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Effect of Global Structure and Temporal Organization on Chord Processing

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This study further explores the effect of global context on chord processing reported by E. Bigand and M. Pineau (1997). Expectations of a target chord were varied by manipulating the preliminary harmonic context while holding constant the chord(s) prior to the target. In Experiment 1, previously observed priming effects were replicated with an on-line paradigm. Experiment 2 was an attempt to identify the point in chord sequences that is responsible for the occurrence of the priming effect. In Experiment 3, Bigand and Pineau's findings were extended to wider harmonic contexts (i.e., defined at three hierarchical levels), and new evidence was provided that chord processing also depends on the temporal organization of the musical sequence. Neural net simulations globally support J. J. Bharucha's (1987, 1994) view that priming effects result from activations spreading via a schematic knowledge of Western harmony.

The processing of incoming events is affected by the context in which they appear. It is well known, for example, that the identification of a target word is facilitated by the prior presentation of a prime. Priming occurs when the prime is semantically related (D. E. Meyer & Schvaneveldt, 1971), syntactically congruent (Colé & Segui, 1994; Goodman, McClelland, & Gibbs, 1981), or physically related to the target (Goldinger, Luce, Pisoni, & Marcario, 1992). The first two priming effects are knowledge based, whereas the latter is form based (Forster, 1987).

Similarly, it has been well established that a previous musical context influences expectations of incoming sound events (Bharucha & Stoeckig, 1986, 1987; Boltz, 1989a, 1989b; Jones, Boltz, & Klein, 1993; Schellenberg, 1995; Schmuckler, 1989; Schmuckler & Boltz, 1994). Musical expectancy is governed by a number of features, some of them reflecting the influence of general principles of perceptual organization (e.g., melodic contour, melodic interval size), others reflecting the importance of the listeners' knowledge of a given musical idiom (like the tonal-harmonic hierarchy). In the present study, we are concerned with musical expectancies derived from knowledge of the tonal-harmonic hierarchy.

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Knowledge-Based Musical Expectations

Various theoretical frameworks may account for knowledge-based expectations. The generally accepted theoretical explanation is based on the concept of spreading activation (Collins & Loftus, 1975; Quillian, 1967). Memory is conceived of as a network of interconnected nodes, each of them representing a concept. When a concept is presented, the node representing the concept is activated, and this activation spreads through the network. Related concepts are activated, and this activation facilitates their processing when they appear (priming effect). The spreading activation model accounts well for priming effects in word lists (D. E. Meyer & Schvaneveldt, 1971; D. E. Meyer, Schvaneveldt, & Ruddy, 1974). Priming is based on a fast-acting and automatic activation that spreads within the mental lexicon via the long-term connections between semantically related items.

Knowledge-based musical expectations may be understood in terms of activations spreading through an associative net. In the Western musical system, a small set of events (12) are combined in a highly constrained way. The 12 notes of the chromatic scale are organized in several subsets of seven notes, called diatonic scales. Each scale permits seven diatonic chords, each of which is constructed on a different degree of the scale. Chords built on the first (I), the fifth (V), and the fourth (IV) degree of the scale (referred to as *tonic, dominant,* and *subdominant* chords, respectively) are more frequent in tonal musical pieces than are chords built on the other degrees of the scale (Francès, 1958/1988; Krumhansl, 1990). Identical chords may occur in a variety of different keys. Chords sharing a parent key are said to be harmonically related (such as the chords C and B♭, which both belong to the key of F). Harmonically related chords are more frequently associated in tonal musical pieces than are other chords.

A number of experimental studies have shown that these regularities (referred to as *tonal hierarchy*) are internalized through passive exposure to Western tonal music (Francès, 1958/1988; Krumhansl, 1990). According to Bharucha (1987, 1994), this knowledge may be conceived of as a network of interconnected units. The network contains three layers of units (the notes, the chords, and the keys). Each tone unit is connected to three major and three minor chord units. For example, the tone c is connected to the chords C, F, and A major and the chords C, A, and F minor. Each chord is linked to three major keys. The C-major chord, for example, is associated with the C, F, and G major keys. The regularities of the Western musical system are represented by the strength of the connections that link tone units to chords and key units. This pattern of connections constitutes nontemporal knowledge of Western harmony that generates automatic and schematic expectations in listeners (Bharucha, 1987, 1994).

When three triadic tones are played (say c-e-g), the units representing these tones are activated, and phasic activation (i.e., the change of activation) is sent toward major and minor chord units. The chord unit connected to the three tones receives the strongest activation (C-major chord in this example). In a second cycle of reverberation, phasic activations from the active chord units spread via connected links toward the key units (bottom-up activation) and start to reverberate toward tone units (top-down activation). In the next cycle, activated key units send back activation toward major and minor chord units, which simultaneously receive bottom-up activations from the tone units. After several cycles, the model reaches equilibrium in such a way that the chords with the closest harmonic relations receive the strongest activation (see Bharucha, 1987).

Empirical studies that used a priming paradigm provide strong support for Bharucha's model (Bharucha & Stoeckig, 1986, 1987; Tekman & Bharucha, 1992). For example, Bharucha and Stoeckig (1986) asked participants to decide as quickly as possible whether a target chord following a prime chord was or was not in tune. The priming effect was illustrated by (a) a tendency for participants to judge targets to be in tune when harmonically related to the prime and out of tune when unrelated and (b) shorter response times for in-tune targets when related and for out-of-tune targets when unrelated. According to the authors, a previous musical context (one chord in these experiments) generates the expectancy that related chords will follow, resulting in greater consonance and faster processing for expected chords. For example, the processing of the B♭ major chord is facilitated compared to the processing of the F# major chord when it occurs after a C-major prime chord. In Bharucha's model, the relative activation that reverberates in the neural net after the C-major chord is higher for the B♭ chord than for the F# chord.

Effects of Global and Local Context

In both the linguistic and musical fields, a key concern is to specify how spreading activation models can account for the influence of global context on expectancy formation: Are expectations the result of activations that spread through a schematic knowledge set? Do they involve the existence of other processes that integrate local structure within a coherent whole (Kintsch, 1988; Till, Mross, & Kintsch, 1988)? Psycholinguistic research has shown that the long-term connections between lexical items are not the sole source of context effects. Hess, Foss, and Carroll (1995) even argued that "the locus of context effects is primarily outside of the lexicon, in processes that determine semantic relationships among incoming words" (p. 63).

