Memory & Cognition
2009, 37 (3), 368-381
doi:10.3758/MC.37.3.368

The effect of task and pitch structure on pitch–time interactions in music

Jon B. Prince and Mark A. Schmuckler
University of Toronto, Ontario, Canada

and

William F. Thompson
Macquarie University, Sydney, Australia

Musical pitch–time relations were explored by investigating the effect of temporal variation on pitch perception. In Experiment 1, trained musicians heard a standard tone followed by a tonal context and then a comparison tone. They then performed one of two tasks. In the cognitive task, they indicated whether the comparison tone was in the key of the context. In the perceptual task, they judged whether the comparison tone was higher or lower than the standard tone. For both tasks, the comparison tone occurred early, on time, or late with respect to temporal expectancies established by the context. Temporal variation did not affect accuracy in either task. Experiment 2 used the perceptual task and varied the pitch structure by employing either a tonal or an atonal context. Temporal variation did not affect accuracy for tonal contexts, but did for atonal contexts. Experiment 3 replicated these results and controlled potential confounds. We argue that tonal contexts bias attention toward pitch and eliminate effects of temporal variation, whereas atonal contexts do not, thus fostering pitch–time interactions.

Music is one of the most complex psychological phenomena in humans. From trained performers to casual listeners, the perception of music requires detailed processing of intricately patterned multidimensional stimuli. The two primary dimensions of music—pitch and time—have received the greatest attention in music cognition research. Although most researchers have investigated these dimensions separately, there is considerable interest in the extent to which they interact in perception and memory (Jones, 1987; Krumhansl, 2000).

For pitch, Western music divides the range of an octave (the pitches that fall between a given pitch and a second one of twice its frequency) into 12 equal, logarithmically spaced pitches that, when used according to the stylistic rules of Western music, produce a sense of musical key, or tonality (Krumhansl, 1990). When a musical passage establishes a tonality, the degree of perceived stability, or goodness of fit with the surrounding musical context, varies across the 12 pitch classes.[1] Theoretically, these pitch classes can be grouped into three hierarchical levels on the basis of their relative stability (Lerdahl, 1988): the tonic triad (the three most stable pitches within the key; i.e., the pitches C, E, G, in the key of C major), the remaining diatonic tones within the key (i.e., D, F, A, B), and the nondiatonic tones (the least stable, out-of-key pitches; i.e., C♯, D♯, F♯, G♯, A♯).

Along with pitch structure, temporal structure plays a critical role in the perception of music (Jones, 1976). There is a rich literature on how time functions in Western music, including work on rhythmic patterns and the perception of meter (Jones, 1987; Jones & Boltz, 1989; Longuet-Higgins & Lee, 1982; Palmer & Krumhansl, 1990; Povel, 1981; Steedman, 1977). A regular pattern of durations, or rhythmic figures, creates a sense of weak and strong temporal positions, or beats (Lerdahl & Jackendoff, 1983). The term *meter* refers to the temporal pattern that arises from this alternation between weak and strong beats. Similar to the variation in tonal stability in the pitch dimension, there is variation in metric stability for the different temporal positions in a piece of music, grouped into metric hierarchies on the basis of their perceived stability (Palmer & Krumhansl, 1990).

Given the existence of considerable variation in both pitch and temporal dimensions in music, a natural question that arises involves the nature of the interrelation between these dimensions. In fact, several researchers have addressed the question of how these dimensions combine as part of the perception of musical events. Whereas some evidence supports the view that these dimensions are independent (Fries & Swihart, 1990; Krumhansl, 1991; Makris & Mullet, 2003; Mavlov, 1980; Monahan & Carterette, 1985; Palmer & Krumhansl, 1987a, 1987b; Peretz, 1990, 1996; Peretz & Kolinsky, 1993; Peretz et al., 1994; Pitt & Monahan, 1987; Schön & Besson, 2002; Smith & Cuddy, 1989; Thompson, 1993, 1994; Thompson, Hall, & Pressing, 2001), other evidence suggests the opposite

J. B. Prince, jon.prince@utoronto.ca

(Abe & Okada, 2004; Boltz, 1989a, 1989b, 1989c, 1991, 1993a, 1993b, 1995, 1998b; Crowder & Neath, 1995; Deutsch, 1980; Griffiths, Johnsrude, Dean, & Green, 1999; Jones, 1987; Jones, Boltz, & Kidd, 1982; Jones, Johnston, & Puente, 2006; Jones, Moynihan, MacKenzie, & Puente, 2002; Jones & Ralston, 1991; Jones, Summerell, & Marshburn, 1987; Kelley & Brandt, 1984; Kidd, Boltz, & Jones, 1984; Monahan, Kendall, & Carterette, 1987; Nittono, Bito, Hayashi, Sakata, & Hori, 2000; Schellenberg, Krysciak, & Campbell, 2000; Schmuckler & Boltz, 1994).

The wealth of evidence supporting both independent and interactive processing arguments has led to a number of theories attempting to reconcile these divergent results. Accordingly, the primary research question has shifted from determining whether pitch and time primarily involve independent versus interactive processing to delineating the circumstances (e.g., stimuli, tasks, cognitive strategies) that affect the interrelations among these dimensions. Three of the main approaches distinguish between early versus late processing (Hébert & Peretz, 1997; Peretz & Kolinsky, 1993; Pitt & Monahan, 1987; Thompson et al., 2001; Tillmann & Lebrun-Guillaud, 2006), global versus local level of analysis of musical events (Bigand, Madurell, Tillmann, & Pineau, 1999; Tillmann & Lebrun-Guillaud, 2006), and the degree of perceived musical coherence in the contexts (Boltz, 1998a, 1998c, 1999). The main challenge in developing models of the interrelation between musical pitch and temporal structure is to account for the complex and often conflicting data on the issue.

Although no theoretical framework accounts for all the findings of independent versus interactive processing of pitch and time dimensions, Jones and colleagues have offered what is probably the most well-known account: the model of dynamic attending (Barnes & Jones, 2000; Jones et al., 2006; Jones et al., 2002; Large & Jones, 1999). According to this theory, a regular rhythm established by a preceding sequence causes an oscillation in attentional energy that is synchronized with the rhythm of the sequence (Large & Jones, 1999). More recent work has expanded this theory to pitch–time entrainment, in which listeners track successive events in a sequence, extracting both the pitch and temporal pattern structures (Jones et al., 2006). Listeners extrapolate the pattern structure to form dynamic expectancies in both dimensions, anticipating where (in pitch space) and when (in temporal space) subsequent events are to occur. This dynamic attending model is built on the notion that the pitch and temporal content of a sequence contribute interactively in driving listeners' attention to future events; hence, by definition, pitch and time have an interactive relation.

Jones and colleagues have provided a variety of findings consistent with the notion of dynamic attending and with interactive processing of pitch and temporal events (Jones et al., 2006; Jones et al., 2002). Jones et al. (2002), for instance, have described an elegant example of this idea by demonstrating that pitch judgments of rhythmically expected tones are more accurate than judgments of unexpected events. In that study, participants heard a standard tone, followed by an isochronous sequence of eight random pitches (i.e., atonal), followed by a comparison tone, and judged whether the comparison tone was higher or lower in pitch than the standard tone. If the intervening sequence had a regular rhythmic (isochronous) structure, this sequence established temporal expectancies, such that participants implicitly expected the comparison tone to occur at a specific time. Jones et al. (2002) found that, when the comparison tone occurred on time, the accuracy of the pitch height judgments was better than when it did not. Subsequent work (Jones et al., 2006) further explored this finding by having participants listen for a pitch change in a repeating nine-tone sequence. Consistent with the earlier findings, these authors found that the pitch content of the sequences and target, as well as the timing of the target tone, affected the accuracy of detecting a pitch change. Hence, both sets of findings demonstrate the importance of temporal and pitch expectancy formation and highlight the idea that variation in the temporal structure of a sequence can influence pitch processing.

Other research on pitch–time interactions, however, has revealed effects that do not fit with the dynamic attending theory. As an example, Palmer and Krumhansl (1987a, 1987b) manipulated the form of a melody by holding the pitch constant in one condition, holding time constant in another, and using the original melody in yet another. A second experiment disrupted the phase of the pitches and durations, and further experiments used durations from a recording that had subtle variations in expressive timing. Musicians of varying skill levels judged how complete the melody sounded; in all cases, both tonal and metric hierarchies affected ratings in an additive and linear fashion. Thus, there was no interaction of pitch and temporal structure.

There is also neuropsychological research that supports the view that pitch and time are independent in music perception (Fries & Swihart, 1990; Mavlov, 1980; Peretz, 1990, 1996; Peretz & Kolinsky, 1993; Peretz et al., 1994). In particular, Peretz (1990) investigated melodic processing in 4 patients with unilateral damage to the temporal lobe. Two of the patients had damage on the right hemisphere; the other two had lesions in the left hemisphere. The patients with right-hemisphere damage exhibited selective pitch processing deficits with preserved temporal processing, whereas the others showed the opposite pattern. Thus Peretz (1990) observed a double dissociation between pitch and temporal processing, suggesting that anatomically and functionally independent systems underlie the two dimensions.

