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Hear it playing low and slow: How pitch level differentially influences time perception

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ABSTRACT

Variations in both pitch and time are important in conveying meaning through speech and music, however, research is scant on perceptual interactions between these two domains. Using an ordinal comparison procedure, we explored how different pitch levels of flanker tones influenced the perceived duration of empty interstimulus intervals (ISIs). Participants heard monotonic, isochronous tone sequences (ISIs of 300, 600, or 1200 ms) composed of either one or five standard ISIs flanked by 500 Hz tones, followed by a final interval (FI) flanked by tones of either the same (500 Hz), higher (625 Hz), or lower (400 Hz) pitch. The FI varied in duration around the standard ISI duration. Participants were asked to determine if the FI was longer or shorter in duration than the preceding intervals. We found that an increase in FI flanker tone pitch level led to the underestimation of FI durations while a decrease in FI flanker tone pitch led to the overestimation of FI durations. The magnitude of these pitch-level effects decreased as the duration of the standard interval was increased, suggesting that the effect was driven by differences in mode-switch latencies to start/stop timing. Temporal context (One vs. Five Standard ISIs) did not have a consistent effect on performance. We propose that the interaction between pitch and time may have important consequences in understanding the ways in which meaning and emotion are communicated.

1. Introduction

Our ability to perceive the passage of time is a cognitive process critical to our interactions with the environment and with others (Agostino, Peryer, & Meck, 2008; Bays, Foley, & Zabrucky, 2013; Buhusi & Meck, 2005; Conway, 2004; Meck, 2003, 2005; Meck, Doyère, & Gruart, 2012). Timing can be particularly important in conveying meaning and emotion in both speech (Cutler, Dahan, & van Donselaar, 1997; Juslin & Laukka, 2003; Murray & Arnott, 1993) and music (Juslin, 2000; Juslin & Laukka, 2003; Webster & Weir, 2005). Changes in pitch are also important in emphasizing meaning and conveying emotion (Juslin, 2005; Scherer, Johnstone, & Klasmeyer, 2003), however; the perceptions of time and pitch in music are generally studied independently (Allman, Teki, Griffiths, & Meck, 2014; Griffiths, 2012; Krumhansl, 2000). This may be due, in part, to double dissociations in performance on pitch and timing tasks within neuropsychological populations (Di Pietro, Laganaro, Leemann, & Schnider, 2004; Hyde & Peretz, 2004), as well as to neural dissociations in healthy participants (Jerde, Childs, Handy, Nagode, & Pardo, 2011). Such findings suggest that pitch and time perception rely on independent systems.

Nevertheless, the perceptions of pitch and time do interact behaviorally (Arvanti, 2009; Boltz, 1998; Henry & McAuley, 2009; Krumhansl, 2000; Lebrun-Guillaud & Tillmann, 2007; Schellenberg, Krysciak, & Campbell, 2000). For instance, higher pitched tones are overestimated in duration compared to lower pitched tones (Brigner, 1988; Cohen, Hansel, & Sylvester, 1954; Matthews, 2013). On the other hand, empty intervals are judged as *shorter* than a standard interval when the comparison intervals are flanked by at least one higher frequency tone and are judged as *longer* when flanked by at least one lower frequency tone (Pfeuty & Peretz, 2010). While such interactions between pitch and timing have been observed, studies have not identified the psychological mechanisms, according to standard models of time perception, that underlie these temporal distortions. As these interactions might enhance the communicative value of auditory signals, characterizing the mechanisms of resulting distortions and understanding if and how they might be modulated is of considerable interest.

The information-processing model of scalar timing theory outlines psychological processes underlying time perception and makes specific quantitative predictions for how distortions at each processing stage

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should affect temporal estimates. Scalar timing theory incorporates clock, memory, and decision stages into its information-processing architecture (Gibbon, Church, & Meck, 1984; Hinton & Meck, 1997; van Rijn, Gu, & Meck, in press). Briefly, this model proposes that at the onset of a stimulus to be timed a switch closes, allowing pulses to be emitted from a pacemaker at a certain rate and collected in an accumulator. At the offset of a signal, the switch opens and the number of pulses collected in the accumulator is compared to durations stored in memory to determine whether the timed duration is longer or shorter than remembered intervals. This model typically attributes within-trial distortions in time perception and timed performance to either changes in the rate of a pacemaker or the flow of pulses emitted by a pacemaker through a mode switch into an accumulator (Lejeune, 1998; Meck & Benson, 2002). These two components of the clock stage are, thus, of particular interest here.

Changes in the rate of the pacemaker shift psychometric timing functions either to the left (a relative increase in clock speed) or to the right (a relative decrease in clock speed), with a magnitude proportional to the standard interval being timed (Coull, Cheng, & Meck, 2011; Lake & Meck, 2013; Meck, 1983, 1986, 1996, 2006). Alternatively, distortions influencing the behavior of the mode switch, which controls the flow of pulses from the pacemaker to an accumulator by alternating between an open and a closed state, can result in proportional or additive distortions across durations, depending on the nature of the change in switch activity. Attention is thought to modulate mode-switch activity (Buhusi & Meck, 2009; Fortin et al., 2009; Lake & Meck, 2013; Meck, 1984; Penney, Holder, & Meck, 1996). If attentional resources are divided throughout the timing of a stimulus, the mode switch is said to 'flicker' between an opened and a closed state (Lui, Penney, & Schirmer, 2011; Lustig & Meck, 2001, 2011; Penney, Allan, Meck, & Gibbon, 1998; Penney, Gibbon, & Meck, 2000). Flickering of the mode switch would result in temporal distortions that, like changes in pacemaker rate, are proportional to the duration of the stimulus being timed. On the other hand, the *latency* with which the mode switch closes, allowing pulses to pass through to the accumulator to start the timing process, as well as the latency with which the mode switch opens to stop the accumulation process, can be modulated. Latency effects are independent of stimulus duration, resulting in distortions of temporal estimates that are additive, rather than proportional, across stimulus durations (Gibbon & Church, 1984). In other words, functions are shifted by a relatively fixed value regardless of the stimulus duration being timed. It should be noted that while differences in start/stop latencies bias temporal estimates, these differences should not affect temporal sensitivity (Gibbon & Church, 1984).