To date, the possible role played by global structures in chord processing has never been investigated in music. Schmuckler and Boltz (1994) used a long musical context as a prime. However, because the harmonic expectation for the target chord was varied by using different final events, the study was unable to differentiate between the potential influences of global and local structures. A first attempt to address this issue was recently provided by Bigand and Pineau (1997). In their study, the global harmonic context was manipulated while the chord prior to the target was held constant. One example of the sequences they used is presented in Figure 1. Expectations for the last chord (the target) were varied by changing the harmonic context created by the first six chords. In one context, the last chord was part of an authentic cadence (V–I), whereas in the other context, the last chord took the form of a fourth harmonic degree following an authentic cadence (I–IV). Given this change in harmonic function (tonic chord versus subdominant chord), it was assumed that participants' expectation of the target chord would be greater in the first context, all other local parameters being held constant. The effect of global context on expectancy formation was supported by the fact that participants reported a lower degree of completion for sequences ending on an unexpected chord (Experiment 1), took longer to decide whether the last chord belonged to the sequence when the last chord was unexpected (Experiment

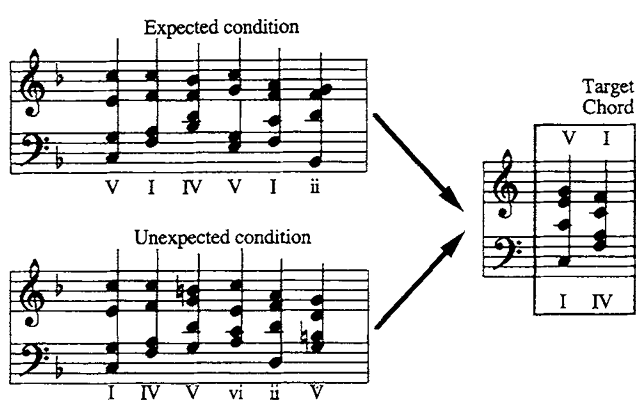

Figure 1. One example of the chord sequences used in Experiments 1 and 2.

2), and took longer to decide whether the last chord was consonant or dissonant when it was unexpected (Experiment 3). Pineau and Bigand (1997) replicated these findings with a larger set of chord sequences.

The first purpose of the present study was to extend these effects of global context in several ways. In Experiment 1 we attempted to replicate Bigand and Pineau's (1997) findings with a "self-paced listening" procedure that registered the on-line processing of both types of prime sequences. This procedure makes it possible to implement some methodological controls that were lacking in the earlier study. In Experiment 2, we manipulated the length of the prime in order to identify the point in the chord sequences that was responsible for the facilitation effects. Our purpose in Experiment 3 was to increase the complexity of the prime by manipulating the harmonic context at three hierarchical levels of the musical structure. In addition, this manipulation was crossed with systematic changes in the temporal organization of the sequence. According to Jones and Boltz's (1989) theory of dynamic attending, expectancies about the *what* of the event are not independent of expectancies about the *when* of these events. Therefore, a peculiar change in the temporal structure of the sequence may interfere with the harmonically based expectancy (Schmuckler & Boltz, 1994).

A Neural Net Simulation of the Global Context Effect in Music

The second main purpose of the present study was to test a spreading activation account of the global context effect in music. Bharucha's (1987) model goes some way toward addressing the dynamic character of expectancies as they develop over time. With the onset of an event, activation spreads inside the model and reaches equilibrium. This activation pattern reflects Western tonal hierarchy and takes into account the key membership of a chord.

> After the offset of an event, the activation begins to decay exponentially over time. If another event occurs before activation has decayed appreciably, the phasic activation due to that next event will add onto the residual levels of activation from the previous event, thereby creating a pattern of activation that can be influenced by an entire sequence of events, weighted according to recency (Bharucha, 1987, p. 17).

In other words, the activation of a unit i in the network is a function not just of the most recent event e but also of the previous event, $e - 1$, the activation of $e - 1$ being itself a function of event $e - 2$, and so on.

The total activation, $a_{i,e}$, of a unit i (a tone, a chord, or a key) after an event e is thus an additive function of three quantities: (a) the decayed activation caused by previous events $e - 1$, (b) the bottom-up activation caused directly by the stimulus itself (i.e., the tones), and (c) the indirect activation received from other units in response to event e (this spreading activation reflects the key membership of the event e). The total activation, $a_{i,e}$, of a unit i is given by the following equation:

$$a_{i,e} = a_{i,e-1}(1 - d)^t + A + \sum_{c=1}^{q} \Delta a_{i,e,c},$$

where d represents the rate (varying between 0 and 1) at which activation decays following the offset of the last event, t represents the time elapsed since the last offset, A represents the stimulus activation, and $\Sigma_{c=1}^{q} \Delta a_{i,e,c}$ represents the total phasic activation of unit i in response to event e, accumulated over the q reverbatory cycles that are necessary to reach equilibrium.

The first term thus represents the global context, the second term represents the stimulus effect, and the third term represents the local context (the most recent event). The first and third terms of the equation are the important ones from the point of view of priming. The third term represents the activation of chords when the key membership has been taken into account, and the first term is simply a decaying sum of these patterns from previous chords. Each chord makes an independent contribution to the final activation, weighted by recency. When only one chord is played, the first term is equal to zero and the activation pattern is determined by the second and third terms. Bharucha and Stoeckig's (1986, 1987) experiments confirmed the model's predictions when a single chord was used as prime. Until now, no study has attempted to test the model with long chord sequences, for which the first term becomes important. To address this issue, we implemented Bharucha's (1987) model on Matlab (1997; see the Appendix) and, for each experiment, conducted simulations and compared the outcomes with participants' data.

Experiment 1

Our first objective in this experiment was to replicate Bigand and Pineau's (1997) findings with an additional methodological control. In this study, we defined the chord sequences of the unexpected condition by modifying those of the expected condition through small changes in pitch (see *Materials* section below for more details). Although we took considerable care while performing these modifications, they may have rendered these chord sequences more awkward and less musically fluent than those in the expected condition. If they did, reaction times for the target chord in the unexpected condition may have been longer because the sequences in the unexpected condition sounded less natural and, for that reason, took more time to be processed. The method used in Bigand and Pineau's study provided no way of addressing this problem because reaction times were recorded only for the sole target chord. In the present experiment, participants were asked to play the chords at their own tempo by pressing a computer key (self-paced listening method) and to decide as quickly as possible whether the last chord of the sequence was consonant. The interonset interval (IOI) between each chord was registered. Longer processing times for the chord sequences in the unexpected condition would result in greater average IOIs in this condition. Our second objective in this experiment was to compare the relative activation observed in the network on the chord preceding the target (i.e., the *penultimate chord*) in the expected and unexpected conditions: Higher activation for the target chord in the expected condition would demonstrate that the model is able to capture subtle changes in global harmonic context.

Method

Participants. Thirty volunteer subjects participated in this experiment. Fifteen were students in psychology with no formal musical training who did not play musical instruments (referred to below as "nonmusicians"). Fifteen were graduate students in the music department of the University of Dijon (referred to below as "musicians").

