F(2, 48) = 0.52$, $p = .600$, $\omega_p^2 = -.004$, and tempo, $F(2, 24) = 1.79$, $p = .194$, $\omega_p^2 = .007$, were nonsignificant. The interaction between octave and tempo was also nonsignificant, $F(2, 48) = 1.84$, $p = .170$, $\omega_p^2 = .011$. Participants were similarly sensitive to timing offsets regardless of tempo and the octave of the probe tone.

3.2. Pitch of the preceding context

Figure 2 illustrates bias and sensitivity as a function of the octave and tempo of the tone sequence preceding the probe click in the pitched-context condition. We analyzed bias via a 3 octave × 2 tempo repeated measures ANOVA. The main effect of octave was small, but significant, $F(2, 58) = 4.07$, $p = .022$, $\omega_p^2 = .036$, and followed an inverted U-shaped pattern with probe clicks perceived as earliest when preceded by a 5th octave sequence. The main effect of tempo was also significant, $F(1, 29) = 4.61$, $p = .040$, $\omega_p^2 = .161$. Similar to our findings in the pitched-probe condition, participants were unbiased in their ratings of probe clicks that followed a sequence of tones with 600 ms IOIs, but tended to perceive clicks following a 400 ms IOI tone sequence as arriving early. The interaction between octave and tempo was again nonsignificant, $F(2, 58) = 1.35$, $p = .268$, $\omega_p^2 = .004$.

Finally, we analyzed sensitivity in the pitched-context condition via a 3 octave × 2 tempo repeated

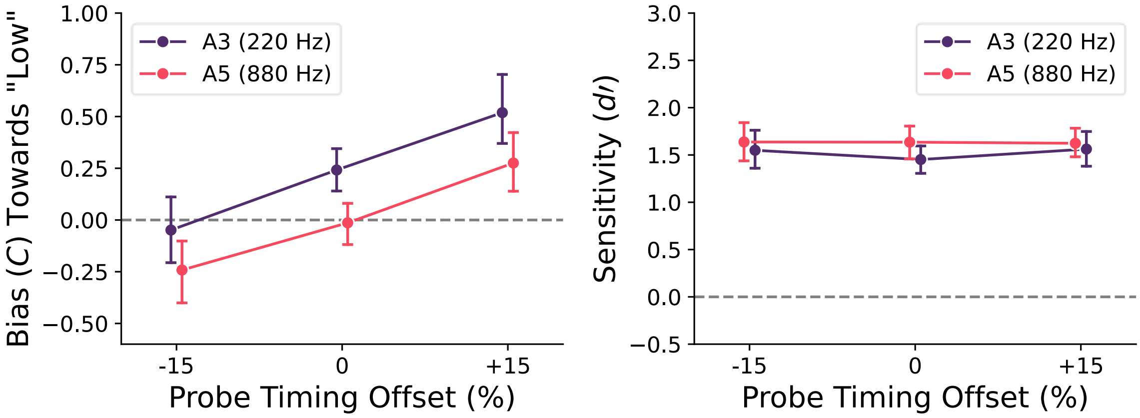

Figure 3. Timing biases perceived pitch. Bias (left) and sensitivity (right) of pitch discrimination in Experiment 2. Negative timing offsets indicate early timing and positive offsets indicate late timing. Positive values of *C* indicate a bias towards rating probe tones as lower in pitch. Error bars denote within-subject 95% confidence intervals. Later timing biased participants to label probe tones as lower in pitch.

measures ANOVA. The main effect of octave was nonsignificant, $F(2, 58) = 0.12$, $p = .889$, $\omega_p^2 = -.009$, suggesting that participants were similarly sensitive to the timing offset of a probe click regardless of the pitch of the tones preceding it. We did, however, observe a significant main effect of tempo, $F(2, 29) = 7.49$, $p = .010$, $\omega_p^2 = .082$, such that participants were more sensitive to deviations from 600 ms interonset timing than from 400 ms timing. The interaction between octave and tempo was nonsignificant, $F(2, 58) = 3.05$, $p = .055$, $\omega_p^2 = .022$.