In order to determine whether pitch levels influence time perception as a result of changes in pacemaker rate/'flickering' switch activity or mode-switch start/stop latencies, the nature of the temporal task employed must be taken into consideration. In an ordinal comparison procedure (Gu & Meck, 2011), participants compare a comparison stimulus, which varies in duration across trials, to a standard stimulus, which generally has a fixed duration equal to the geometric or arithmetic mean of the distribution of comparison durations. On each trial, participants judge whether the comparison stimulus is 'longer' or 'shorter' in duration than the standard stimulus. Using this procedure often results in timing functions with floor and ceiling effects at anchor comparison durations, as these comparisons are often simple discriminations. As such, assessing whether shifts in timing functions across comparison durations are additive or proportional within a single duration range is usually difficult. In this study, we consider the magnitude of temporal distortion at the point of subjective equality (PSE) across multiple duration ranges to test for underlying mechanisms of temporal distortion (Droit-Volet, Meck, & Penney, 2007; Grommet et al., 2011; Merchant, Harrington, & Meck, 2013).

In the current study, we were also interested in whether or not the magnitude of pitch level-induced temporal distortions could be modulated. Specifically, we hypothesized that the features of the preceding temporal sequence might influence pitch-related distortions in time perception, which would suggest that pitch-related distortions of time are flexibly shaped by their temporal context. Information-processing models of interval timing suggest that repeated presentations of a single duration build up a stronger memory representation of that duration and result in higher temporal sensitivity (Drake & Botte, 1993; Pashler, 2001). We suggest that increased temporal sensitivity might be accompanied by enhanced attention to timing at the expense of non-temporal features of an auditory sequence (Buhusi & Meck, 2009; Buhusi, Sasaki, & Meck, 2002). If attention to pitch is reduced by temporal repetition, latencies to start/stop timing empty intervals flanked by tones of differing pitch might normalize toward the latencies of the repeated interval. If start/stop latencies are responsible for pitch-related distortions of time perception, then temporal repetition might reduce such distortions.

The goals of the present study were to 1) characterize the influence of different pitch levels on temporal estimates, 2) to assess the underlying psychological mechanisms for resulting temporal distortions based on quantitative predictions made by interval timing models for how pacemaker/accumulator versus mode-switch latency distortions should manifest across multiple standard ISI durations and 3) to determine whether temporal repetition might modulate the magnitude of such pitch-induced temporal distortions. We expected our results to support previous evidence of a differential effect of higher versus lower pitches on the perception of interval durations (Pfeuty & Peretz, 2010). Of specific interest here was how the *magnitude* of this effect would change across multiple ISI durations. A proportional effect across increasing standard ISI durations would lend support to a pacemaker/accumulator mechanism that varied in the rate of temporal integration (Meck, 1983, 1996), while a decrease in the magnitude of the effect with increasing standard ISI durations would support a mode-switch latency effect (Buhusi & Meck, 2006; Lejeune, 1998; Meck, 1984). We further predicted that the magnitude of the pitch-level effect would be modulated by temporal repetition, i.e., the number of standard ISIs preceding the final interval (FI), such that temporal repetition would reduce pitch-related biases in temporal estimates. We addressed these hypotheses across two experiments. In Experiment 1, we tested the effect of two different standard ISI durations (300 vs. 600 ms) and the influence of temporal repetition (One vs. Five Standard ISIs). To more conclusively determine the mechanism of distortion, as well as to assess the generalizability of the pitch-level effect across sub-second and supra-second duration ranges, we tested a separate group of participants on a third standard ISI (1200 ms) condition in Experiment 2.

2. Experiment 1

In Experiment 1, we examined whether or not higher and lower flanker tone pitch levels would differentially influence the perceived duration of a FI. We were specifically interested in whether the magnitude of such an effect would remain constant across standard ISI durations or would be proportional to the duration of the standard ISIs being tested. The former would support a mode-switch latency effect while the latter would imply a pacemaker-like mechanism (Lustig & Meck, 2011; Meck & Church, 1983; Meck, Church, & Gibbon, 1985; Penney et al., 2000). Additionally, we assessed if increasing the number of standard ISIs presented prior to the FI to be timed could reduce the magnitude of pitch-related distortion.

2.1. Method

2.1.1. Participants

Forty-six healthy adults participated in this experiment. One participant was removed from analyses due to fatigue and four participants were excluded for poor timing discrimination, such that logistic functions could not be properly fit to individual participant timing data, leading to a final sample size of 41 (20 males, 21 females; 18–40 years,

$M = 22.95$; $SD = 4.71$). All participants reported normal or corrected-to-normal vision and normal hearing. The study protocol was approved by the Duke Medical Institutional Review Board and written informed consent was obtained prior to study inclusion. All participants received monetary compensation.

2.1.2. Stimuli and apparatus

All tone waveforms were created at a 44,100 Hz sampling rate using MATLAB software (MathWorks, Natick, MA). Tones were 50 ms in duration with a 3 ms linearly ramped rise and fall time. FI tones were pure sine waveforms with logarithmically-spaced fundamental frequencies of 400, 500 and 625 Hz. Standard tones were complex waveforms with a fundamental frequency of 500 Hz and two higher harmonics (1000 and 1500 Hz). The complexity added to the standard tone waveforms changed the timbre of the standard tones, such that the 500 Hz standard tones were easier to distinguish from the 500 Hz FI tones. Stimuli were presented using Presentation software (Neurobehavioral Systems, Inc., Albany, CA). Tones were delivered dichotically with headphones.