Materials. Four chord sequences were used. All of them contained eight chords and were closed by an authentic cadence (V–I). Beyond this same global harmonic structure, they differed in several aspects related to the melodic contour of the upper and bass voices, the sequential order of the chords (i.e., the set of roman numerals), and the voicing (the specific pitch height of the component tones). Given these variations, these four chord sequences all sounded different from each other. The first six chords of these sequences were systematically varied in such a way that the four new sequences were in the dominant key. As far as possible, the melodic contour of the outer voices (i.e., soprano and bass voices) remained unchanged, and the changes in pitch were minimal so that the registers remained similar. The last two chords were acoustically identical, but their harmonic functions changed with the context: In one context the last chord functioned as a tonic chord (I), part of an authentic cadence (V–I), and in the other context it functioned as a subdominant chord (IV) following an authentic cadence (see Figure 1). Target chords were rendered dissonant by increasing the pitch of the fifth by a semitone. The intensity of the augmented fifth was the same as that of the other tones, thus making the dissonance quite salient.

Apparatus. All stimuli were played with sampled piano sounds produced by the EMT10 Yamaha Sound Expander. Velocity was constant for all pitches. The sound stimuli were recorded using SoundEditPro software at CD quality (16 bits and 44 kHz), and the experiment was run on PsyScope software (Cohen, MacWhinney, Flatt, & Provost, 1993). The tempo of the sequence was controlled by each participant individually thanks to an interactive self-paced listening technique. Pressing a key caused the computer to play a chord, and this chord continued to sound until the participant pressed the key again. There was no silence between chords, and the IOIs were entirely under the participant's control. When the last chord was played, the participant pressed one of two other keys to indicate whether or not this chord was in tune. A PsyScope buttonbox timer was used to measure the IOI and response times. Times were measured to an accuracy of 1 ms (see Cohen et al., 1993).

Procedure. The experimental procedure was split into two phases. During the first phase, the participants were trained to differentiate between dissonant and consonant chords. Eight chords were played in isolation and in a random order, and participants had to make a consonant–dissonant judgment as quickly as possible. Participants were informed when their responses were incorrect by an acoustic feedback signal. Only the participants who made fewer than five errors were allowed to continue the experiment. The others repeated the training session before being allowed to continue.

During the second phase, participants were asked to play the eight chords of the sequences by pressing a key and to make a quick consonant–dissonant judgment for the eighth chord. They were informed that all of the sequences contained eight chords and that half would finish with a dissonant chord and half with a consonant one. A feedback signal sounded when participants answered incorrectly.

Design. Crossing the manipulations of harmonic context (two levels) and consonance (two levels) produced four possible versions for each of the four chorales, yielding a total of 16 experimental patterns to be tested with each group of listeners. The 16 sequences were presented in a random order.

Results

Consonant–dissonant judgments for the target chord. The percentages of correct responses averaged across the four chorales are presented in Figure 2 (top panel). Because the dissonances were salient, these percentages were high for both groups of participants. Nevertheless, percentages of correct responses were higher for expected target chords and for musicians. Both effects were significant: $F(1, 28) = 6.77, p < .02, MSE = 0.0249$; $F(1, 28) = 13.03, p < .001, MSE = 0.0639$. No significant interaction was observed, but there was a slight bias in musicians to judge consonant targets as dissonant when unexpected. The second dependent measure related to the reaction time necessary for consonant–dissonant judgments (see Figure 2, bottom panel). Response times for correct responses were 98 ms shorter on average for expected tonic chords, $F(1, 28) = 29.22, p < .001, MSE = 9{,}910$; 132 ms shorter on average for dissonant chords, $F(1, 28) = 23.97, p < .001, MSE = 21{,}833$; and 288

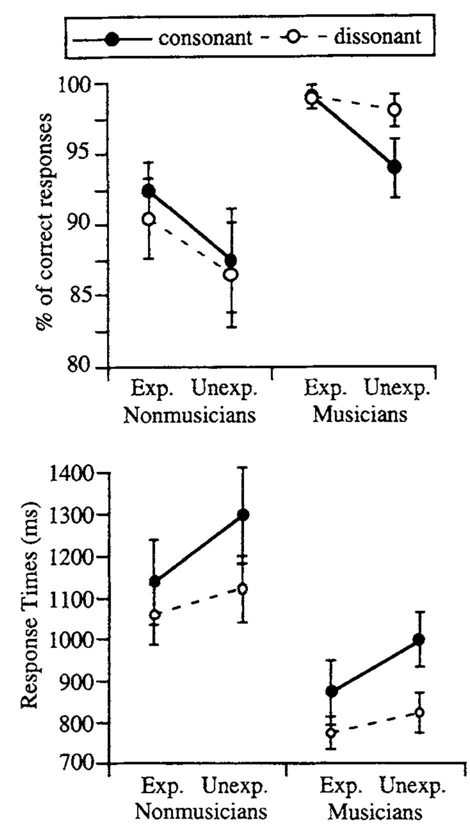

Figure 2. Percentage of correct responses (top) and correct response times (bottom) averaged across chord sequence set observed when the target chord was expected (Exp.; V–I) and unexpected (Unexp.; I–IV) in Experiment 1.

ms faster in musicians, $F(1, 28) = 7.38$, $p < .02$, $MSE = 336{,}086$. There was a significant Harmonic Context × Consonance interaction, $F(1, 28) = 8.03$, $p < .01$, $MSE = 7{,}364$: Response times were faster for dissonant chords than consonant ones, and this difference was greater in the unexpected condition. These findings are consistent with the crossed interaction observed by Bharucha and Stoeckig (1987).

IOI profiles. The IOI values observed from Chord 1 to Chord 7 in the two contexts are presented in Table 1. IOIs were on average 141 ms shorter for musicians, $F(1, 28) = 7.49$, $p < .02$, $MSE = 1{,}084{,}759$. The IOI values correspond to averaged tempos of 96 quarter notes per minute for nonmusicians and 124 quarter notes per minute for musicians. The fact that there was no main effect of context on the IOI values ($F < 1$) indicates that the chords defining the expected and unexpected conditions were perceived with the same fluency. This result suggests that the difference in response times between expected and unexpected targets may not be caused by a general slowness in processing the chord sequences of the unexpected condition. The IOIs varied considerably as a function of chord position, $F(6, 168) = 23.99$, $p < 001$, $MSE = 6{,}129$. Planned comparisons indicated that IOI increased linearly from Chord 1 to Chord 6, $F(1, 28) = 25.59$, $p < .001$, $MSE = 4{,}038$, as well as from Chord 6 to Chord 7, $F(1, 28) = 17.56$, $p < .001$, $MSE = 14{,}871$. This result suggests that participants (notably the nonmusicians) slowed down the tempo on the seventh chord in order to be ready to judge the incoming target chord.