More recently, Prince, Thompson, and Schmuckler (2008) found an asymmetric relation between pitch and time, with pitch variation influencing temporal judgments but with temporal variation having no impact on pitch judgments. In that study, musically trained listeners heard a simple tonal context consisting of a melody accompanied by supporting chords and a metronome setting the tempo, followed by a probe tone that varied in its pitch and timing. In different conditions, participants judged whether this probe event was a member of the diatonic set (pitch judgment) or was on or off the beat (temporal judgment). In the pitch condition, the accuracy of key judgments varied as a function of the tonal stability of the probe: Probes occupying a higher position in the tonal hierarchy were judged more accurately than were tonally unstable probes. In this condition, variation in the irrelevant (temporal) dimension had no impact on pitch judgments. In the temporal condition, temporal position judgments similarly showed an influence of the probe's metric stability. In contrast to the previous condition, however, irrelevant pitch variation influenced temporal judgments. Specifically, participants' responses exhibited a congruity effect in which tonally stable probes were reported as occurring at metrically stable positions and tonally unstable probes were reported as occurring at metrically unstable positions. Prince et al. argued that this asymmetry arises due to a learned, inherent bias in the processing of typical Western tonal music that generally contains more elaborated and compelling pitch variation, relative to rhythmic/temporal variation. Consequently, pitch is more salient than time in Western tonal music, automatically drawing more attention than time and thus dominating in the perception of music.

How can the findings of Prince et al. (2008) be reconciled with the theory of dynamic attending? Whereas Jones et al. (2002) found effects of time on a pitch judgment, Prince et al. did not. A close comparison of these two studies reveals a number of factors that might have led to the divergent pattern of results. As one example, there were considerable experimental task differences between the studies. In Jones et al. (2002), listeners participated in an auditory short-term recognition memory paradigm in which they judged the relative pitch height of a standard and comparison tone that were separated by an intervening sequence. In contrast, Prince et al. employed a variant of the probe-tone procedure (Krumhansl, 1990; Krumhansl & Kessler, 1982; Krumhansl & Shepard, 1979), in which listeners rate a probe event relative to a preceding context in terms of its perceived goodness-of-fit along some musical dimension. Thus, the differences in the findings could simply have arisen from comparing a memory paradigm and a rating paradigm. In fact, these two tasks have been used in a complementary fashion only infrequently, although it is worth noting that in a different study, Krumhansl (1979) employed both the probe-tone similarity rating method and a memory paradigm and observed convergent findings. Regardless, such direct comparisons are few, and it remains possible that basic paradigm differences account for these findings.

A related difference between these two studies involves the nature of the processing required by the two tasks. Jones et al.'s (2002) pitch height comparison task relied primarily on a perceptual comparison (i.e., higher vs. lower pitch). In contrast, Prince et al.'s (2008) rating procedure is a cognitive task, one that requires more complex processing. Thus, the difference between the two studies may have arisen from the types of processing required of the listener.

In addition to experimental task differences, there were differences in critical aspects of Jones et al.'s (2002) and Prince et al.'s (2008) experimental stimuli. Probably the most fundamental distinction in this regard involves the structure of the context employed in these projects. In Jones et al. (2002), the intervening sequence consisted of a set of isochronously presented random pitches that did not induce a tonal percept and thus did not resemble a typical Western melody. In contrast, Prince et al. employed simple, harmonically and rhythmically diverse tonal contexts. Accordingly, it could be that this divergence in the presence versus absence of tonal structure in the context led to the differences between these studies. Indeed, this possibility aligns with Prince et al.'s argument that the presence of rich pitch structure in typical Western music drives listeners to focus more on pitch structure and less on temporal structure. A related stimulus difference involved the distinction between the isochronous stimuli of Jones et al. (2002) and the rhythmic diversity of the context in Prince et al. This issue is explored more fully in the General Discussion section.

The objective of the present study was to explore these explanations in accounting for the divergent findings of Jones et al. (2002) and Prince et al. (2008). In three experiments, we examined pitch–time relations by looking for an influence on pitch processing arising from the violation of temporal expectancies, the finding most clearly identified by Jones et al. (2006; Jones et al., 2002) as indicative of pitch–time interactions. Additionally, all experiments employed a variant of the short-term memory paradigm used by Jones et al. (2002), in which listeners heard a standard tone, an intervening sequence, and a comparison tone. These experiments differed, however, in the nature of the task (Experiment 1) and the pitch structure of the intervening context (Experiments 2 and 3). Specifically, in Experiment 1, we tested the impact of task (cognitive vs. perceptual) on pitch–time interrelations. The presence of tonal information was held constant in this experiment by employing the simple tonal contexts of Prince et al. as the intervening sequence. In Experiment 2, we assessed the role of varying the pitch structure (tonal vs. atonal) of the context. Tonal contexts established a key area via a hierarchical distribution of pitch classes, whereas atonal contexts consisted of random pitches that did not establish a key area. The task type remained constant in Experiment 2, using only pitch height judgments. In Experiment 3, we also tested how pitch structure affected temporal expectancies and controlled for various stimulus differences between the tonal and atonal contexts.

EXPERIMENT 1

The purpose of Experiment 1 was to examine how violating temporal expectancies would influence the accuracy of pitch judgments that followed tonal contexts while the type of processing required by the task was manipulated. To achieve this goal, we included contexts that conformed to the rules of Western tonal music (Aldwell & Schacter, 2002) and used either a perceptual or a cognitive task. The perceptual task was based on the pitch height comparisons used by Jones et al. (2002), in which the participants compared the pitch of a standard and comparison tone separated by a sequence of intervening tones. Because participants in this task were instructed to ignore the intervening tones, the actual pitch structure of the context

Table 1
Frequency of Standard and Comparison Tones, Correct Judgments of Pitch Height, and Key Membership Judgment in Experiment 1

Frequency (Hz)	Standard Pitch	Comparison Pitch	Pitch Height Judgment	Key Membership Judgment
440		A$_4$	Higher	In key
428	A$-_4$			
415		G♯$_4$	Higher/lower	Out of key
404	G$+_4$			
392		G$_4$	Higher/lower	In key
381	G$-_4$			
370		F♯$_4$	Lower	Out of key

was irrelevant, especially because the task itself involved a perceptual comparison. The cognitive task used the same stimuli as those used in the perceptual task but required listeners to determine whether the comparison tone that followed the context belonged in the key of that context. Thus, this classification required participants to attend to the tonality of the context and to evaluate how the final tone fit within this structure. This task, then, required participants to ignore the initial standard tone and, thus, was more of a cognitive task.

The stimuli in this experiment consisted of a standard tone, followed by a tonal context, followed by a final comparison tone whose timing was early, on time, or late, relative to the temporal framework induced by the context. This methodology of violating temporal expectancies by manipulating comparison timing was borrowed from Jones et al. (2002). Using a simple tonal context (borrowed from Prince et al., 2008) as the intervening sequence between the standard and comparison tones presents a methodological problem for the perceptual task. Specifically, because the contexts induce an organized tonal framework, listeners may be able to use this organization to help encode and remember the standard and comparison tones. Indeed, listeners regularly mentally encode pitches presented in a musical context according to their positions in the tonal hierarchy (Bharucha, 1984, 1996). Consequently, listeners might simply identify the standard and comparison tones within the tonal framework and then use their knowledge of the pitch height relation within the tonal framework to determine which pitch was higher. For example, if the standard tone was the second scale degree and the comparison tone was the third, listeners could determine that the comparison tone was higher by the fact that the third scale degree is higher than the second. Because musicians can easily make use of such information in the presence of a tonal context (Deutsch, 1980), this strategy would circumvent the task by obviating the need to remember carefully the pitch heights of the standard and comparison tones. Furthermore, use of this technique would mean that participants applied a strategy that changed the perceptual task to a cognitive one, defeating the purpose of the task manipulation.

One way to prevent participants from using this strategy is to eliminate the ability to encode the standard tone into a tonal framework. The most straightforward means of accomplishing this goal would be to use standard tones that are not members of the pitch classes employed in Western music. The comparison tones, however, and the tonal context itself, would employ pitches drawn from the typical pitch classes of tonal music. Accordingly, standard tones in this experiment consist of frequencies halfway between the frequencies of two neighboring members of the equal-tempered Western pitch set; these pitches are called "quarter tones" in musical terminology. Table 3 lists the frequencies of some equal-tempered and quarter tones (the latter are indicated by a "+" or "−" sign).

If task type accounts for the divergences between Jones et al. (2002) and Prince et al. (2008), violating temporal expectancies should affect performance only in the perceptual task and not in the cognitive task. This prediction stems from the fact that the former experiment revealed an effect of time on a pitch judgment as part of a perceptual task, whereas no such effect appeared in the latter experiment, which used only cognitive tasks. In contrast, if task type does not generate these differences, temporal variation of the comparison tone should have comparable effects across both perceptual and cognitive tasks.

Method

Participants. Twelve adult musicians, each with at least 8 years of formal training, received either credit in an introductory psychology class at the University of Toronto at Mississauga or payment of $10 for participating in this experiment. The average amount of musical training was 10.1 years (*SD* = 1.9), and the average age was 18.3 years (*SD* = 0.5). Half of the participants were currently musically active, and none reported possessing absolute pitch.