2.1.3. Procedure

An ordinal comparison procedure (Gu & Meck, 2011) was used to investigate how the pitch levels of flanker tones influenced the perceived duration of empty ISIs. On each trial, participants focused on a fixation cross and were presented with a standard tone sequence followed by two FI tones. The standard tone sequence was composed of either two or six standard tones (500 Hz) marking one or five ISIs, respectively. Standard ISIs were either 300 or 600 ms (see Fig. 1). Following the standard tone sequence, two FI tones were presented. It should be noted that an intermediate ISI, bounded by the last standard flanker tone and the first FI flanker tone was always the same duration as the preceding standard ISIs (either 300 or 600 ms). FI tones were either higher (625 Hz), lower (400 Hz), or the same (500 Hz) fundamental frequency as the standard tones. In the 300 ms ISI condition, FIs were 240, 264, 284, 316, 336, or 360 ms. In the 600 ms ISI condition, FIs were 480, 528, 576, 624, 672, or 720 ms. Participants were instructed to indicate whether or not the FI sounded like it was 'speeding up' or 'slowing down' compared to the preceding ISIs and were given 3000 ms to make their responses via keyboard press. An inter-trial interval of 1000 ms elapsed before the next trial began. Participants completed either the One ISI ($n = 18$) or Five ISI condition ($n = 23$). Standard ISI durations (300 ms vs. 600 ms) were blocked within participants, with order counterbalanced. Trials within each standard ISI duration block were presented in three runs of 54 trials. Within each run, nine trials were presented at each FI duration for each FI tone frequency. A total of 162 trials were thus presented for each of the two standard ISI duration conditions. Participants were given the opportunity to rest in between runs. Participants received no performance feedback.

2.2. Results

In order to assess the effect of different pitch levels on time perception and timing sensitivity, the proportion of 'long' responses given at each FI duration for the three FI tone frequencies were calculated for each participant as a function of the two standard ISI durations (300 and 600 ms) and temporal context (One ISI and Five ISI) as illustrated in Fig. 2. For each participant, the proportion of 'long' responses, p('Long' Response), as a function of the final interval (FI) was fitted with a Logistic function defined by four parameters: threshold, slope, guess rate, and lapse rate. The threshold and slope were set as free parameters that were estimated using maximum likelihood estimation, whereas guess and lapse rates were fixed at 0 and 0.1, respectively. The fit of these Logistic functions was determined for all participants using an unconstrained least squares minimization (pDevs > 0.25). The location of the function at p('Long' Response) $= 0.5$ was taken as the point of subjective equality (PSE). Response precision was determined using the Weber fraction (WF), which is the difference limen, $(t(p(\text{'Long' Response}) = 0.75) - t(p(\text{'Long' Response}) = 0.25))\,/\,2$, divided by the PSE.

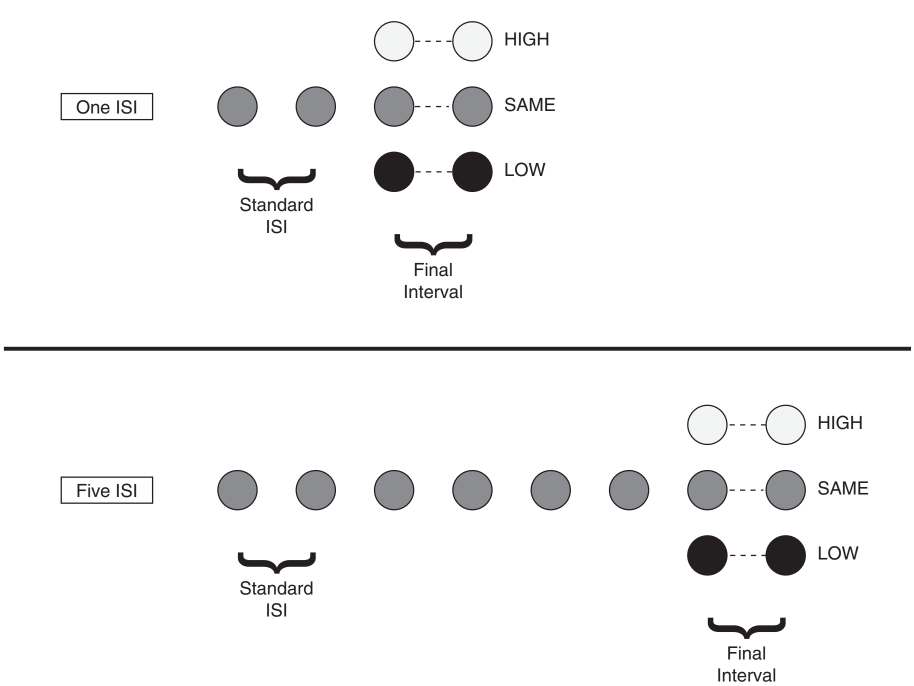

Fig. 1. Trial design for Experiments 1 and 2. Each trial consisted of either One or Five Standard ISIs (Experiment 1: 300 or 600 ms; Experiment 2: 1200 ms) flanked by two or six 50-ms flanker tones with a fundamental frequency of 500 Hz. An intermediate ISI of the same duration as the standard ISIs elapsed between the final standard flanker and the first final interval (FI) flanker tone. The FI was flanked by tones of either the same, higher, or lower pitch than the preceding standard flanker tones. The duration of the FI varied around the standard ISI duration. Participants were asked to judge whether the FI sounded like it was 'speeding up' or 'slowing down' compared to the preceding intervals.