Neural net simulation. The input into the simulation was defined by the three triadic tones of each chord of the sequences, irrespective of their pitch height. Such an input is a simplification of the musical sequences because it captures neither the voicing of the chord nor the nontriadic tones (such as the seventh). Simulations were conducted with the first seven chords of each sequence. Given that chords had the same duration and were played without interoffset–interonset silence, the time that elapsed since the last offset (t) was identical for each chord (see program in the Appendix). The weights of the connections were identical to those of Bharucha's (1987) study: .244 for links between major chords and keys, .22 for links between minor chords and keys, and .0122 for links between tones and chords. The rate at which activation decayed (d) was .04, as in the study by Bharucha (1987).

Table 1
Interonset Intervals (in Milliseconds) Averaged Over the Four Chord Sequences Observed in Both Contexts From Chord 1 to Chord 7 in Experiment 1

	Musicians		Nonmusicians	
Chord	Expected	Unexpected	Expected	Unexpected
1	463.80	453.01	597.40	593.43
2	475.19	473.93	606.18	608.64
3	476.82	474.77	616.92	612.38
4	481.93	477.08	614.96	618.24
5	478.36	478.30	612.00	619.04
6	489.06	489.67	626.19	629.30
7	500.39	546.19	679.26	700.21

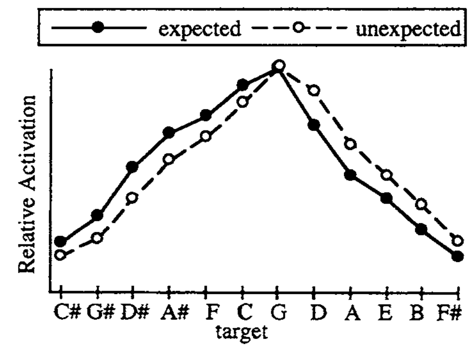

Figure 3. Relative activations observed for major chord units once the network has reached equilibrium on the penultimate chord in the expected and unexpected contexts (Experiment 1). For convenience, the state of the network is represented with reference to the C-major key. In this key, the C chord unit represents the target.

Figure 3 shows the state of the network (averaged over the sequences) observed for the major chord units in the expected and unexpected contexts. For convenience, the relative activations are represented with reference to the C-major key. For both contexts, the G-major chord unit (i.e., the most recent chord) received the strongest activation. The effect of global context is expressed for all the other chord units. In the expected condition, the target chord was systematically the second most activated unit. It was always the third most activated unit in the unexpected condition. In other words, the C-major chord unit received stronger activation in the expected condition than in the unexpected condition. A Student t test performed on the four pieces with the relative activation of the C chord unit as the dependent variable indicated that this difference in activation was statistically significant, $t(3) = 11.44$, $p < .005$.

Discussion

In Experiment 1 we replicated Bigand and Pineau's (1997) findings using a different experimental procedure. Both studies indicated that different harmonic contexts affected the processing of the last chord of musical sequences even when the immediate local contexts were held constant. This result demonstrates that harmonic expectancies not only occur sequentially from chord to chord but also depend on the harmonic function of the chord in the extended temporal context. The current experiment provides new evidence that the facilitation effects observed on the target chord in the expected condition are unlikely to be caused by the greater fluency of the chord sequences in this condition. IOI profiles remained at the same level in both contexts, thus confirming that the chord sequences in the unexpected condition were not incoherent or more surprising than the others. A spreading activation model accounts well for such a global context effect. The present simulation indicates that target chords were more strongly activated in the expected context than in the unexpected one. These findings demonstrate that Bharucha's (1987) model manages to capture subtle change in the global harmonic structures of the sequences.

Experiment 2

Our purpose in Experiment 2 was to further investigate the effect of global context by manipulating the length of the prime. Longer musical contexts are more likely to create nonambiguous musical structures than are short musical contexts. The difference in the function of the target chord, then, should be weak or nil with short primes and should increase with longer ones. Therefore, manipulating the length of the prime makes it possible to evaluate the critical amount of information necessary to provoke the priming effect. If the context effect were to be replicated with a very short context (i.e., one chord), other theoretical explanations of this "global" context effect might be put forward to challenge the cognitive interpretation (see Bharucha & Stoeckig, 1987, and Bigand & Pineau, 1997, for a discussion). Manipulating the length of the prime also makes it possible to further investigate the spreading activation account of global context effects. According to Bharucha (1987), one chord suffices for the model to generate precise harmonic expectancy. However, the way in which the state of the network would change as a function of the length of the prime is unknown.

Method

Participants. Thirty-six subjects participated in this experiment. Twenty-one were students in psychology with no formal musical training who did not play musical instruments (nonmusicians). Sixteen were graduate students in the music department of the University of Dijon (musicians). None had taken part in Experiment 1.

Material. The chord sequences from Experiment 1 were used again. They were subdivided into fragments containing the last two chords, the last three chords, the last five chords, and all eight chords. Dissonant target chords were defined as described in Experiment 1.

Apparatus. All stimuli were played with sampled piano sounds produced by the EMT10 Yamaha Sound Expander. Velocity was constant for all pitches. The fragments were played with the same tempo as used by Bigand and Pineau (1997) in order to replicate their findings in at least one experimental condition. The experiment was run on PsyScope software (Cohen et al., 1993).

Procedure. The experimental procedure was split into two phases. The first phase was identical to that described in Experiment 1. During the second phase, participants were asked to perform a quick consonant–dissonant judgment for the chord ending the fragment. Two orders of presentation were used. Half of the participants started the experiment by listening to the two-chord fragments, then continued the experiment with fragments of increasing length (i.e., three-chord and then five-chord fragments), and finished the experiment with the eight-chord sequences. The other half of the participants started by listening to the eight-chord sequences, then continued the experiment with fragments of decreasing length, and finished with two-chord fragments. The participants were always informed of the length of the fragments. Consequently, they always knew when the target chord was to appear.

Design. Crossing the manipulations of harmonic context (two levels), length of the fragments (four levels), consonance (two levels), and the four chord sequences produced a total of 64 experimental patterns to be tested with each group of listeners. The two orders of presentation of the fragments were counterbalanced between the participants.