Stimuli. Table 1 denotes the frequencies of the standard and comparison tones employed in this experiment. Altogether, there were four possible comparison tones drawn from the Western tonal pitch set: F♯$_4$, G$_4$, G♯$_4$, and A$_4$. There were three possible standard tones in this experiment made of the quarter tones whose frequencies lay halfway between the frequencies of the four adjacent comparison tones (these quarter tones are referred to as G−, G+, and A−). Each standard tone was associated with the two comparison tones whose frequencies were directly lower or higher than the frequencies of the standard tone. Therefore, for each standard tone, one comparison tone was lower and one was higher in pitch (also shown in Table 1).

Figure 1 shows a schematic representation of the structure of an experimental trial. Each trial began with one of the three standard tones; these standards had a duration of 250 msec. The standard tone was followed by a 750-msec silent interval, after which the tonal context was heard. Four different tonal contexts, consisting of a melody with harmonic accompaniment, were used; these contexts appear in Figure 2. For the sake of continuity, these contexts are the same as those used in Prince et al. (2008). All contexts had a tempo of 120 beats per minute, with 4 beats per measure, meaning that a single beat (a quarter note) lasted 500 msec; thus, the tonal context lasted 4 sec in total. A metronome click sounded on each beat (every 500 msec) throughout the context and continued beyond the

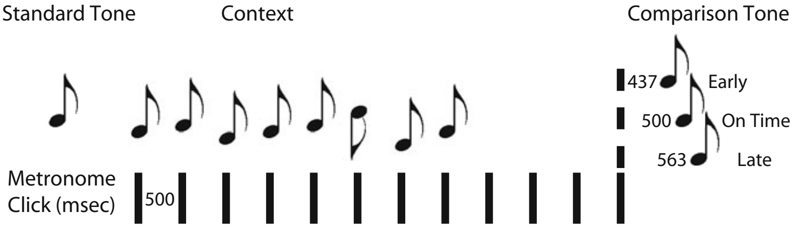

Figure 1. Schematic of a trial.

end of the context for another 4 beats (2 sec). This click maintained the temporal framework of the tonal context and provided a break between this context and the comparison tone.

Following the interval of metronome clicks, one of the four comparison tones was heard for 250 msec. The timing of this comparison tone comprised the principal (and critical) temporal manipulation, with the comparison tone occurring early, on time, or late relative to the temporal framework that the context established. Because the context had one beat every 500 msec (the time interval corresponding to the metronome clicks), an on-time comparison tone occurred exactly 500 msec after the final metronome click. In contrast, an early comparison tone occurred 437 msec after the final metronome click (63 msec early), whereas a late comparison tone occurred 563 msec after the final metronome click (63 msec late). These ±63-msec shifts represent a 12.6% deviation from the on-time comparison tone. This value was chosen on the basis of Jones et al. (2002), who found that deviations at about this level (12.7%) produced the strongest effect of temporal expectancy violation.

Crossing three standard tones (G−, G+, A−) with two comparison tones each (higher, lower) with three temporal positions (early, on time, late) and four tonal contexts resulted in 72 unique trials. All stimuli were created using Finale and SONAR software on a PC and employed a piano timbre that was harmonically complex (i.e., not a pure tone). All stimuli were exported to .wav files with a sampling frequency of 44.1 kHz. The loudness of the stimuli was set to a comfortable listening level.

Apparatus. The experiment was run on a Macintosh G4 computer running OSX 10.3 with a ViewSonic VG175 monitor. The Experiment Creator package (www.ccit.utoronto.ca/billt/BillThompson_files/experiment.html) controlled presentation of the stimuli. Participants heard the stimuli through Sennheiser HD280Pro headphones and made their responses using the computer keyboard. The experiment took place in an IAC soundproof booth that provided a quiet listening environment.

Procedure. After providing informed consent and prior to beginning the experiment, all participants completed a questionnaire about musical experience. At the start of each trial, participants heard the experimental stimulus and then responded according to the task instructions. For the perceptual task, participants were asked to judge whether the comparison tone was higher or lower in pitch than the standard tone and were explicitly instructed to ignore the intervening context. For the cognitive task, participants were asked to judge whether the comparison tone belonged in the key of the context and were explicitly instructed to ignore the standard tone. The "a" and ";" keys were the response keys, with the assignment of keys (higher/lower, in/out of key) counterbalanced across participants. Within a given block, trial order was randomized for each participant. There were two blocks of trials for each task, with half of the participants performing the perceptual task before the cognitive task and the remainder performing the blocks in the reverse order. There were 288 trials, which, altogether, took about 1 h to complete.

Results and Discussion

The principal analysis for this experiment involved comparing accuracy for the primary experimental manipulations as a function of task and temporal position. Therefore, percent correct was calculated for each participant, collapsing across the three standard tones (G−, G+, A−) and their associated responses (higher/lower, in/out of key). Average percent correct was then analyzed in a five-way mixed model ANOVA, with the within-subjects factors of task (perceptual vs. cognitive), temporal position (early, on time, late), block repetition (first vs. second repetition), and context (four melodies, one for each context; see Figure 2). There was also a between-subjects factor of task order (which task the participants completed first). There were no significant effects from this analysis, neither main effects nor interactions. Most importantly, there was no effect of temporal position [$F(2,20) < 1$, $MS_e = .01$], nor was there any interaction between task and temporal position [$F(2,20) < 1$, $MS_e = .01$]. Figure 3 graphs percent correct as a function of task and temporal position.

The failure to observe an impact of varying temporal position on pitch judgment accuracy stands in stark contrast to findings reported by Jones et al. (2006; Jones et al., 2002), in which violation of temporal expectations (early vs. on time vs. late) significantly hindered pitch judgments. As a point of comparison, the perceptual task of the present experiment was the most directly comparable to that of Jones et al. (2002): Both studies employed a typical recognition memory paradigm and required participants to perform a perceptual pitch height comparison task. Yet Jones et al. (2002) found an impact of temporal variation on pitch judgments, whereas the present experiment failed to yield such an effect.

The most obvious distinction between the present perceptual task and that in Jones et al. (2002) involved the nature of the intervening pitches between the standard and comparison tones. Whereas Jones et al. (2002) used random pitches, the present experiment employed a simple tonal context. Accordingly, the divergence in findings between these studies suggests that it is the presence of tonal structure that causes listeners to become less sensitive to the violations of temporal expectancies. The implications of this conclusion are explored in Experiments 2 and 3.

The inclusion of a cognitive task in this experiment extended the investigation of the impact of temporal expectancy violations in pitch processing to judgments requiring a different type of processing. Comparable to the perceptual judgments, temporal expectancy violations failed to influence pitch judgments in this more complex cognitive task. Such results suggest that the type of task does not influence the nature of musical pitch–time relations, in that

Figure 2. Musical sequences used in Experiment 1.

both perceptual and cognitive tasks responded similarly to expectancy violations. Consequently, this experiment fails to support the suggestion that pitch–time interactions vary as a function of the type of processing of musical stimuli.

Together, these findings imply that neither task differences (recognition memory vs. rating techniques) nor the type of task (cognitive vs. perceptual) is responsible for the divergence in findings between Jones et al. (2006; Jones et al., 2002) and Prince et al. (2008). Rather, these results imply that it is the presence of tonal structure in the context that underlies the differences between these two sets of findings.

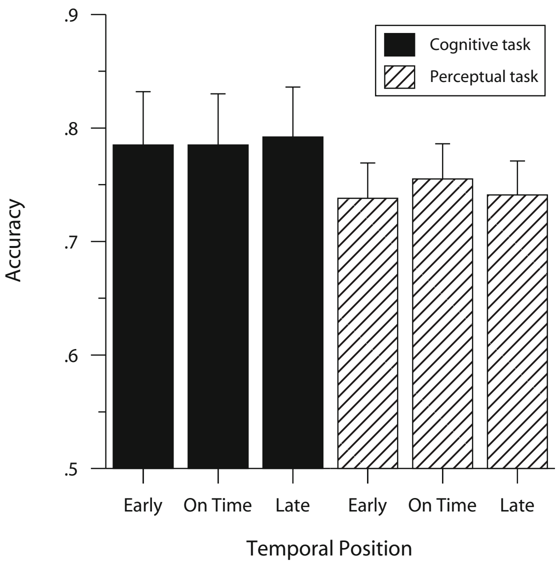

Figure 3. Accuracy for the perceptual and cognitive task across temporal position in Experiment 1.

One limitation to this result, however, is that there was no overt manipulation of the presence versus absence of tonal structure. Currently, the evidence for the presence of tonal structure affecting pitch–time relations is indirect at best and is based largely on interpreting a null result (i.e., the failure to find an impact of temporal variation on pitch judgments). Therefore, this conclusion would be more compelling if a direct manipulation of tonal structure was employed. If the presence of tonal information affects whether or not temporal variation influences pitch judgments, then intervening contexts devoid of such structure should produce an observable effect of temporal expectancy violations. Specifically, the accuracy of on-time judgments should exceed that of early and late pitch judgments for atonal intervening contexts. In contrast, if the intervening context does contain tonal information, temporal expectancy violations should fail to influence pitch judgments. Investigating these predictions was our goal in Experiment 2.