4. Discussion (Experiment 1)

In Experiment 1, we measured both how a sound's own pitch and the pitch of its context influence its perceived timing. We asked participants to track the beat of an isochronous sequence of clicks or tones, maintain the beat through two silent intervals, and then determine whether a final probe tone or click arrived early or late, relative to that beat. We observed a strong biasing effect of the probe's own pitch on judgments of its timing, as well as a weaker effect of its context. Participants consistently perceived higher-pitched probe tones as earlier than lower-pitched tones (Figure 1). This finding is consistent with previous observations associating higher pitch with faster perceived timing in both music (e.g., Boltz, 2011; Collier & Hubbard, 1998) and speech (Boltz, 2017; Feldstein & Bond, 1981).

In contrast, the effect of the pitch context followed an inverted U-shaped curve, such that probes following middle-octave sequences were perceived as earliest (Figure 2). This pattern resembles the inverted U-shaped relation between pitch and perceived tempo identified by Pazdera and Trainor (2022) whenever participants heard a range of stimuli spanning more than three octaves. However, we anticipated that any bias in the perceived tempo of the pacing signal should exert a bias in the opposite direction on the perceived timing of the probe. For example, if a low-pitched sequence is perceived (and internally represented) as slower than its true tempo, then a subsequent click that occurs on the true beat will arrive earlier than the internal expectation. Thus, if middle-octave sequences are perceived as fastest, we would expect these to be the contexts that make subsequent probes sound the latest – not the earliest. Therefore, we find it unlikely that the effect of the preceding pitch context originated from a biased internal representation of tempo. Rather, our pattern of results is more consistent with pitch biasing the perceived duration of the silent interval between the pacing signal and the probe. This explanation is also consistent with prior observations that perceived interval timing can be biased by the pitch of flanking tones (Lake et al., 2014; Pfeuty & Peretz, 2010).

The biasing effects of pitch were not found to differ across tempos; however, tempo itself did affect timing judgments. Participants in both the pitched-probe and pitched-context versions of the task showed near-zero bias when judging deviations from 600 ms interonset timing. Yet, they showed a general bias to judge probes as early following a pacing signal with 400 ms interonset timing. This pattern is consistent with findings by Vos, van Assen, and Fraňek (1997), who noted a bias for people to perceive the final tones of fast sequences as having sped up.

5. Methods (Experiment 2)

Having observed a strong biasing effect of a tone's own pitch on its perceived timing, our next goal was to determine whether this bias also occurs in reverse. That is, are tones that arrive earlier than expected perceived as higher in pitch than those played later? Experiment 2 addressed this question using a pitch discrimination paradigm, in which participants listened to an isochronous, repeating standard tone and judged whether a subsequent (potentially mistimed) probe tone was shifted higher or lower in pitch. We tested pitch discrimination at two different octaves to assess whether the effect of timing on perceived pitch differs between octaves.

5.1. Participants

Thirty undergraduate students (9 male, 21 female) from McMaster University participated in the study for course credit. Ages ranged from 18–22 years (*M* = 18.6, *SD* = 1.1). We conducted the experiment in-lab between March and April 2022 under special COVID-19 safety protocols, as approved by the local research ethics board.

5.2. Materials

Our stimuli were complex tones with identical design to Experiment 1, with the exception that we included one additional overtone of the fundamental frequency to improve pitch clarity. We again implemented the experiment using jsPsych (de Leeuw, 2015). The experiment was hosted on Pavlovia, and ran in Google Chrome on a 2011 iMac in our lab. Stimuli were presented at 75 dBA via a pair of Sennheiser HD 201S headphones.

5.3. Procedure

The study followed a 3 offset (Early: -15%, On Time: 0%, or Late: +15%) × 2 octave (3rd or 5th) within-subjects design. Within each condition, the probe tone could be presented either higher or lower in pitch relative to the standard. Third-octave standard tones were A3 (220 Hz), with the probe tone shifted by ± 1 Hz. Fifth-octave standard tones were A5 (880 Hz), with the probe tone shifted by ± 4Hz.

Participants completed a pitch discrimination task in which they responded via a key press (up or down arrow) whether a probe tone was higher or lower in pitch than a repeating standard tone. The standard tone repeated six times on each trial at a steady interonset interval of 500 ms, and the probe tone played 425 ms, 500 ms, or 575 ms after the final repetition of the standard. There was no time limit for the participant's response, and the next trial began 1.5 s after the participant responded.