Results

The percentages of correct responses averaged across the four chorales are presented in Figure 4 (top panel). Large numbers of correct responses were observed for expected target chords and for musicians. Both effects were significant: $F(1, 34) = 9.58$, $p < .01$, $MSE = 0.247$; $F(1, 34) = 10.31$, $p < .01$, $MSE = 4.582$. There was no other significant effect. Averaged response times for correct consonant–dissonant judgments are presented in Figure 4 (bottom panel). Response times for correct responses were shorter for expected tonic chords, $F(1, 34) = 29.24$, $p < .001$, $MSE = 46{,}985$; were shorter for dissonant than for consonant chords, $F(1, 34) = 10.47$, $p < .005$, $MSE = 149{,}540$; and varied with the size of the fragments, $F(3, 102) = 11.37$, $p < .001$, $MSE = 219{,}395$. Contrast analysis revealed a significant quadratic trend, $F(1, 34) = 22.57$, $p < .001$,

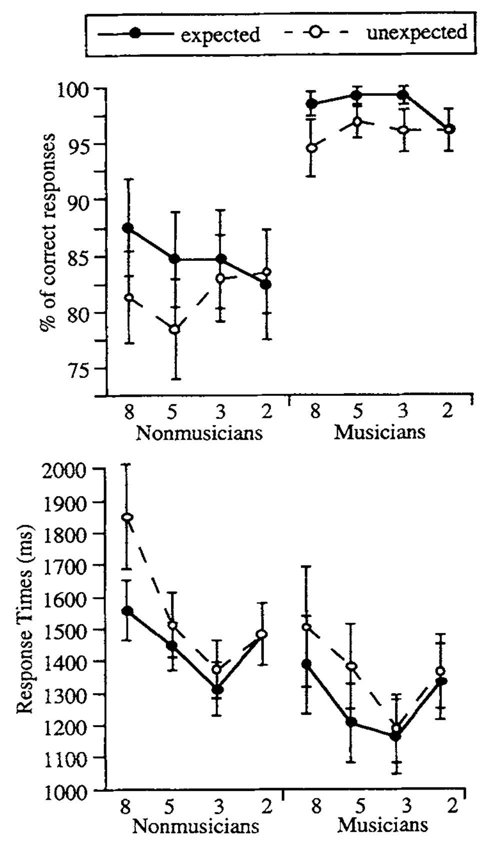

Figure 4. Percentage of correct responses (top) and correct response times (bottom) averaged across type of target (consonant vs. dissonant) and chord sequence set observed for expected and unexpected targets as a function of the length of the prime in Experiment 2.

MSE = 194,735. A linear decrease in response time was observed between the eight-chord fragments and the three-chord fragments, $F(1, 34) = 23.11$, $p <$ 001, *MSE* = 319,589. However, response times increased significantly from the three-chord fragments to the two-chord fragments, $F(1, 34) = 16.96$, $p < .001$, *MSE* = 106,622. As expected, the effect of the harmonic context was more pronounced for longer fragments, $F(3, 102) = 3.48$, $p < .02$, *MSE* = 75,405. Contrast analyses indicated that the difference in harmonic context decreased linearly with the size of the fragments, $F(1, 34) = 7.50$, $p < .01$, *MSE* = 100,851. Indeed, the effect of harmony failed to reach a significant level with three-chord fragments, $F(1, 34) = 2.13$, $p = .15$, *MSE* = 33,504, but was significant for five-chord fragments, $F(1, 34) = 9.66$, $p < .005$, *MSE* = 56,198, and for eight-chord fragments, $F(1, 34) = 12.86$, $p < .001$, *MSE* = 119,576. The Harmonic Context × Length of the Fragments interaction tended to differ in musicians and nonmusicians. However, the three-way interaction did not reach significance, $F(3, 102) = 1.78$, $p = .15$, *MSE* = 75,405. In addition, the Harmonic Context × Consonance interaction was marginally significant, $F(1, 34) = 3.46$, $p = .07$, *MSE* = 52,992. As already observed in Experiment 1, response times were faster for dissonant chords than consonant ones, and this difference was greater in the unexpected condition (see Table 2).

Simulations were conducted as described in Experiment 1. There were two input vectors for the three-chord condition (corresponding to the sixth and seventh chords), four input vectors for the five-chord condition, and seven input vectors for the eight-chord condition (see Experiment 1). The relative activation for the target chord was averaged over the sequences. Figure 5 presents the difference in relative activation as a function of the context (expected vs. unexpected) and the length of the prime. Target chord units were more activated in the expected context, and the amount of relative activation linearly decreased with the length of the prime. However, the model did not simulate an interactive effect: The effect of context was immediately present in the three-chord condition and did not increase with the length of the prime. An analysis of variance (ANOVA) performed with sequence as a random factor and relative activation as the dependent measure indicated significant effects of global context, $F(1, 3) = 13.79$, $p < .0016$, *MSE* = .0001, and of the length of the prime, $F(2, 6) = 31.33$, $p < .001$, *MSE* = 0.000056, but no significant interaction. In addition, as already reported in Experiment 1, the target chord was never the most activated chord unit whatever the context or the length of the prime. The most activated unit always corresponded to the most recent chord.

Table 2
Averaged Response Times (in Milliseconds) Observed in Experiment 2 for Consonant and Dissonant Targets in the Expected and Unexpected Conditions

Target chord	Musicians		Nonmusicians	
	Expected	Unexpected	Expected	Unexpected
Consonant	1,309	1,467	1,479	1,584
Dissonant	1,234	1,252	1,419	1,523

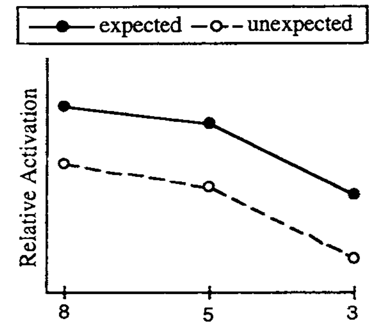

Figure 5. Relative activations spreading to the target chord unit in the expected and unexpected conditions as a function of the length of the prime (Experiment 2). Relative activations were registered after the network had reached equilibrium on the chord immediately preceding the target.

Discussion

In Experiment 2 we replicated the effect of harmonic context reported in Experiment 1 using fragments of different length. Consonant–dissonant judgments were more accurate and faster when the target chord was expected. The critical finding is that this context effect diminished and finally disappeared as the length of the prime decreased. This result suggests that the processing of the target chord depends on all of the information accumulated from the beginning of the context. This finding raises a first problem for Bharucha's (1987) model. Activations following exposure to chords are effectively accumulated in the network from the beginning of the sequence. This information helped to increase the relative stability of the target chord in both contexts. However, it did not enhance the contrast between the contexts: A difference of one chord differentiated the contexts just as effectively as did a contextual difference of six chords. In contrast, human participants obviously reacted to this increasing difference in context. This discrepancy suggests that harmonic expectancy might develop over time with a varying dynamism in humans. Further simulations were performed with different values for the decay parameter (d). They did not eliminate this discrepancy. At best (i.e., for $d = .02$), the neural net managed to simulate a consistent interactive effect of context and the length of the prime, but only for the eight-chord and five-chord conditions.