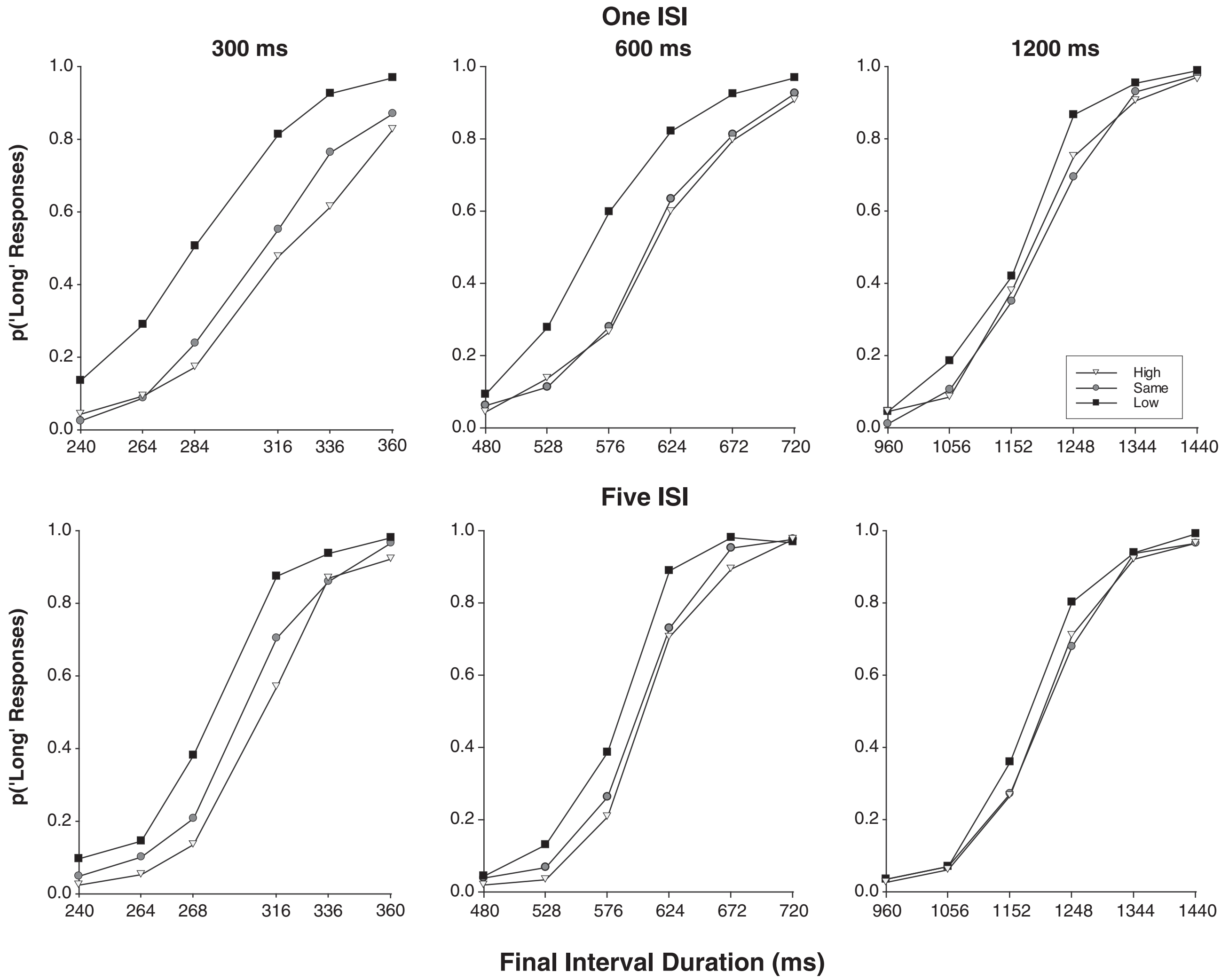

Fig. 2. Proportion of 'long' responses plotted as a function of the final interval (FI) duration (in ms) for the 300 ms and 600 ms standard interstimulus interval (ISI) conditions used in Experiment 1 and the 1200-ms standard ISI condition used in Experiment 2. Separate graphs are presented for the number of standard ISIs presented prior to the FI (One ISI or Five ISIs). In each graph, separate functions are plotted for the different FI flanker tone pitches (Low, Same, and High).

2.2.1. Point of subjective equality (PSE) scores

PSE values, across Standard ISI Duration and Number of Standard ISIs, generally showed that High FIs were underestimated compared to Same FIs, while Low FIs were overestimated compared to Same FIs, as shown in Table 1. Such findings support Pfeuty and Peretz (2010) who also found a differential effect of high and low pitches on temporal judgments.

As we were interested in how the *magnitude* of this pitch-level effect might be influenced by both Standard ISI Duration and the Number of Standard ISIs preceding the FI, difference scores were calculated for each participant according to the following equations:

$$[\text{PSE (High)}-\text{PSE(Same)}]/\text{PSE(Same)}$$
and
$$[\text{PSE (Low)}-\text{PSE(Same)}]/\text{PSE(Same)}.$$

These normalized scores allowed us to compare PSE shifts across the two standard ISI duration conditions. Positive values represent the

Table 1
Measures of subjective equality and sensitivity to time as a function of the number of standard interstimulus intervals, pitch level, and interstimulus interval.

# of standard ISIs	Final interval tones	Point of subjective equality scores			Weber Fraction scores		
		Experiment 1		Experiment 2	Experiment 1		Experiment 2
		300 ms	600 ms	1200 ms	300 ms	600 ms	1200 ms
One ISI	High	324.181 (6.54)	611.599 (10.08)	1175.776 (10.23)	0.102 (.029)	.063 (.008)	.051 (.007)[a]
	Same	312.996 (5.20)	607.335 (7.23)	1183.849 (10.82)	0.070 (.013)	.072 (.015)	.050 (.007)
	Low	275.421 (8.02)	558.275 (7.32)	1146.708 (11.35)	0.101 (.033)	.067 (.011)	.042 (.008)
Five ISI	High	314.569 (3.56)	605.470 (4.74)	1202.396 (9.58)	.049 (.016)	.036 (.006)	.045 (.007)
	Same	302.413 (3.42)	600.894 (3.39)	1197.012 (11.98)	.056 (.013)	.039 (.004)	.042 (.008)
	Low	287.365 (3.47)	578.752 (4.04)	1171.954 (10.18)	.051 (.008)	.035 (.008)	.033 (.005)

[a] Data are from Experiments 1 and 2 in which the number of standard durations varied (One and Five Standards) as well as the Interstimulus Interval (ISI — 300, 600, 1200 ms). Numbers are means (±SEM).

underestimation of duration compared to Same FIs, while negative values represent the *overestimation* of duration compared to Same FIs. If pitch level shifted PSEs with a magnitude proportional to the standard ISI duration, as would be expected if the effects were driven by a change in pacemaker rate or mode-switch flickering, then the magnitude of these normalized difference scores should not differ between the different standard ISI duration conditions. Alternatively, the magnitude of the normalized difference scores would be expected to decrease with increasing ISIs if pitch level influenced temporal estimates by affecting mode-switch latencies to close/open.