EXPERIMENT 2

The results in Experiment 1 revealed that temporal expectancy violations did not affect accuracy on a perceptual or cognitive pitch judgment task in a context with tonal pitch structure. In Experiment 2, we extended this finding by testing whether the presence versus absence of tonal pitch structure would affect the efficacy of temporal expectancy violations on pitch judgments. In order to provide the most direct comparison to Jones et al. (2002), in this experiment, we examined the impact of these tonal and temporal variables by using only a perceptual pitch judgment. Therefore, we again used the pitch height comparison task originally adapted from Jones et al. (2002) for Experiment 1.

Method

Participants. Twelve adult musicians, each with at least 8 years of formal training, received either credit in an introductory psychology class at the University of Toronto at Mississauga or payment ($10) for participating in this experiment. The average amount of musical training was 9.5 years ($SD = 1.4$), and the average age was 19.1 years ($SD = 0.9$). Half of the participants were currently musically active, and none reported possessing absolute pitch.

Stimuli, Apparatus, and Procedure. All stimuli were created with the same equipment as in Experiment 1. The format of the stimuli was analogous to that of the stimuli in Experiment 1: a standard tone, followed by a context, followed by a comparison tone. In fact, half of the trials in this experiment used the same stimuli as in Experiment 1. Because the context for these trials consisted of a simple tonal sequence, these stimuli are referred to here as the *tonal stimuli*.

For the remaining trials of this experiment, the intervening context between the standard and comparison tones consisted of random pitches that failed to instantiate a tonal percept. These trials, using what we refer to as the *atonal stimuli*, had four possible standard tones (F♯$_4$, G$_4$, G♯$_4$, A$_4$) and six possible comparison tones (F$_4$, F♯$_4$, G$_4$, G♯$_4$, A$_4$, A♯$_4$), all drawn from the equal-tempered Western scale. These standard and comparison tones appear in Table 2. Just as in the tonal trials, each standard tone was associated with two comparison tones, one lower and one higher in pitch (see Table 2).

The tonal and atonal trials were the same, except for the context sequences. The contexts in the atonal trials consisted of eight 250-msec tones, one every 500 msec, each presented simultaneously with a metronome click (the same metronome pulse used in the tonal trials). The pitches in the context consisted of randomly chosen (without replacement) pitches, ranging from E$_4$ to B$_4$ (330–484 Hz) in quarter-tone increments (see Table 3). Accordingly, the atonal context consisted of a random set of 8 out of 15 unique pitches. The atonal context did not include the standard or comparison tones for that specific trial.

Crossing each of the four standard tones (F♯$_4$, G$_4$, G♯$_4$, A$_4$) with two comparison tones (lower, higher), three temporal positions (early, on time, late), and three different possible random contexts created a total of 72 trials per block. Figure 4 depicts an example atonal context for a trial in which F♯$_4$ was the standard tone and G$_4$ was the comparison tone.

This experiment was run using the same apparatus and procedure as in Experiment 1. Listeners heard two blocks of randomly ordered tonal trials and two blocks of randomly ordered atonal trials; half of the participants received the tonal blocks first, and half received the atonal blocks first. The entire procedure lasted approximately 1 h.

Results and Discussion

The principal analysis for this experiment employed a four-way mixed model ANOVA, with the within-subjects factors of context type (tonal vs. atonal), temporal position (early, on time, late), and block repetition (first vs. second repetition). There was also a between-subjects factor of context order (whether participants were given

Table 2
Frequency of Standard and Comparison Tones, and Correct Pitch Height Judgment, in Experiments 2 and 3

Frequency (Hz)	Standard Pitch	Comparison Pitch	Pitch Height Judgment
466		A♯$_4$	Higher
440	A$_4$	A$_4$	Higher
415	G♯$_4$	G♯$_4$	Higher/lower
392	G$_4$	G$_4$	Higher/lower
370	F♯$_4$	F♯$_4$	Lower
349		F$_4$	Lower

Table 3
Frequency of All Possible Intervening Pitches in Experiment 2

Frequency (Hz)	Pitch Names
494	B_4
480	$\text{B}{-}_4$
466	$\text{A}\sharp_4$
453	$\text{A}{+}_4$
440	A_4
428	$\text{A}{-}_4$
415	$\text{G}\sharp_4$
404	$\text{G}{+}_4$
392	G_4
381	$\text{G}{-}_4$
370	$\text{F}\sharp_4$
360	$\text{F}{+}_4$
349	F_4
339	$\text{F}{-}_4$
330	E_4

the tonal or atonal blocks first). For this analysis, all data were collapsed across the individual standard tones (G−, G+, A− for the tonal trials; $\text{F}\sharp_4$, G_4, $\text{G}\sharp_4$, A_4 for the atonal trials), associated response type (lower, higher), and the context repetition (4 tonal contexts, 72 atonal contexts). This analysis failed to reveal any significant main effects for any of the main experimental factors. In fact, the only noteworthy result arising out of this analysis was a significant interaction between context type and temporal position [$F(2,20) = 7.16$, $MS_e = .002$, $p < .01$, $\eta_p^2 = .42$]. Figure 5 depicts this interaction, graphing pitch height accuracy as a function of temporal position for both tonal and atonal contexts.

Two subsequent one-way ANOVAs compared pitch height judgments as a function of temporal position for each context type individually, with temporal position as the sole within-subjects factor. For the tonal contexts, there was no effect of temporal position [$F(2,22) = 1.02$, $MS_e = .002$, $p = .38$, $\eta_p^2 = .09$]. For the atonal trials, however, there was a significant effect of temporal position [$F(2,22) = 4.33$, $MS_e = .003$, $p < .05$, $\eta_p^2 = .28$], with accuracy for on-time comparison tones exceeding that for early and late comparison tones. Supporting this pattern of results was a significant quadratic trend across temporal position [$F(1,11) = 3.53$, $MS_e = .002$, $p < .05$, $\eta_p^2 = .32$]. This final analysis replicates the findings of Jones et al. (2006; Jones et al., 2002), who repeatedly observed increased accuracy for pitch judgments of events occurring at predictable (i.e., expected) temporal locations relative to events occurring at unexpected times.

Overall, this experiment demonstrates that the temporal regularity of an event can influence perceptual judgments of pitch height and thus implicates the operation of a pitch–time interaction in musical processing. However, and in keeping with the initial predictions for this experiment, this finding was qualified by whether the intervening context that induces temporal expectations concomitantly induces a tonal percept. Specifically, if the intervening context was tonally structured, violations of temporal expectancies did not influence pitch judgments. In contrast, if the intervening context was atonal, participants were sensitive to deviations from temporal regularity in their pitch judgments.

There are, however, alternative explanations that might limit these findings. The most notable factor is the rhythmic structure of the tonal and atonal contexts. The tonal contexts consisted of rhythmically diverse events that varied in their relative durations, whereas the atonal context contained isochronous note events. Could this divergence in rhythmic structure have produced the observed difference in results between tonal and atonal conditions? An affirmative answer would be based on an assumption that the observed variation in rhythmic properties produces contexts that vary in their ability to induce a temporal structure. The weaker temporal structure would, therefore, be less effective in generating temporal expectancies in listeners, ultimately resulting in a weaker (or nonexistent) impact of deviations from the regularity of the temporal structure.

Although this explanation is possible theoretically, it counterintuitively argues that the more rhythmically diverse and musically realistic (tonal) context was less effective in inducing a temporal structure than was the isochronous and less musically realistic (atonal) context. Such an argument, however, flies in the face of theoretical analyses of rhythmic and metrical structure (Cooper & Meyer, 1960; Lerdahl & Jackendoff, 1983), formal modeling of how listeners apprehend metrical structure (Longuet-Higgins & Lee, 1982; Steedman, 1977; Temperley, 2001, 2008), and empirical results on the perception of metric information (Griffith & Todd, 1999; Palmer & Krumhansl, 1990; Povel, 1981; Prince et al., 2008). Accordingly, one could argue that the more realistic, rhythmically diverse tonal contexts should have induced temporal expectations more effectively than would isochronous atonal contexts. Regardless, the difference in rhythmic diversity between the tonal and atonal contexts does represent a potentially important point of divergence between these stimuli.

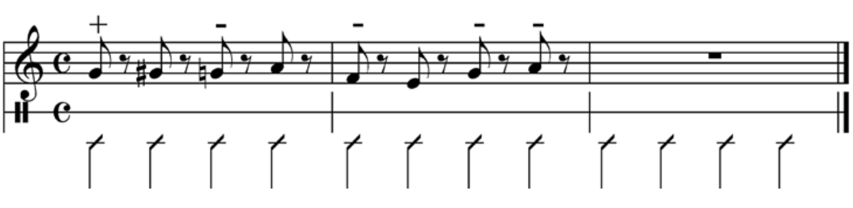

Figure 4. Example atonal sequence from Experiment 2. Plus (+) and minus (−) signs indicate quarter tones.