The manipulation of larger temporal contexts should therefore make it possible to investigate further a spreading activation account of global context effects. According to several theoretical accounts of musical expectancy, a temporary modulation (i.e., a temporary change in musical key) creates a deep musical tension in listeners that needs to be resolved by a return to the main key (Lerdahl & Jackendoff, 1983). As stated by L. B. Meyer (1956), "a feeling of harmonic completeness arises when the music returns to the harmonic bases from which it began" (p. 150). This return is strongly expected because it represents the harmonic closure of the overall piece. Bharucha's (1987) model is likely to predict the opposite. As soon as a musical discourse enters a new key, the activations resulting from the chords of this new key predominate over those caused by the previous key. Because the previous activations exponentially decrease over time, the model might predict that the musical sequence should continue in the current key. It is noteworthy that this prediction fits well with certain empirical findings showing that listeners are much less sensitive to large-scale structure than is generally claimed in music theory (Cook, 1987).

Experiment 3

Our primary aim in Experiment 3 was to test these predictions by manipulating the effect of context at three hierarchical levels of musical structure. Examples of the chord sequences used are presented in Figure 6. As in the previous experiments, we manipulated the global harmonic context while holding the chord prior to the target constant. All the sequences contained two sections delineated by a *firmata* (i.e., an increase in duration on the seventh chord). In the highly expected condition, both sections were in the same key, and the target chord was part of an authentic cadence (V–I) that closed the overall structure. In the unexpected condition, both sections were in the dominant key, and the target chord was a fourth harmonic degree following an authentic cadence (I–IV). These two conditions replicated those of the previous experiments. In the middle-expected condition, the first section was in the main key, and the second was in the dominant key. The first section was harmonically identical to that of the highly expected condition, and the second section was identical to that of the unexpected condition. Although the chords of the second section were strictly identical, the target chord in the middle-expected condition was no longer a fourth harmonic degree following an authentic cadence. In this context, it could be analyzed as part of an authentic cadence (V–I) that returned to the main key. According to some theoretical accounts of musical expectations (Lerdahl & Jackendoff, 1983; L. B. Meyer, 1956), processing of the target chord should be facilitated in this middle-expected condition compared with the unexpected condition. Similarly, no major difference should be observed between the middle-expected and highly expected conditions. In contrast, a spreading activation model predicts that processing of the target chord will be facilitated in the highly expected condition and that no main difference will be observed between the middle-expected and unexpected conditions.

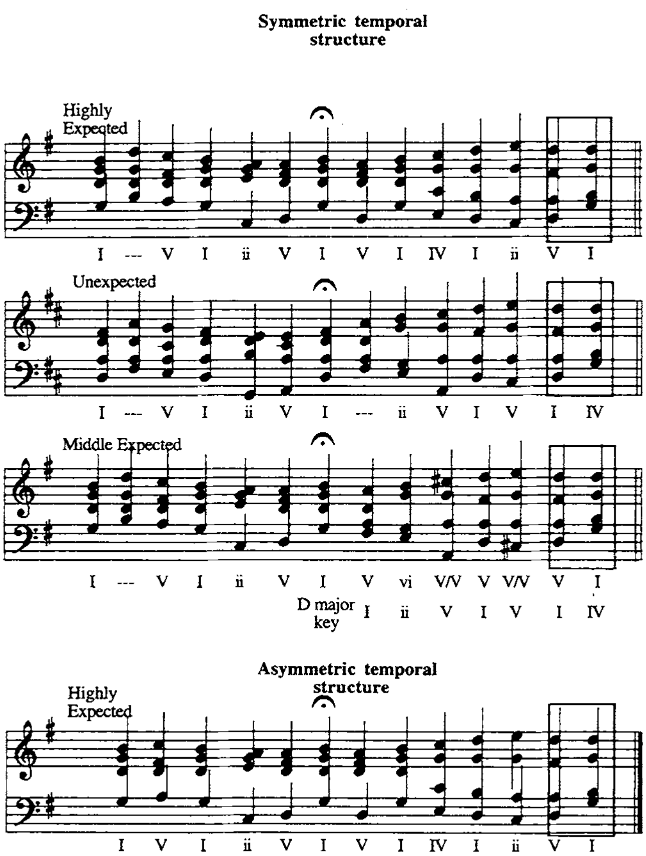

Figure 6. Examples of the chord sequences used in the highly expected, unexpected, and middle-expected conditions (top) and in the asymmetric temporal condition (bottom) of Experiment 3.

Our second aim in Experiment 3 was to cross the manipulation of the global harmonic context with a change in the temporal structure of the sequence. According to Jones and Boltz (1989), temporal organization displays rhythmic accents that dynamically orient listeners' attention. Changing the temporal organization of the sequence can then be sufficient to modify the mental representation of the musical structure (Bigand, 1997; Bigand & Pineau, 1996).

In Experiment 3, the temporal organization of the chord sequence was varied slightly. In the first temporal condition (referred to as the *symmetric structure*), the firmata was on the seventh chord. In the second temporal condition (referred to as the *asymmetric structure*), one chord was removed in the first section of the chorale and the firmata was on the sixth chord. In all cases, the second section contained seven chords (see the bottom of Figure 6). According to Jones (1987), the former temporal context would draw attention to the 14th chord whereas the second temporal context would draw attention to the 13th chord (see Jones & Boltz, 1989). Accordingly, processing of the target chord would be facilitated more by the first temporal organization than by the second. In addition, Jones (1987) argued that pitch and temporal structures are processed integrally, so that the expectation about the *what* of the incoming events interacts with the expectation about the *when* of these events. Various empirical findings support this assumption (Boltz, 1989a, 1989b; Schmuckler & Boltz, 1994), and we assumed that processing of the target chord in the unexpected condition would be affected most significantly in the asymmetric condition.

Method

Participants. Forty subjects participated in the experiment. A group of 20 students from the University of Dijon who had never learned a musical instrument nor received formal musical training formed the group of nonmusicians. Twenty students and professors from the Conservatory of Troyes formed the group of musicians. They all practiced music as a professional activity, had received a high level of formal musical training, and played musical instruments.

Material. Thirty-six chord sequences in the style of J. S. Bach chorales were used (see Figure 6). They were created in order to ensure that strict constraints were observed. All sequences contained two sections delineated by a firmata. In the highly expected condition, both sections were in the same key and the target chord was part of a full cadence (V–I). In the unexpected condition, both sections were in the dominant key and the target chord was a fourth harmonic degree (I–IV). Both types of sequence shared similar melodic contours in the higher and lower voices (i.e., soprano and bass). Certain tones were changed in such a way that the sequences of the unexpected condition were in the dominant key. These two conditions replicated those of the previous experiments. In the middle-expected condition, the first section was identical to that of the highly expected condition and the second section was harmonically identical to that of the unexpected condition.