The normalized PSE difference scores were submitted to a 2 × 2 × 2 mixed model ANOVA with Pitch (High/Low) and Standard ISI Duration (300 ms/600 ms) as within-participant factors and Number of Standards (One ISI/Five ISI) as a between-participant factor. As expected, we observed a main effect of Pitch, $F(1,39) = 48.30$, $p < 0.001$, $\eta^2 = 0.55$, with High FIs ($M = .025$, $SE = 0.008$) underestimated compared to Low FIs ($M = -0.066$, $SE = 0.01$). There was no main effect of Standard ISI Duration, but a significant Pitch ∗ Standard ISI Duration interaction (see Fig. 3) was observed, $F(1,39) = 12.72$, $p = 0.001$, $\eta_p^2 = 0.25$, indicating that pitch-level effects were smaller in the 600 ms than in the 300 ms ISI condition. These ISI differences were observed for both High FIs, $t(40) = 2.81$, $p = 0.008$, 95% CI [0.0091, 0.055], Cohen's $d = 0.44$, and Low FIs, $t(40) = -2.13$, $p = 0.04$, 95% CI [−0.45, −0.0011], Cohen's $d = 0.33$. In other words, High FIs caused greater underestimation of duration, and Low FIs led to greater overestimation of duration in the 300 ms compared to the 600 ms condition. This difference in the magnitude of pitch level-induced temporal distortion across the standard ISI durations is consistent with a mode-switch latency effect. With respect to temporal repetition, there was no main effect of Number of Standard ISIs, but there was a trend toward a Pitch ∗ Number of Standard ISIs interaction (see Fig. 4), $F(1,39) = 4.02$, $p = 0.052$, $\eta_p^2 = 0.093$. Post-hoc independent t-tests showed that the magnitude of pitch-level effects were larger in the One ISI versus the Five ISI condition for Low FIs, $t(23.264) = 2.256$, $p = 0.034$, 95% CI [0.0046, 0.10], Hedge's $g = .78$, but not High FIs, $t(39) = 0.022$, $p = 0.98$. The reduced magnitude of the pitch-level effect with more repetitions of the standard ISI duration for Low FIs provides some support for the hypothesis that temporal repetition reduces pitch-related temporal distortions.

2.2.2. Weber Fraction (WF) values

WF values were submitted to a 3 × 2 × 2 mixed model ANOVA with Pitch (High/Low/Same) and Standard ISI Duration (300 ms/600 ms) as within-participant factors and Number of Standard ISIs as a between-participant factor. We observed a main effect of Standard ISI Duration, $F(1,39) = 4.98$, $p = 0.031$, $\eta_p^2 = 0.11$, with significantly higher WFs in the 300 ms ($M = 0.069$, $SE = 0.008$) than in the 600 ms ($M = 0.050$, $SE = 0.004$) standard ISI condition. As higher WFs correspond to lower temporal sensitivity, this pattern suggests that temporal sensitivity was higher in the 600 ms condition than in the 300 ms condition. As expected, a main effect of Number of Standard ISIs was also observed, $F(1,39) = 5.92$, $p = 0.02$, $\eta_p^2 = 0.13$, with higher sensitivity observed in the Five ISI ($M = 0.044$, $SE = 0.004$) than in the One ISI condition ($M = 0.079$, $SE = 0.008$). This finding further supports previous reports that increasing the number of standard intervals enhances temporal sensitivity (Drake & Botte, 1993; Pashler, 2001). No main effect or interactions with Pitch were observed, suggesting that Pitch did not significantly influence temporal sensitivity.

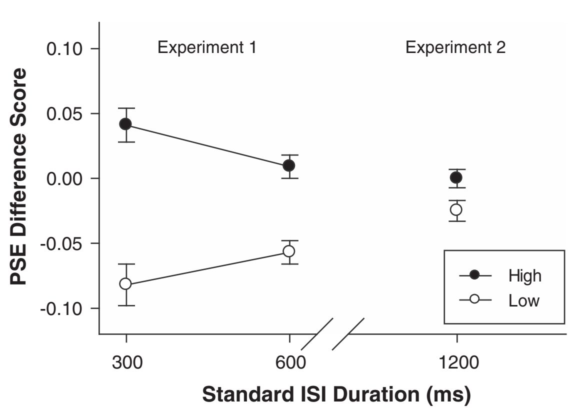

Fig. 3. Mean (±SEM) point of subjective equality (PSE) difference scores plotted as a function of the standard interstimulus (ISI) duration. The data illustrate the interaction between difference scores for High and Low pitch level conditions and standard ISI duration from Experiments 1 and 2.

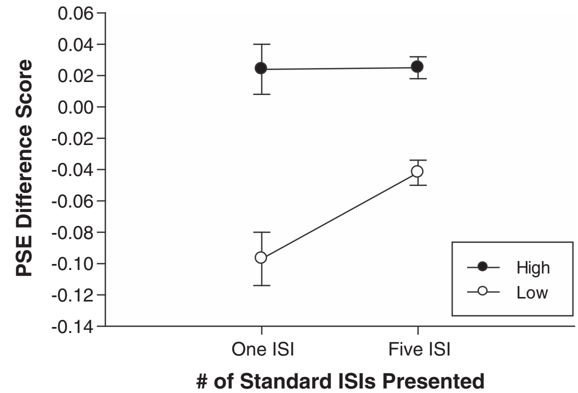

Fig. 4. Mean (±SEM) point of subjective equality (PSE) difference scores plotted as a function of the number of standard interstimulus intervals (ISI). The data illustrate the interaction between pitch level and number of ISIs observed in Experiment 1.

2.3. Discussion

As hypothesized, in Experiment 1, we found a divergent effect of pitch level on time perception, demonstrating that higher pitch levels resulted in the underestimation of duration, while lower pitch levels resulted in the overestimation of duration. Interestingly, the magnitudes of the pitch-related effects on temporal distortions were larger in the 300 ms standard ISI condition than in the 600 ms standard ISI condition. Our results also suggested that it might be possible to modulate this effect by increasing the number of times that the standard ISI duration was presented prior to the FI, though this effect was not statistically significant.