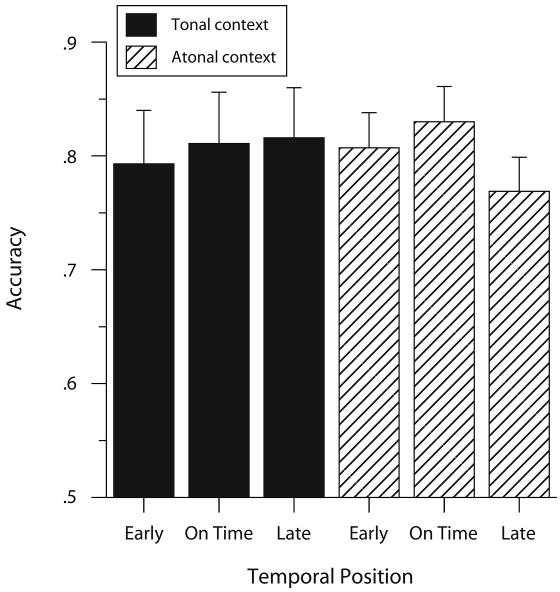

Figure 5. Accuracy for tonal and atonal trials across temporal position in Experiment 2.

A second difference between the two sets of contexts is that there were four unique tonal contexts, whereas the atonal contexts used 72 different sequences of random pitches. Perhaps repeating the same four tonal contexts somehow reduced the strength of listeners' temporal expectancies, relative to the atonal contexts. This explanation too seems unlikely, given that repeating the tonal contexts should have made them more predictable and, therefore, easier to ignore. In turn, the salience of the pitch structure would decrease and presumably magnify the effect of the temporal structure, resulting in stronger temporal expectancies in the tonal contexts. Although the results of Experiment 2 are opposite to this reasoning, it remains possible that this difference contributed to these results.

A third alternative explanation is that monophonic (consisting of only a single melodic line) versus homophonic (consisting of a melody line with an underlying sequence of chords) contexts could vary either in establishing temporal structure or in generating pitch–time interactions. In this case, the monophonic texture of the atonal contexts might have enabled stronger pitch–time interactions, whereas the homophonic texture of the tonal contexts did not. However, two observations raise doubts about this explanation: (1) There is no theoretical or empirical reason to believe that this factor affects the pattern of pitch–time interactions; the music cognition literature has not as yet highlighted any pitch–time processing differences between monophony and homophony. (2) Research on pitch–time relations has used both monophonic and homophonic stimuli, and no systematic differences between these stimuli have emerged in terms of their likelihood to engender independent versus interactive processing (Palmer & Krumhansl, 1987a, 1987b).

A fourth difference between the two sets of stimuli is that the atonal contexts consisted of randomly ordered sequences of tones with large and small pitch intervals, whereas the tonal contexts contained coherent melodic lines characterized by smaller pitch intervals between subsequent notes. Yet again, although on the basis of the existing literature there is no reason to expect that this difference would alter the strength of temporal expectancies, it nevertheless remains a theoretically possible influence on the present results.

A final difference between the atonal and tonal contexts is that the tonal contexts used seven pitch classes, whereas the atonal contexts used 15 separate pitches (although only 8 were heard in a given context), including quarter tones. Once again, although there is no reason to suspect that varying the number of pitch classes would affect the role of temporal expectancy profiles, it remains a point of departure between the context types.

As this discussion shows, even though none of these alternatives provides an especially compelling explanation for the present data, none can be ruled out definitively on the basis of Experiment 2. Accordingly, it would be reassuring to control these factors in another experiment and to determine whether the present findings could be replicated. Exploring this issue was the goal of Experiment 3.

EXPERIMENT 3

The previous two experiments suggested that the presence or absence of tonal pitch structure determined the existence of a temporal expectancy profile in pitch height comparisons. Before these findings could be taken as definitive, however, it remained necessary to consider several specific stimulus differences between the tonal and atonal contexts that could have influenced the observed results. To investigate the role of these factors, in Experiment 3, we used contexts comprising random sequences of isochronous pitches containing the same number of distinct pitch classes that either established a key area (tonal context) or did not (atonal context). As before, the task was a relative pitch height judgment; participants' accuracy was evaluated as a function of the temporal expectancy of the comparison tone.

Method

Participants. Twelve adult musicians, each with at least 8 years of formal training, received either credit in an introductory psychology class at the University of Toronto at Mississauga or payment ($10) for participating in this experiment. The average length of training was 9.8 years (*SD* = 2.4), and the average age was 19.8 years (*SD* = 3.9). Eleven of the participants were currently musically active (at an average of 3.8 h per week), and none reported possessing absolute pitch.

Stimuli, Apparatus, and Procedure. The stimuli were created with the same equipment as in the previous experiments and used the same format of a relative pitch height judgment of standard and comparison tones separated by an intervening context. The standard and comparison tones were the same as those in the atonal trials of Experiment 2 (see Table 2). In all trials, the standard sounded for 250 msec, followed by a 750-msec silent interval and then an intervening context that consisted of a sequence of twelve 500-msec tones, producing a 6-sec context. A metronome accompanied the contexts and continued for 2 sec after the context stopped.

The trials in Experiment 3 had entirely new contexts between the standard and comparison tones, for both tonal and atonal conditions. The tonal contexts distributed the 12 isochronous tones among seven diatonic pitch classes, in such a way that there were three occurrences of both the first and fifth scale degrees, two occurrences of the third scale degree, and one occurrence of each of the remaining scale degrees (second, fourth, sixth, seventh). This distribution strongly correlated with the major tonal hierarchy (Krumhansl, 1990; Krumhansl & Kessler, 1982) ($r = .96$). The atonal contexts also distributed the 12 context tones among seven pitches (also with two pitches having three occurrences each and one having two occurrences), but in a pattern that did not correlate with the tonal hierarchy. Transposing this "atonal hierarchy" through all 12 possible iterations and correlating each with the major and minor tonal hierarchies produced ubiquitously low correlation coefficients ($-.21 < r < .21$ and $-.21 < r < .3$, respectively). In other words, the tonal contexts corresponded strongly to a major tonal hierarchy, whereas the atonal contexts did not correspond well to any major or minor key. Because both tonal and atonal contexts employed random arrangements of tones, each contained a wide variety of pitch intervals between notes. Accordingly, the only recognizable distinction between the tonal and atonal contexts was the presence versus absence of tonal structure, respectively; all other factors, as was highlighted earlier, were equivalent.

As in the previous experiments, changing the timing of the comparison tone constituted the temporal position manipulation. Unlike in the previous experiments, there were five possible timings of the comparison tone, corresponding to very early (-126 msec), early (-63 msec), on time, late ($+63$ msec), or very late ($+126$ msec). These timings represent 25.2% and 12.6% deviations from the on-time (i.e., expected) temporal position. The very early and very late temporal positions were introduced to expand the variety of timings in order to investigate how violating temporal expectancies by larger amounts (i.e., beyond those typically tested by Jones and colleagues) might affect listeners' accuracy.

There were three repetitions of each of the four standard tones (each of which was associated with two comparison tones), five timings, and two types of context (tonal, atonal), resulting in 240 unique conditions. This experiment was run using the same apparatus and procedure as in Experiment 2. Listeners were asked to determine whether the comparison tone was lower or higher in pitch than the standard tone and were explicitly instructed to ignore the intervening context. Listeners heard one block of randomly ordered tonal trials and a second block of randomly ordered atonal trials; half of the participants heard the tonal block first, and the other half heard the atonal block first. The entire procedure lasted approximately 1 h.

Results and Discussion

The accuracy data were analyzed using a three-way mixed model ANOVA. The within-subjects factors were context type (tonal vs. atonal) and temporal position (very early, early, on time, late, very late); the between-subjects factor was context order (whether participants heard the tonal or atonal blocks first). For this analysis, all data were collapsed across the four standard tones, their matching responses (lower, higher), and the three repetitions. There was a main effect of temporal position [$F(4,40) = 3.58$, $MS_e = .01, p < .05, \eta_p^2 = .26$]. The only other significant effect was the interaction between context type and timing [$F(4,40) = 5.15$, $MS_e = .01, p < .01, \eta_p^2 = .34$]. This interaction was explored in two further one-way ANOVAs; temporal position was the within-subjects factor.

For the tonal contexts, there was a main effect of timing [$F(4,44) = 2.88$, $MS_e = .01, p < .05, \eta_p^2 = .21$]. However, this effect did not correspond to a conventional temporal expectancy profile. Instead, the early temporal position elicited the highest accuracy, followed by the very late and very early temporal positions. Four pairwise t tests revealed that accuracy for the on-time temporal position did not differ significantly from that for any of the other four temporal positions: very early–on time [$t(11) = 1.1, p = .29$]; early–on time [$t(11) = 2.1, p = .06$]; on time–late [$t(11) = 1, p = .36$]; very late–on time [$t(11) = -0.95$, $p = .36$]. Instead, there was a significant cubic trend [$F(1,11) = 5.6$, $MS_e = .01, p < .05, \eta_p^2 = .34$]. Figure 6 displays these data.

The atonal contexts also exhibited an effect of timing [$F(4,44) = 7.4$, $MS_e = .004, p < .001, \eta_p^2 = .4$], but this effect too followed an unexpected pattern. There was a significant fourth-order trend [$F(1,11) = 28.4$, $MS_e = .004, p < .001, \eta_p^2 = .72$], with accuracy for the on-time temporal position better than that for the early and late positions, but with accuracy for the very early and very late temporal positions improved relative to that for the early and late positions. Figure 6 depicts these data. Another four pairwise t tests of temporal positions (the same as for the tonal contexts) revealed that the accuracy for on-time comparison tones was significantly above that for early and late positions (early–on time [$t(11) = -4.49, p < .001$]; on time–late [$t(11) = 4.87, p < .001$]); conversely, accuracy for on-time comparison tones did not exceed that for the very early and very late temporal positions (very early–on time [$t(11) = -2, p = .07$]; on time–very late [$t(11) = 1.68, p = .12$]).