In order to manipulate the position of the firmata, we removed one ornamental chord of the first section. In all the sequences, the removed chord was located at the beginning of the sequence. Nothing else was changed in the second temporal condition. As in the previous experiments, the last two chords were physically identical in all 36 chord sequences. Because the findings of Experiments 1 and 2 revealed high percentages of correct responses for musicians and nonmusicians, the dissonance of the target chords was reduced in Experiment 3. An augmented octave was added in the target chord, and its MIDI velocity was one third of that of the other tones. The velocity of the octave in the consonant target was correspondingly increased to ensure that both the consonant and dissonant targets shared the same overall intensity.

Apparatus. All stimuli were played with sampled piano sounds produced by the EMT10 Yamaha Sound Expander. Velocity was constant for all pitches with the exception of the target chord (see above). The fragments were played at a tempo of 80 quarter notes per minute. The firmata was created by slowing down the tempo to 55 quarter notes per minute on either the seventh or the sixth chord of the sequences. The sound stimuli were recorded using SoundEdit-Pro software at CD quality (16 bits and 44 kHz), and the experiment was run on PsyScope software.

Procedure. The experimental procedure was split into two phases. The first phase was the same as in Experiment 1 except that participants were trained in making consonant–dissonant judgments with 36 chords played in isolation. During the second phase, participants were asked to perform a speeded reaction time judgment for the chord ending the fragment. They were informed that the sequence contained a firmata placed roughly in the middle and that the target chord for judgment would occur seven chords after the firmata.

Design. Crossing the manipulations of harmonic context (three levels), consonance (two levels), temporal organization (two levels), and the six chord sequences yielded a total of 72 experimental sequences to be tested within each group of listeners. These sequences were played in a different random order for each participant.

Results

The percentages of correct responses are presented in Figure 7. There was no main effect of the harmonic context, but the Harmonic Context × Consonance interaction was significant, $F(2, 76) = 6.93, p < .002, MSE = 0.9219$. With

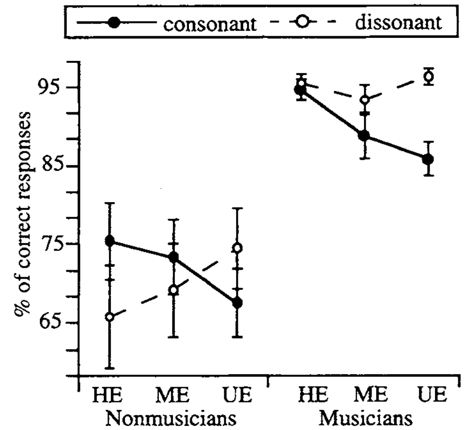

Figure 7. Percentage of correct responses averaged across temporal conditions and chord sequence set (Experiment 3). HE = highly expected condition; ME = middle-expected condition; UE = unexpected condition.

consonant target chords, the percentage of correct responses linearly decreased from the highly expected condition to the unexpected condition, $F(1, 38) = 12.07, p < .005, MSE = 0.82829$. A reversed linear trend was observed with dissonant target chords, $F(1, 38) = 4.99, p < .05, MSE = 0.6628$. This interaction replicated the crossed interaction reported by Bharucha and Stoeckig (1987). Participants exhibited a bias toward judging targets to be out of tune when unexpected and in tune when expected. Planned comparisons indicated that this crossed interaction was significant when the highly expected and unexpected conditions were compared, $F(1, 38) = 13.83, p < .001, MSE = 0.8965$, and when the unexpected and middle-expected conditions were compared, $F(1, 38) = 6.52, p < .02, MSE = 0.8050$. In addition, musicians produced a higher level of correct responses than did nonmusicians, $F(1, 38) = 23.33, p < .001, MSE = 8.4710$, but there was no other significant effect.

Averaged response times for correct consonant–dissonant judgments are presented in Figure 8. Response times for correct responses varied as a function of the global context, $F(2, 76) = 15.95, p < .001, MSE = 18.117$. Most of this effect was explained by a linear trend, $F(1, 38) = 30.19, MSE = 19{,}109$; correct response times grew progressively longer from the highly expected condition to the unexpected condition. Planned comparisons revealed that response times were 44 ms shorter in the highly expected condition than in the middle-expected condition, $F(1, 38) = 8.49, p < .001, MSE = 19{,}353$. Response times were 39 ms shorter on average in the middle-expected condition than in the unexpected condition, $F(1, 38) = 7.89, p < .01, MSE = 15{,}890$.

The effect of the harmonic context depended on the temporal organization, $F(2, 76) = 2.98, p = .056, MSE = 7{,}907$. The effect of temporal organization was more pronounced in the unexpected condition than in the two expected conditions, $F(1, 38) = 6.76, p < .02, MSE = 6{,}319$. As we assumed, response times increased considerably in the unexpected condition when the second temporal organization was used. This interactive effect was more

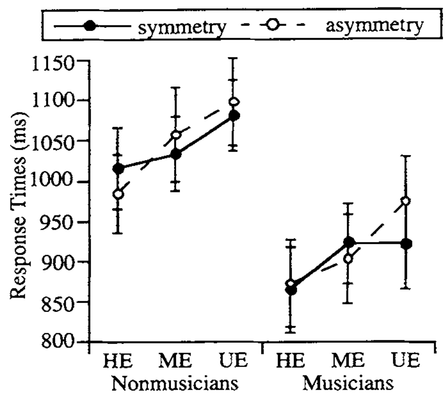

Figure 8. Correct response times averaged across type of target (consonant vs. dissonant) and chord sequence set (in Experiment 3). HE = highly expected condition; ME = middle-expected condition; UE = unexpected condition.

pronounced in musicians, as a marginally significant three-way interaction demonstrates, $F(2, 76) = 2.84$, $p = .064$, $MSE = 7{,}907$. Further analysis revealed that the Harmonic Context × Temporal Organization interaction was significant in musicians, $F(2, 38) = 3.69$, $p < .04$, $MSE = 7{,}153$, but failed to reach a significant level in nonmusicians, $F(2, 38) = 2.26$, $p = .12$, $MSE = 8{,}363$. In musicians, the second temporal organization caused response times to increase by 52 ms on average in the unexpected condition, although it did not affect response times in the other conditions. In addition, response times were shorter for musicians, $F(1, 38) = 3.76$, $p = .060$, $MSE = 593{,}219$, and the effect of the harmonic context also tended to vary as a function of both the temporal organization and the consonance of the chord, $F(2, 76) = 3.00$, $p = .055$, $MSE = 13{,}053$.