Our findings support those of Pfeuty and Peretz (2010) by showing a differential effect of high and low pitch levels on time perception. We extend these findings by showing that the magnitude of this effect decreased with increasing ISI duration. As the magnitudes of pitch-level effects on time perception were not proportionally constant across the two ISI conditions, a pacemaker-like mechanism was likely not responsible for the observed temporal distortions. The observation that the magnitude of the effect was proportionally smaller with a longer ISI duration is consistent with a mode-switch latency mechanism, for which the absolute magnitude of the effect would remain relatively stable across increasing ISI durations and, thus, the proportional magnitude of the effect would decrease. Nevertheless, to more definitively conclude that the current results reflect a magnitude of distortion that decreases with increasing ISI duration, assessing a third duration range would be advantageous.

Studies have suggested that interval timing relies on different mechanisms for sub-second and supra-second timing (e.g., Lewis & Meck, 2012; Lewis & Miall, 2003; Matell & Meck, 2000, 2004; Meck, Penney, & Pouthas, 2008; Rammsayer & Ulrich, 2011). In a second experiment, we used a 1200 ms standard ISI duration in order to concurrently assess if pitch-related distortions extend into a supra-second time range and if the magnitude of distortion would decrease further at this longer ISI value, lending further support to a switch latency mechanism. We hoped that this second study might also clarify whether or not temporal repetition modulates the magnitude of the pitch-level effect on temporal estimates.

3. Experiment 2

In this experiment, we assessed the magnitude of temporal distortions in an ordinal comparison task using a supra-second standard ISI duration (1200 ms). If the proportional magnitude of the pitch-level effect using this longer standard ISI duration further decreased from the magnitude of the effect in the 600 ms standard ISI condition tested in Experiment 1, it would further support the idea that pitch level modulates time perception via a mode-switch latency effect. Demonstrating that pitch level continues to distort temporal estimates in the 1200 ms ISI condition would indicate that pitch-level effects do not exclusively rely on sub-second timing systems.

3.1. Method

3.1.1. Participants

Forty participants served in this experiment, with one participant excluded based on poor timing discrimination, such that Logistic functions could not be properly fit to individual timing data, resulting in a final sample of 39 (19 males, 20 females; 18–40 years, $M = 20.41$; $SD = 4.14$). Participants received monetary compensation or course credit for serving in the experiment.

3.1.2. Procedure

Experiment 2 was identical to Experiment 1 with the following exceptions. In this experiment, only one standard ISI duration (1200 ms) was tested. FIs were 960, 1056, 1152, 1248, 1344, and 1440 ms. Participants completed either the One ISI (n = 20) or Five ISI condition (n = 19). In the One ISI condition, trials were presented in 3 runs of 54 trials, resulting in a total of 162 trials, as in Experiment 1. In the Five ISI condition, the number of trials presented at each FI duration for each FI flanker tone pitch (High/Low/Same) was reduced from 9 to 6, resulting in a total of 108 trials presented in 3 runs of 36 trials. The total number of trials was reduced in this condition to limit participant fatigue.

3.2. Results

3.2.1. Point of subjective equality (PSE) scores

The proportion of 'long' responses at each FI duration for the three FI flanker tone pitches are plotted for the 1200 ms standard ISI conditions (see Fig. 2). A mixed model 2 × 2 ANOVA with Pitch (High/Low) as a within-participant factor and Number of Standards (One ISI/Five ISI) as a between-participant factor confirmed that a main effect of Pitch, $F(1,37) = 10.54$, $p < 0.01$, $\eta_p^2 = 0.22$, was still observed in the 1200 ms ISI condition. This result suggests that pitch-level distortions are not solely based on sub-second timing mechanisms. No main effect or interactions with Number of Standards were observed.

After confirming that the pitch-level effect on temporal estimates extended into supra-second durations, PSE difference scores for the 1200 ms standard ISI conditions were compared to the 600 ms standard ISI conditions in Experiment 1 in a 2 × 2 × 2 mixed model ANOVA with Pitch (High/Low) as a within-participant factor and Standard ISI Duration (600 ms/1200 ms) and Number of Standards (One ISI/Five ISI) as between-participant factors, to further compare the magnitude of the pitch-level effect across standard ISI conditions. As in Experiment 1, we observed a main effect of Pitch, $F(1,76) = 39.80$, $p < 0.001$, $\eta_p^2 = 0.34$, with High FIs ($M = 0.0043$, $SE = 0.006$) underestimated compared to Low FIs ($M = -0.040$, $SE = 0.006$). There were again no main effects of Standard ISI Duration or Number of Standard ISIs. Also consistent with Experiment 1, there was a significant Pitch ∗ Standard ISI Duration interaction (see Fig. 3), $F(1,76) = 8.14$, $p = 0.006$, $\eta_p^2 = 0.097$. The magnitude of the pitch effect decreased for both High and Low FIs in the 1200 ms standard ISI condition. This effect was statistically significant for Low FIs, $t(78) = -2.37$, $p = 0.02$, 95% CI [−0.054, −0.0048], Hedge's $g = 0.53$, but not for High FI, $t(78) = 0.71$, $p > 0.10$. These reductions in the proportional magnitude of pitch-level effects with the use of a longer standard ISI duration further support a mode-switch latency mechanism of distortion. Again, there was no significant interaction between Pitch and Number of Standard ISIs, potentially indicating that pitch-level effects are not modulated by temporal context. However, such an effect may not have been detectible due to the decreased magnitude of the pitch-level effect itself.

3.2.2. Weber Fraction (WF) values

WF values for the 1200 ms standard ISI conditions and 600 ms standard ISI conditions from Experiment 1 were submitted to a mixed model ANOVA with Pitch (High/Low/Same) as a within-participant factor and Standard ISI Duration (600 ms/1200 ms) and Number of Standards (One ISI/Five ISI) as between-participant factors. As in Experiment 1, we observed a main effect of Number of Standard ISIs, $F(1,76) = 8.05$, $p = 0.006$, $\eta_p^2 = 0.096$, with higher temporal sensitivity observed in the Five ISI ($M = 0.038$, $SE = 0.003$) than in the One ISI condition ($M = 0.057$, $SE = 0.004$). Unlike Experiment 1, there was no main effect of Standard ISI Duration, suggesting that temporal sensitivity did not improve from the 600 ms to 1200 ms standard ISI conditions as it did from the 300 to 600 ms condition. Again, no significant main effect or interactions with Pitch were observed, $ps > 0.05$.