The session consisted of 20 repetitions of each combination of offset, octave, and pitch shift, for a total of 240 trials. We organized trials into four blocks of 60, with self-paced breaks between blocks. Each block consisted of 10 repetitions of each combination of offset and pitch shift, randomly ordered. All trials within a block used standard tones of the same octave to reduce task difficulty, and octave alternated between blocks in an ABAB pattern in which the octave of the first block varied randomly between participants. Four practice trials preceded the main experimental trials and used a standard pitch of A4 (440 Hz) with ± 6 Hz shifts and a 0% probe tone offset. Feedback was provided on practice trials only.

6. Results (Experiment 2)

We calculated the bias (C) and sensitivity (d') of each participant's pitch discrimination by considering trials as hits when the participant correctly identified a pitch increase, and false alarms when they misidentified a pitch decrease as an increase. We again corrected for extreme hit rates and false alarm rates using the Hautus (1995) method. Under our scoring framework for Experiment 2, higher values of C correspond to greater conservatism about rating tones as high (i.e., a bias to rate tones as low).

Figure 3 illustrates bias and sensitivity as a function of probe offset and octave. We analyzed bias via a 3 offset × 2 octave repeated measures ANOVA. Results indicated a large, significant main effect of probe offset on bias, $F(2, 58) = 14.73$, $p < .001$, $\omega_p^2 = .351$. As the probe timing became later, participants became increasingly biased to label the probe as lower in pitch than its standard. Octave also significantly affected bias, $F(1, 29) = 14.40$, $p = .001$, $\omega_p^2 = .126$. Participants tended to rate probe tones on third-octave trials as lower in pitch than their standards but were relatively unbiased on fifth-octave trials. Offset and octave did not significantly interact, $F(2, 58) = 0.18$, $p = .833$, $\omega_p^2 = -.009$, suggesting that probe timing biased pitch discrimination similarly across octaves.

We next analyzed sensitivity via a 3 offset × 2 octave repeated measures ANOVA. Neither offset, $F(2, 58) = 0.25$, $p = .784$, $\omega_p^2 = -.009$, nor octave, $F(1, 29) = 0.91$, $p = .347$, $\omega_p^2 = .006$, significantly affected sensitivity, and offset and octave did not significantly interact, $F(2, 58) = 0.23$, $p = .794$, $\omega_p^2 = -.009$.

7. Discussion (Experiment 2)

Experiment 1 demonstrated that the pitch of a sound influences its perceived timing. In Experiment 2, we tested whether the timing of a sound also impacts its perceived pitch. We asked participants to listen to an isochronous sequence of standard tones, and to determine whether a final, potentially mistimed tone was higher or lower in pitch. We observed a strong bias to perceive probe tones as lower in pitch, the later they arrived (Figure 3). Previous work by Madsen and colleagues has suggested that tempo changes can drive illusory pitch changes in the same direction (Duke et al., 1988; Geringer & Madsen, 1984; Madsen et al., 1984). Our results suggest that even single-interval timing changes can bias perceived pitch.

The biasing effects of timing on perceived pitch were similar across both octaves we tested. Octave did, however, directly bias perceived pitch change. At A3 (220 Hz) participants showed a bias to perceive the probe tone as lower in pitch than the standard, whereas at A5 (880 Hz) participants were relatively unbiased at judging pitch change. We are not aware of any previous studies directly comparing biases in pitch discrimination at different octaves.

8. General Discussion

Together, our experiments demonstrate strong, bidirectional interactions of pitch and time in auditory perception. Using similar experimental paradigms, we evaluated both the effect of pitch on perceived timing and the effect of timing on perceived pitch. Both experiments revealed a perceptual association between higher pitch and earlier timing. The bidirectional nature of these perceptual biases suggests that pitch and timing are integrated during auditory processing.

The concept that our brains integrate pitch and tempo into a unified percept has been proposed for decades (e.g., Boltz, 2017; Cohen et al., 1954; Henry & McAuley, 2013; Jones, 1976), though models and theories of pitch perception and time perception largely remain independent (however, see Large, 2000, for one example of incorporating pitch into an oscillator model of rhythm perception). We should begin to take seriously the growing body of evidence that our brains integrate pitch and timing information, and work towards integrating pitch and timing models. Doing so will be a critical next step in developing and consolidating our understanding of music perception, and of auditory perception more broadly.

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