At first glance, the effect of temporal position in this experiment seems contradictory to a typical temporal

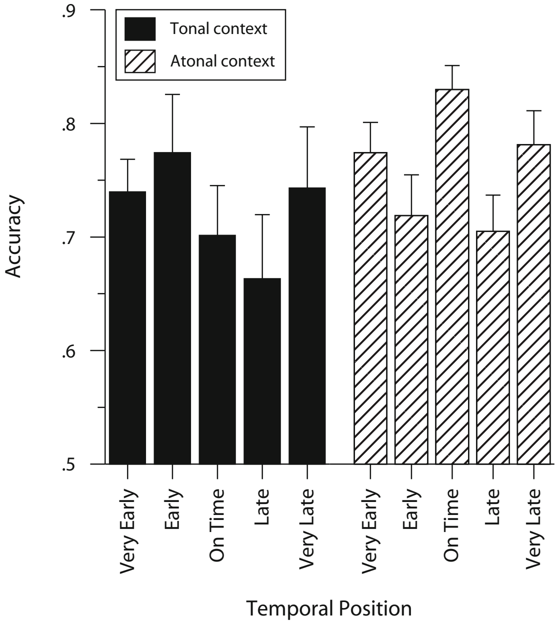

Figure 6. Accuracy for tonal and atonal trials across temporal position in Experiment 3.

expectancy profile in which accuracy decreases as the timing of the events diverges from the expected temporal position. Certainly, for the tonal contexts, the pattern of accuracy across temporal positions does not replicate the temporal expectancy profile found by Jones and colleagues. In fact, the significant effect of temporal position on accuracy for the tonal contexts does not follow any interpretable pattern and may simply be a spurious finding, resulting from early comparison tones' higher accuracy than late comparison tones'.

As for the atonal contexts, these results confirm the previous findings of Jones et al. (2006; Jones et al., 2002) by once again indicating increased accuracy for on-time comparison tones relative to early and late comparison tones. Also confirming the findings of Experiment 2, this pattern was restricted to comparison tones following atonal sequences but disappeared for comparison tones following tonal sequences.

The results for the atonal contexts also extend these previous findings, in a manner intriguingly consistent with the dynamic attending hypothesis. Consider the underlying assumption of the theory of dynamic attending: Attentional energy vacillates via linked oscillators that are synchronized with the rhythm of the presented stimulus (Large & Jones, 1999). Computational work on modeling the perception of temporal patterns in music proposes that some of these linked oscillators function at subdivisions of the tactus level, according to the metric hierarchy (Large & Palmer, 2002). Therefore, the strength of temporal expectancies varies as a function of the metric hierarchy. In Experiment 3, the very early and very late comparison tones corresponded to a 25.2% shift from the on-time temporal position, an amount that corresponded to a quarter of the interonset interval (IOI) of 500 msec, whereas the 12.6% shift translated to an eighth of the IOI. In terms of the metric hierarchy (Palmer & Krumhansl, 1990), a quarter subdivision (very early, very late) of the tactus (500-msec IOI) is a more stable temporal position than an eighth subdivision (early, late). Accordingly, very early and very late comparison tones were actually more metrically stable than the early and late comparison tones, so note occurrences at those locations would violate temporal expectancies to a lesser degree. Thus, the improved accuracy of the more extreme temporal shifts relative to the smaller shifts in these data aligns well with dynamic attending theory.

Overall, by replicating the finding of a temporal expectancy profile in atonal but not tonal contexts, Experiment 3 definitively rules out the importance of the stimulus factors highlighted previously. Specifically, this experiment employed both tonal and atonal contexts having exactly the same rhythmic structure (isochronous pitches), with the same number of unique sequences (120 each). Furthermore, all of the sequences were monophonic, consisted of random tones containing a mixture of large and small consecutive pitch intervals, and included seven unique pitch classes. Accordingly, the only conceivable candidate remaining to explain the differential impact of the tonal versus atonal contexts is the presence versus absence of the pitch structure of tonality.

GENERAL DISCUSSION

The circumstances under which temporal variations affected the accuracy of a pitch judgment were explored in three experiments. In Experiment 1, the accuracy of cognitive and perceptual pitch judgments of a comparison tone following a context that induced both tonal and metric hierarchies was uninfluenced by violations of temporal expectancies for that comparison tone. In Experiment 2, we extended this finding by explicitly manipulating the presence versus absence of tonal structure in the intervening context and using a perceptual pitch height judgment. This experiment obtained an effect of temporal expectancies on pitch judgments, but only when the intervening context did not instantiate a tonal percept. The pattern of this effect replicated previously reported findings of temporal influences on pitch perception (Jones et al., 2006; Jones et al., 2002), in which listeners processed temporally expected events better than they did temporally unexpected events. Experiment 3 replicated the findings of Experiment 2 and ruled out several remaining potential confounds in the difference between the tonal and atonal stimuli of Experiment 2. The results of this experiment also indicated that the accuracy for very early and very late comparison tones in atonal trials improved relative to accuracy for the smaller temporal shifts, a nonintuitive result that is nevertheless consistent with the theory of dynamic attending because the more extreme temporal positions were actually more metrically stable. Regardless, it appears that it is the presence versus absence of a tonal framework, and not the type of processing required (cognitive or perceptual), that drove the appearance of pitch–time interactions in the form of temporal expectancies in this study.

These findings shed light on experimental investigations of the processing of musical dimensions, specifically on the divergence in results between Jones et al. (2006; Jones et al., 2002) and Prince et al. (2008). On the basis of a theory of dynamic attending, Jones et al. (2006; Jones et al., 2002) argued that both temporal and pitch pattern structures drive listeners' attention by producing dynamic temporal and pitch expectancies for when (in temporal space) and where (in pitch space) subsequent events will occur. Such a model assumes an inherent interaction between the processing of pitch and temporal information, with deviations in one dimension influencing the apprehension of information in the other dimension. In contrast, Prince et al. (2008) noted an asymmetry in pitch–time relations, with pitch variation influencing temporal processing, but with temporal variation failing to influence pitch processing for Western tonal music. These authors explained this finding by suggesting that listeners learn to place more emphasis on pitch variation than on temporal variation in typical Western musical contexts, resulting in an inherent bias to attend to pitch over time. As for why there would be an inherent bias toward pitch information in Western musical contexts, Prince et al. highlighted the fact that pitch is a more musically elaborated dimension than time, containing more variation, uniqueness, and less predictability. This greater degree of variation in pitch likely draws listeners' attention to this dimension at the expense of time. Consequently, given years of exposure, this preferential focus on pitch becomes automatic, so that any typical Western musical context involuntarily invokes greater attention to pitch.

Taken together, Prince et al. (2008) and the present study provide evidence for this idea, using a set of convergent procedures. Prince et al.'s findings of an asymmetric pattern of results, in which pitch variation influenced temporal classifications in tonal music (but not vice versa), are consistent with this hypothesis. Although illuminating, this earlier study provides only partial support for a pitch focus hypothesis. The present project, however, provides more direct evidence, because systematic manipulation of the tonality of the stimuli affected the focus on pitch information, as indicated by a corresponding variation in how temporal expectancies influenced pitch judgments. Thus, these studies provide complementary experimental findings, demonstrating both pitch influences on temporal judgments (Prince et al., 2008) and temporal influences on pitch judgments (the present study). The notion of an inherent focus on pitch variation in Western musical contexts parsimoniously explains these findings.

It is important to realize, however, that the present findings do not suggest that the critical factor is the presence versus absence of any pitch structure in a musical context. Rather, these results suggest that it is the form of the pitch structure that is crucial. In Jones et al. (2006) the sequences did contain hierarchical pitch structure, although this structure was along the lines of classic serial pattern structure (Deutsch & Feroe, 1981; Jones, 1987; Restle, 1970, 1972; Simon, 1972). For Jones et al. (2006), the serial pattern structure of the sequence, relative to the pattern in which the target tone was embedded, influenced change detection of the target. Most importantly, these authors found that the temporal predictability of the target tone simultaneously influenced change detection of the target. Therefore, it would be a misrepresentation to suggest that there is something special about pitch structure per se that underlies the divergence between the present findings and Jones's work.

This point leads to two related questions: What is it about tonal structure that distinguishes it from other forms of pitch structure (such as serial pattern structure), and what other forms of pitch structure might have comparable effects on pitch–time interactions? Regarding the first question, there is currently no definitive answer, but it is likely that the sheer amount of experience that listeners have with tonal structure is relevant. Listeners are sensitive to other pitch structures and can learn them, but tonality is by far the most prevalent in Western music. Perhaps a similar level of exposure to some other form of pitch structure might have similar effects. Another possibility is that tonality consists of a multileveled hierarchical structure of pitch events, with varying degrees of perceived relatedness between the pitches of the chromatic set and the induced tonal center. In contrast, although serial patterns can contain multileveled hierarchical structure (Deutsch & Feroe, 1981), the actual sequences employed by Jones et al. (2006) were not multileveled, but consisted of a much simpler hierarchical serial pattern. If this explanation is accurate, employing intervening sequences containing a richer hierarchical serial pattern might reduce the impact of temporal expectancy violations on pitch height judgments, similar to what occurred in this study.