3.3. Discussion

In Experiment 2, we found that the proportional magnitude of the pitch-level effects on time perception continued to decrease from a 600 ms to a 1200 ms standard ISI duration, adding further support to the idea that changes in mode-switch latency are responsible for driving these temporal distortions. Importantly, the presence of a pitch-level effect in the 1200 ms ISI condition suggests that pitch-level induced temporal distortions are not exclusively mediated by sub-second timing systems. Such evidence may help direct further research into the neural structures underlying pitch-induced distortions in time perception. Additionally, no further evidence was found to support the hypothesis that temporal repetition might modulate the magnitude of these pitch-level effects. The WF results continued to suggest that temporal repetition can improve temporal sensitivity, but, as in Experiment 1, no evidence was found to support the modulation of this effect by pitch level.

4. General discussion

In this study, we found, across multiple duration ranges, that pitch level differentially distorted time perception. When FI flanker tones increased in pitch from preceding standard intervals, participants were more likely to report that the interval sounded like it was 'speeding up', whereas when the flanker tones decreased in pitch, participants were more likely to report that the interval sounded like it was 'slowing down'. Importantly, by comparing these pitch-level effects across multiple standard ISI durations, we found that their proportional magnitude decreased as the standard ISI duration increased. This minimization of distortion is consistent with variations in mode-switch latencies to start/stop timing, as opposed to the standard pacemaker/accumulator mechanism (Allman & Meck, 2012; Lejeune, 1998; Penney et al., 1996; van Rijn et al., in press).

While the magnitude of these pitch-level distortions decreased with increasing standard ISI duration, we found evidence of the pitch-level effect across sub-second and supra-second ranges. As sub-second and supra-second timing are thought to be mediated by different underlying neural structures (Cordes & Meck, in press), the current findings may direct future research on the neural architecture mediating pitch-related distortions of time perception. Finally, we found that increasing the number of standard ISI presentations prior to the FI enhanced temporal sensitivity in Experiment 1 as predicted, supporting the role of temporal repetition in improving timing accuracy (Drake & Botte, 1993; McAuley & Jones, 2003; Pashler, 2001), though this effect was not observed for the 1200 ms ISI condition in Experiment 2. We found no consistent evidence that pitch-level distortions were modulated by temporal repetition.

It is important to note that the length of the flanker tones did not scale with the increasing standard ISI duration. The ratio of the empty interval duration to flanker tone duration may have influenced the magnitude of pitch-level induced temporal distortion, with the proportional magnitude of the effect decreasing as the ratio increased (Pfeuty & Peretz, 2010). The decreasing magnitude of the pitch-level distortions may also have masked a potential effect of temporal repetition on duration estimates. Future studies could examine this issue by scaling the flanker tone durations with the duration of the standard ISI.

Examining our current findings within the context of existing data on the relationship between pitch and time perception, we believe that our results lend support to the internal-marker hypothesis for empty interval timing (Grondin, 1993), in suggesting that different latencies to start/stop timing empty intervals flanked by tones of different pitch levels are due to different latencies to perceive the beginning/end of the flanker tones themselves. The idea that latencies to start/stop timing influence temporal estimates is central to the internal-marker hypothesis. Essential to this idea is the proposal that empty intervals are timed from the offset of the first marker to the onset of the second marker, while filled intervals are timed from signal onset to signal offset. Neurophysiological evidence has corroborated the basic tenets of empty interval timing endorsed by the internal-marker hypothesis (Tse & Penney, 2006). Several studies have shown that different marker properties, such as marker size, duration, and modality, influence the perceived duration of empty intervals (Grondin, Ivry, Franz, Perreault, & Metthe, 1996; Hasuo, Nakajima, Osawa, & Fujishima, 2012; Ono & Kitazawa, 2009), which may suggest that such factors also modulate latencies to start/stop timing.

The opposing directions of time distortions for filled and empty intervals of high vs. low pitches (Brigner, 1988; Cohen et al., 1954; Matthews, 2013; Pfeuty & Peretz, 2010) appear to be consistent with predictions made by the internal-marker hypothesis for how different start/stop latencies might influence time perception. Specifically, if it is assumed that the latency to *start* timing a lower pitched tone is longer than the latency to start timing a higher pitched tone, and/or the latency to *stop* timing a lower pitched tone is shorter than the latency to stop timing a higher pitched tone, then a lower pitched tone would be underestimated in duration compared to a higher pitched tone (Brigner, 1988; Cohen et al., 1954; Matthews, 2013). At the same time, a shorter latency to stop timing and/or a longer latency to start timing a lower pitched flanker tone, would result in the overestimation of the duration of an empty interval flanked by at least one lower pitched tone than an interval flanked by at least one higher pitched tone as was observed in the current study and by Pfeuty and Peretz (2010). The current study did not separately manipulate the pitch of the first and second flanker tones and thus we cannot conclusively say whether or not start latencies, stop latencies or both were responsible for driving the pitch-induced temporal effects observed here. Nevertheless, as Pfeuty and Peretz (2010) previously reported biases in temporal estimates *regardless* of whether or not the first, second, or both final flanker tone pitches were manipulated, we believe it is likely that differences in latencies to start and stop timing both contributed to the distortions in time perception that we see here.

Such an appeal to the internal-marker hypothesis and to different latencies to start/stop timing flanker tones to help integrate the current findings with previous literature leads us to believe that the effects of pitch observed here are the result of the different pitch levels of the FI tones, rather than *relative* changes in pitch between the standard tones and FI flanker tones. We believe that evidence from both Pfeuty and Peretz (2010) and the current study support this assertion. First, Pfeuty and Peretz (2010) showed that FIs flanked by at least one lower pitched tone were overestimated in duration compared to FIs flanked by at least one higher pitched tone, regardless of whether or not it was the first, second or both flanker tones that were different in pitch from the standard interval tones. We also believe that the asymmetry in the distortion magnitudes for high and low pitch FIs observed in the current study (see Fig. 2) supports a pitch level, rather than relative pitch change, explanation. As pitch is perceived logarithmically, we chose High and Low flanker tone frequencies that were perceptually equidistant from the standard tone frequency. In other words, the ratios of High and Low FI flanker tone frequencies to standard tone frequencies were equal. If the pitch-related distortions reported in this study were the result of *relative* changes in pitch from the standard tones to the FI flanker tones, the magnitude of these effects should have been equal, rather than asymmetrical as we observed across all three standard ISI conditions.