This prediction could provide at least a partial answer to the second question as well: whether forms of pitch structure other than tonality might have a similar effect on pitch–time interactions. In fact, there are various possibilities along these lines. In addition to the use of more complex hierarchical serial patterns, another possibility involves examining the impact of structural aspects, such as the relations between notes in the intervening context and the standard and comparison tones. Indeed, early work in this field found that recognition memory of a standard tone followed by an intervening sequence and a subsequent comparison tone was influenced by whether the intervening sequence repeated the standard tone (Deutsch, 1972, 1975). More generally, evidence that including such a critical tone in the context influences pitch height comparisons and the role of temporal expectancies would provide compelling convergent evidence for the idea that the pitch structure of musical contexts influences pitch–time interactions.

A limitation to these findings stems from the fact that the present study employed musically trained participants, whereas Jones et al. (2002) used participants with less than 6 years of musical training. Along these lines, perhaps there is something about musical expertise that affects listeners' expectancies. For instance, maybe musicians' greater explicit knowledge of music exacerbated their tendency as listeners to focus more on pitch than time. Or perhaps the musicians' increased musical skill allowed them to maintain a high level of attention for all events, not just those occurring on the beat. In terms of the dynamic attending theory (Barnes & Jones, 2000; Jones, 1987; Jones & Boltz, 1989; Large & Jones, 1999), musicians might be able to widen the peaks of the attentional energy oscillations that are synchronized with the beat. Conversely, untrained listeners' insufficiently refined music listening skills would hinder their ability to process events that do not occur at their expected temporal location, the time at which attentional energy reaches its maximum. If this explanation is true, testing nonmusicians in a fashion similar to that used in the present study should produce different results than those observed here.

Although this explanation is plausible, there are reasons to believe that musical training did not contribute to the present findings. First, and most obviously, this explanation fails to account for the effect of timing observed in the atonal trials of Experiments 2 and 3. If musicians' greater experience preferentially directed their attention to pitch or widened their temporal window of functional attention, they should have shown the same impact of temporal deviations, regardless of the presence versus absence of tonal structure in the context. Second, several studies have investigated expertise effects of pitch–time relations in music perception, and none found any qualitative differences in the pattern of pitch–time integration between musicians and nonmusicians (Boltz, 1989a; Hébert & Peretz, 1997; Lebrun-Guillaud & Tillmann, 2007; Makris & Mullet, 2003; Palmer & Krumhansl, 1987a, 1987b; Pitt & Monahan, 1987; Smith & Cuddy, 1989; Tillmann & Lebrun-Guillaud, 2006). Thus, even though nonmusicians lack training in producing music, they nonetheless respond to music in much the same way as musicians who have explicit knowledge of musical relations (Bigand & Poulin-Charronnat, 2006; Koelsch, Gunter, Friederici, & Schröger, 2000). Interestingly, this conclusion suggests that the greater importance of and preferential attention to pitch is likely a strategy for listening that arises primarily out of passive exposure to music and not as a consequence of explicit training.

Given all of these possible explanations and their corresponding theoretical difficulties, it seems that the most parsimonious explanation for the present findings is that, in a typical Western music context, pitch is more salient to listeners than time. The number and complexity of pitch structures in Western music far outweigh those of temporal structures. Therefore, the pitch dimension is more variable, less predictable, and, as a result, of greater informative value than the temporal dimension. Listeners' years of exposure to music with these properties automatically induce a greater focus on pitch than on time in a Western musical context. However, temporal regularity is clearly important in the processing of auditory events; these findings, as well as myriad other results (Garner, 1974; Handel & Lawson, 1983; Jones, 1976; Jones, Kidd, & Wetzel, 1981; Longuet-Higgins & Lee, 1982; Steedman, 1977), attest to this idea. In this regard, the present results can be reconciled with Jones's theory of dynamic attention (Boltz, 1993a; Jones & Boltz, 1989; Jones et al., 2006; Jones et al., 2002; Large & Jones, 1999). Moreover, these findings provide an important qualification to this general theory as to how task characteristics can modulate the role of temporal factors in music perception. The present research therefore extends existing work on dynamic attending by providing detail on the role of pitch structure in temporal expectancy profiles.

Overall, it appears that the pitch structure present in a tonal context exaggerates the perceptual importance of pitch relative to time, thereby reducing or possibly eliminating the occurrence of pitch–time interactions. We hope that this work will aid further efforts in understanding not only how pitch and time integrate in the perception of music, but also, more generally, how the component dimensions of any structured stimulus combine to form a percept.

AUTHOR NOTE

Grants from the Natural Sciences and Engineering Council of Canada to W.F.T. and M.A.S. supported this research. Address correspondence concerning this article to J. B. Prince, Department of Psychology, University of Toronto at Mississauga, 3359 Mississauga Road N., Mississauga, ON, L5L 1C6 Canada (e-mail: jon.prince@utoronto.ca).

REFERENCES

Abe, J.-I., & Okada, A. (2004). Integration of metrical and tonal organization in melody perception. *Japanese Psychological Research*, **46**, 298-307.

Aldwell, E., & Schacter, C. (2002). *Harmony and voice leading*. Belmont, CA: Thomson/Schirmer.

Barnes, R., & Jones, M. R. (2000). Expectancy, attention, and time. *Cognitive Psychology*, **41**, 254-311.

Bharucha, J. J. (1984). Anchoring effects in music: The resolution of dissonance. *Cognitive Psychology*, **16**, 485-518.

Bharucha, J. J. (1996). Melodic anchoring. *Music Perception*, **13**, 383-400.

Bigand, E., Madurell, F., Tillmann, B., & Pineau, M. (1999). Effect of global structure and temporal organization on chord processing. *Journal of Experimental Psychology: Human Perception & Performance*, **25**, 184-197.

Bigand, E., & Poulin-Charronnat, B. (2006). Are we "experienced listeners"? A review of the musical capacities that do not depend on formal musical training. *Cognition*, **100**, 100-130.

Boltz, M. G. (1989a). Perceiving the end: Effects of tonal relationships on melodic completion. *Journal of Experimental Psychology: Human Perception & Performance*, **15**, 749-761.

Boltz, M. G. (1989b). Rhythm and "good endings": Effects of temporal structure on tonality judgments. *Perception & Psychophysics*, **46**, 9-17.

Boltz, M. G. (1989c). Time judgments of musical endings: Effects of expectancies on the "filled interval effect." *Perception & Psychophysics*, **46**, 409-418.

Boltz, M. G. (1991). Some structural determinants of melody recall. *Memory & Cognition*, **19**, 239-251.

Boltz, M. G. (1993a). The generation of temporal and melodic expectancies during musical listening. *Perception & Psychophysics*, **53**, 585-600.

Boltz, M G. (1993b). Time-estimation and expectancies. *Memory & Cognition*, **21**, 853-863.

Boltz, M. G. (1995). Effects of event structure on retrospective duration judgments. *Perception & Psychophysics*, **57**, 1080-1096.

Boltz, M. G. (1998a). The processing of temporal and nontemporal information in the remembering of event durations and musical structure. *Journal of Experimental Psychology: Human Perception & Performance*, **24**, 1087-1104.

Boltz, M. G. (1998b). Task predictability and remembered duration. *Perception & Psychophysics*, **60**, 768-784.

Boltz, M. G. (1998c). Tempo discrimination of musical patterns: Effects due to pitch and rhythmic structure. *Perception & Psychophysics*, **60**, 1357-1373.

Boltz, M. G. (1999). The processing of melodic and temporal information: Independent or unified dimensions? *Journal of New Music Research*, **28**, 67-79.

Cooper, G. W., & Meyer, L. B. (1960). *The rhythmic structure of music*. Chicago: University of Chicago Press.

Crowder, R. G., & Neath, I. (1995). The influence of pitch on time perception in short melodies. *Music Perception*, **12**, 379-386.

Deutsch, D. (1972). Effect of repetition of standard and comparison tones on recognition memory for pitch. *Journal of Experimental Psychology*, **93**, 156-162.

Deutsch, D. (1975). Facilitation by repetition in recognition memory for tonal pitch. *Memory & Cognition*, **3**, 263-266.

Deutsch, D. (1980). The processing of structured and unstructured tonal sequences. *Perception & Psychophysics*, **28**, 381-389.

Deutsch, D., & Feroe, J. (1981). The internal representation of pitch sequences in tonal music. *Psychological Review*, **88**, 503-522.

Fries, W., & Swihart, A. A. (1990). Disturbance of rhythm sense following right hemisphere damage. *Neuropsychologia*, **28**, 1317-1323.

Garner, W. R. (1974). *The processing of information and structure*. Potomac, MD: Erlbaum.

Griffith, N., & Todd, P. M. (Eds.) (1999). *Musical networks: Parallel distributed perception and performance*. Cambridge, MA: MIT Press.

Griffiths, T. D., Johnsrude, I., Dean, J. L., & Green, G. G. R. (1999). A common neural substrate for the analysis of pitch and duration pattern in segmented sound? *NeuroReport*, **10**, 3825-3830.