It might be argued that alternative factors in the experimental design could account for the asymmetrical pitch level effects observed in the current study. For example, while the High and Low FI tones were *proportionally* equidistant from standard tones, the frequency *difference* between Low (400 Hz) flanker tones and the standard tones (500 Hz) was less than that between High (625 Hz) and Same flanker tones. This frequency difference thus could have driven the asymmetrical effects. Nevertheless, we do not believe this is likely, as the larger magnitude of distortion was observed for FIs flanked by lower tones, which had a smaller frequency difference from the standard tones than the higher tones. The asymmetry of higher and lower pitch distortion magnitudes could also have been the result of the higher frequency harmonics added to standard ISI tones. The higher harmonics (with higher tonal frequencies) of the standard flanker tones may have made the change from this complex tone to the High FI flanker tones (composed of single sine waves) sound like a smaller change in pitch than the change in pitch from the standard flanker tones to the Low FI flanker tones. Such a difference in the perceived magnitude of pitch change could have contributed to the reduced magnitude of the pitch effect in the High FI condition. However, the same asymmetry in the pitch effect was observed in a separate group of participants (see Supplemental materials) for whom both standard and final interval flanker tones were composed of single sine waves. Finally, changes in pitch and intensity are interrelated (McBeath & Neuhoff, 2002; Neuhoff & McBeath, 1996; Stevens, 1934). It is therefore possible that changes in perceived loudness from standard to FI flanker tones were responsible for the differential temporal distortion effects observed for high and low FIs. However, participants' debriefing responses suggested that any perceived differences in loudness were less salient than differences in perceived pitch, as only 3 participants across Experiments 1 and 2 reported noticing a change in volume in FI flanker tones. Differences in perceived loudness were therefore unlikely to drive the observed differences in time perception. Taken together, we do not believe that any of these alternative explanations can account for the different magnitudes of pitch level distortions. Accordingly, we believe that this asymmetry suggests that *relative* changes in pitch did not drive the observed differences in time perception, but rather that there is a more direct relationship between time perception and pitch level. Further research using a greater number of FI flanker tone pitches could be conducted to better characterize the relationship between pitch level and temporal distortions.

While our findings support a mode-switch latency effect and we believe that there is convincing evidence that these differences in mode-switch latencies to start/stop timing are the result of different latencies to start/stop timing the flanker tones of differing pitch levels, it is unclear *why* different pitch levels would differentially influence mode-switch behavior. As mode-switch activity is frequently associated with changes in attention (Buhusi & Meck, 2009; Fortin et al., 2009; Lake & Meck, 2013; Penney et al., 1996), we offer the possibility that different pitch levels may attract differing levels of attention. Perceptual changes that signal approach are biologically relevant signals and have been shown to engage defensive mechanisms (Bach, Neuhoff, Perrig, & Seifritz, 2009; Schiff, Caviness, & Gibson, 1962) and capture attention (Ghazanfar, Neuhoff, & Logothetis, 2002; Seifritz et al., 2002). The pitch of an approaching object is perceived as increasing while it approaches and as decreasing while it recedes (Neuhoff & McBeath, 1996), suggesting that pitch may serve as a signal of approach/recession. In line with the idea that signals of approach are prioritized in attention, monkeys show attentional biases toward rising versus falling pitches (Ghazanfar & Maier, 2009). While a direct relationship between pitch levels and attention has not been demonstrated in humans, increases in pitch are also perceived as increases in intensity (Neuhoff, McBeath, & Wanzie, 1999). As rising intensity captures attention (Ghazanfar et al., 2002; Seifritz et al., 2002), a relationship between pitch and intensity indirectly supports the idea that pitch, serving as a signal of approach/recession, may manipulate attention. The overestimation of high pitched tones (and thus the underestimation of empty intervals between such tones) is in line with previous studies showing that approaching or looming objects result in temporal overestimation (Tse, Intriligator, Rivest, & Cavanagh, 2004; van Wassenhove, Buonomano, Shimojo, & Shams, 2008). Nevertheless, future study is necessary to more directly demonstrate a relationship between pitch and attention, and to support the proposal that a relationship between pitch level and attention influences latencies to start/stop timing tones of different pitches.

We have proposed that the cross-modal interaction between pitch and duration may be mediated by differences in the allocation of attention to high and low pitch levels, as these pitches may to serve as biologically relevant signals of approach and recession. However, it is important to note that the current study uses discrete tones rather than pitch sweeps, which more closely resemble the acoustic profile of approaching or receding sound sources. The perceptual distortions observed here may thus suggest that the processing of music-like sequences co-opts the systems responsible for detecting and responding to behaviorally relevant stimuli in order to manipulate attention. Given similarities in pitch and durational changes within the music and language of different cultures (Han, Sundararajan, Bowling, Lake, & Purves, 2011; Patel, Iversen, & Rosenberg, 2006), an association between pitch levels and behaviorally relevant stimuli may be one mechanism by which both music and speech express meaning and communicate emotion. While further work will be necessary to link interactions between pitch and time perception to differences in emotional expression and perception, our current findings may have important implications for understanding how pitch and time interact and how such interactions evoke emotion and communicate meaning (Agostino et al., 2008; Andrade & Bhattacharya, 2003; Juslin & Västfjäll, 2008; Kung, Chen, Zatorre, & Penhune, 2013; Melgire et al., 2005; Samson, Zatorre, & Ramsay, 2002; Schirmer, 2004; Schirmer & Kotz, 2006; Zatorre, Belin, & Penhune, 2002).

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Appendix A. Supplementary data

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