Handel, S., & Lawson, G. R. (1983). The contextual nature of rhythmic interpretation. *Perception & Psychophysics*, **34**, 103-120.

Hébert, S., & Peretz, I. (1997). Recognition of music in long-term memory: Are melodic and temporal patterns equal partners? *Memory & Cognition*, **25**, 518-533.

Jones, M. R. (1976). Time, our lost dimension: Toward a new theory of perception, attention, and memory. *Psychological Review*, **83**, 323-355.

Jones, M. R. (1987). Dynamic pattern structure in music: Recent theory and research. *Perception & Psychophysics*, **41**, 621-634.

Jones, M. R., & Boltz, M. G. (1989). Dynamic attending and responses to time. *Psychological Review*, **96**, 459-491.

Jones, M. R., Boltz, M. G., & Kidd, G. (1982). Controlled attending as a function of melodic and temporal context. *Perception & Psychophysics*, **32**, 211-218.

Jones, M. R., Johnston, H. M., & Puente, J. (2006). Effects of auditory pattern structure on anticipatory and reactive attending. *Cognitive Psychology*, **53**, 59-96.

Jones, M. R., Kidd, G., & Wetzel, R. (1981). Evidence for rhythmic attention. *Journal of Experimental Psychology: Human Perception & Performance*, **7**, 1059-1073.

Jones, M. R., Moynihan, H., MacKenzie, N., & Puente, J. (2002). Temporal aspects of stimulus-driven attending in dynamic arrays. *Psychological Science*, **13**, 313-319.

Jones, M. R., & Ralston, J. T. (1991). Some influences of accent structure on melody recognition. *Memory & Cognition*, **19**, 8-20.

Jones, M. R., Summerell, L., & Marshburn, E. (1987). Recognizing melodies: A dynamic interpretation. *Quarterly Journal of Experimental Psychology*, **39A**, 89-121.

Kelley, Z. A., & Brandt, J. F. (1984). Pitch change recognition as a function of duration in successive dichotic stimuli. *Psychology of Music*, **12**, 43-59.

Kidd, G., Boltz, M. G., & Jones, M. R. (1984). Some effects of rhythmic context on melody recognition. *American Journal of Psychology*, **97**, 153-173.

Koelsch, S., Gunter, T. C., Friederici, A. D., & Schröger, E. (2000). Brain indices of music processing: "Nonmusicians" are musical. *Journal of Cognitive Neuroscience*, **12**, 520-541.

Krumhansl, C. L. (1979). Psychological representation of musical pitch in a tonal context. *Cognitive Psychology*, **11**, 346-374.

Krumhansl, C. L. (1990). *Cognitive foundations of musical pitch*. New York: Oxford University Press.

Krumhansl, C. L. (1991). Memory for musical surface. *Memory & Cognition*, **19**, 401-411.

Krumhansl, C. L. (2000). Rhythm and pitch in music cognition. *Psychological Bulletin*, **126**, 159-179.

Krumhansl, C. L., & Kessler, E. J. (1982). Tracing the dynamic changes in perceived tonal organization in a spatial representation of musical keys. *Psychological Review*, **89**, 334-368.

Krumhansl, C. L., & Shepard, R. N. (1979). Quantification of the hierarchy of tonal functions within a diatonic context. *Journal of Experimental Psychology: Human Perception & Performance*, **5**, 579-594.

Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychological Review*, **106**, 119-159.

Large, E. W., & Palmer, C. (2002). Perceiving temporal regularity in music. *Cognitive Science*, **26**, 1-37.

Lebrun-Guillaud, G., & Tillmann, B. (2007). Influence of a tone's tonal function on temporal change detection. *Perception & Psychophysics*, **69**, 1450-1459.

Lerdahl, F. (1988). Tonal pitch space. *Music Perception*, **5**, 315-349.

Lerdahl, F., & Jackendoff, R. (1983). *A generative theory of tonal music*. Cambridge, MA: MIT Press.

Longuet-Higgins, H. C., & Lee, C. S. (1982). The perception of musical rhythms. *Perception*, **11**, 115-128.

Makris, I., & Mullet, E. (2003). Judging the pleasantness of contour–rhythm–pitch–timbre musical combinations. *American Journal of Psychology*, **116**, 581-611.

Mavlov, L. (1980). Amusia due to rhythm agnosia in a musician with left hemisphere damage: A nonauditory supramodal defect. *Cortex*, **16**, 331-338.

Monahan, C. B., & Carterette, E. C. (1985). Pitch and duration as determinants of musical space. *Music Perception*, **3**, 1-32.

Monahan, C. B., Kendall, R. A., & Carterette, E. C. (1987). The effect of melodic and temporal contour on recognition memory for pitch change. *Perception & Psychophysics*, **41**, 576-600.

Nittono, H., Bito, T., Hayashi, M., Sakata, S., & Hori, T. (2000). Event-related potentials elicited by wrong terminal notes: Effects of temporal disruption. *Biological Psychology*, **52**, 1-16.

Palmer, C., & Krumhansl, C. L. (1987a). Independent temporal and pitch structures in determination of musical phrases. *Journal of Experimental Psychology: Human Perception & Performance*, **13**, 116-126.

Palmer, C., & Krumhansl, C. L. (1987b). Pitch and temporal contributions to musical phrase perception: Effects of harmony, performance timing, and familiarity. *Perception & Psychophysics*, **41**, 505-518.

Palmer, C., & Krumhansl, C. L. (1990). Mental representations for musical meter. *Journal of Experimental Psychology: Human Perception & Performance*, **16**, 728-741.

Peretz, I. (1990). Processing of local and global musical information by unilateral brain-damaged patients. *Brain*, **113**, 1185-1205.

Peretz, I. (1996). Can we lose memory for music? A case of music agnosia in a nonmusician. *Journal of Cognitive Neuroscience*, **8**, 481-496.

Peretz, I., & Kolinsky, R. (1993). Boundaries of separability between melody and rhythm in music discrimination: A neuropsychological perspective. *Quarterly Journal of Experimental Psychology*, **46A**, 301-325.

Peretz, I., Kolinsky, R., Tramo, M. J., Labrecque, R., Hublet, C., Demeurisse, G., & Belleville, S. (1994). Functional dissociations following bilateral lesions of auditory-cortex. *Brain*, **117**, 1283-1301.

Pitt, M. A., & Monahan, C. B. (1987). The perceived similarity of auditory polyrhythms. *Perception & Psychophysics*, **41**, 534-546.

Povel, D. J. (1981). Internal representation of simple temporal patterns. *Journal of Experimental Psychology: Human Perception & Performance*, **7**, 3-18.

Prince, J. B., Thompson, W. F., & Schmuckler, M. A. (2008). *Pitch and time, tonality and meter: How do musical dimensions combine?* Manuscript submitted for publication.

Restle, F. (1970). Theory of serial pattern learning: Structural trees. *Psychological Review*, **77**, 481-495.

Restle, F. (1972). Serial patterns: The role of phrasing. *Journal of Experimental Psychology*, **92**, 385-390.

Schellenberg, E. G., Krysciak, A. M., & Campbell, R. J. (2000). Perceiving emotion in melody: Interactive effects of pitch and rhythm. *Music Perception*, **18**, 155-171.

Schmuckler, M. A., & Boltz, M. G. (1994). Harmonic and rhythmic influences on musical expectancy. *Perception & Psychophysics*, **56**, 313-325.

Schön, D., & Besson, M. (2002). Processing pitch and duration in music reading: A RT–ERP study. *Neuropsychologia*, **40**, 868-878.

Simon, H. A. (1972). Complexity and the representation of patterned sequences of symbols. *Psychological Review*, **79**, 369-382.

Smith, K. C., & Cuddy, L. L. (1989). Effects of metric and harmonic rhythm on the detection of pitch alterations in melodic sequences. *Journal of Experimental Psychology: Human Perception & Performance*, **15**, 457-471.

Steedman, M. J. (1977). Perception of musical rhythm and metre. *Perception*, **6**, 555-569.

Temperley, D. (2001). *The cognition of basic musical structures*. Cambridge, MA: MIT Press.

Temperley, D. (2008). *Music and probability*. Cambridge, MA: MIT Press.

Thompson, W. F. (1993). Modeling perceived relationships between melody, harmony, and key. *Perception & Psychophysics*, **53**, 13-24.

Thompson, W. F. (1994). Sensitivity to combinations of musical parameters: Pitch with duration, and pitch pattern with durational pattern. *Perception & Psychophysics*, **56**, 363-374.

Thompson, W. F., Hall, M. D., & Pressing, J. (2001). Illusory conjunctions of pitch and duration in unfamiliar tone sequences. *Journal of Experimental Psychology: Human Perception & Performance*, **27**, 128-140.

Tillmann, B., & Lebrun-Guillaud, G. (2006). Influence of tonal and temporal expectations on chord processing and on completion judgments of chord sequences. *Psychological Research*, **70**, 345-358.

NOTE

1. A pitch class is a set of all pitches that are a whole number of octaves apart; e.g., the pitch class C consists of the Cs in all octaves.

(Manuscript received September 11, 2008;
revision accepted for publication December 9, 2008.)