Simulations were conducted for each sequence by entering either the first 13 chords (symmetric condition) or the first 12 chords (asymmetric condition) as the input vectors. Simulations were performed with the increase in duration caused by the firmata either taken into account or ignored. The state of the network observed on the penultimate chord was unaffected by this change in duration. Figure 9 (left side) shows the relative activations (averaged over the sequences) observed on the penultimate chord for each experimental condition.

As already reported in Experiments 1 and 2, the target chord never received the strongest activation, but its relative activation was stronger in the highly expected context than in the unexpected one. The simulation revealed four critical findings: (a) The target chord was less activated in the unexpected condition than in the middle-expected condition. (b) The target chord was less activated in the middle-expected condition than in the highly expected condition. (c) The difference between the middle-expected and unexpected conditions was between 5 and 6 times smaller than the difference between either of these conditions and the highly expected condition. (d) The temporal structure of the sequence (symmetric vs. asymmetric) did not alter the state of the network. An ANOVA performed with sequence as a random factor and relative activation as the dependant variable confirmed the significant effect of the global context, $F(2, 10) = 6.26$, $p < .02$, $MSE = 0.0002$. There was no other significant effect. Simulations were also performed with a smaller decay value ($d = .2$). The outcome was similar with one important exception: With this smaller decay (see Figure 9, right side), the activations sent to the target chord linearly decreased as a function of the harmonic context in the same proportion as was observed for the human participants.

Discussion

In Experiment 3 we replicated the facilitation effects reported in Experiments 1 and 2 using a set of new longer chord sequences. Consonant–dissonant judgments were more accurate and faster when the target chords were harmonically closely related to the previous context. This experiment also went one step further in showing that the facilitation effect differed between the unexpected and middle-expected conditions. In the former condition, the target chord was a subdominant chord occurring after an authentic cadence. What caused the change in function of the target chord in the latter condition was the presence of a first section. This section established an initial key in which the target chord acted as a tonic chord. Consequently, the target chord in the middle-expected condition can be analyzed as a tonic chord forming an authentic cadence that closes the overall sequence. The fact that the priming effects differed between the unexpected and middle-expected conditions demonstrates that the effect of the context established at an intermediate level of the musical structure also depends on the larger musical context in which it occurs. This indicates that musical expectations can derive from a high level in the hierarchical structure, an observation that supports L. B. Meyer's (1956, 1973) and Lerdahl and Jackendoff's (1983) theories.

Experiment 3 also demonstrates that harmonic expectancy is not entirely determined by the higher level of the musical structure. The difference observed between the

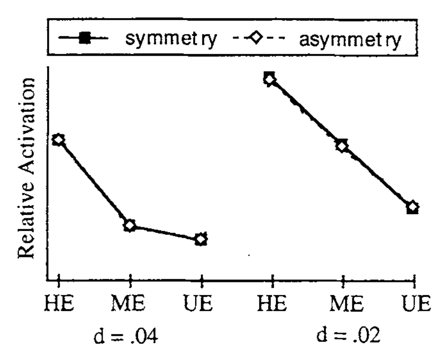

Figure 9. Relative activations spreading to the target chord unit in the highly expected (HE), middle-expected (ME), and unexpected (UE) conditions as a function of the temporal structure (symmetric vs. asymmetric) in Experiment 3. Relative activations were registered after the network had reached equilibrium on the penultimate chord of the sequences for a decay (d) of .04 (left) and .02 (right).

middle-expected and highly expected conditions reveals that harmonic expectancy also depends on an intermediate level of structure situated between the structure immediately surrounding the target and the higher level of the sequence. Indeed, chord sequences in the middle-expected and highly expected conditions differed only between Chords 8 through 13 (Chords 7 through 12 in the asymmetric condition). This small difference was sufficient to significantly affect the processing of the target chord.

Experiment 3 provides some evidence that musical expectations derive from various levels of the hierarchical structure. It is interesting that the strongest facilitation was observed when the target chord was expected at both high and intermediate levels. Facilitation was reduced when it was expected at the higher level only. The weakest priming effect was observed when the target chord was not strongly expected at either high or intermediate levels. In other words, the strength of the priming effects is a function of the number of levels at which the target chord is expected. This suggests that the processing of the target chord is governed by some additive combination of the expectancies generated at various levels of the hierarchic structure. To some extent, the present findings support the idea that the effects of both local and global structures are combined when participants listen to musical pieces (Bigand & Lerdahl, 1992; Krumhansl, 1996; Lerdahl, 1996).

The third main finding of Experiment 3 is that priming effects also depend on the temporal organization of the prime. No main effect associated with this factor was found in this experiment, but temporal organization interacted with the effect of the harmonic structure. The processing of the target chord took longer when the target was both harmonically and rhythmically unexpected. The present finding is congruent with Jones's (1987) theory of dynamic attending. Perceiving a musical sequence is a dynamic context-specific activity that is not guided simply by the activation of abstract knowledge of tonal hierarchy. Jones and Boltz (1989) argued that the temporal and pitch relationships within a piece are inextricably entwined at both a structural and a behavioral level. Musical expectancies inferred from a given piece are dynamically influenced by the unfolding temporal structure, with the result that variations in its temporal structure are able to modulate tonal-harmonic expectancy formation (for similar conclusions, see Bigand, 1997; Boltz, 1989a, 1989b; Schmuckler & Boltz, 1994). In addition, the fact that this interaction between pitch and temporal structures was observed primarily in musicians confirms the results obtained by Bigand (1993).

The last critical finding of Experiment 3 concerns the neural net simulations of these global harmonic and temporal context effects. The fact that activations sent to the target chord differed between the middle-expected and unexpected conditions establishes that harmonic expectancy created by a previous key context remains active in the network until the end of the sequence. The neural net keeps some trace of the first key until the end of the sequence, because activations present at the beginning of the sequence are added to those created by the new key. Moreover, when both keys are harmonically related (which was the case in the present study), the units activated by the first key continue to be activated by the second one: This leads to the retention of the initial activations over a relatively long time span. Bharucha's (1987) model thus accounts for subtle effects of large-scale structures in music. In addition, the fact that the simulations performed with a smaller decay (d = .02) than the one used by Bharucha (1987; d = .04) provided a better fit to the data suggests that the initial model overestimated the strength of the decay.

Finally, the only finding that Bharucha's (1987) model failed to simulate is the interactive effect of the temporal and harmonic structures of the sequences. Varying the decay value does not solve this problem. Simulating such an interaction will probably require the model to incorporate a subprogram tracking the rhythmic structure of the sequence. This will imply a more drastic change in the overall architecture of the neural net. It should be emphasized, however, that this discrepancy primarily relates to the musicians' data. The simulations provide a good match with the nonmusicians' data.

General Discussion

In the present study we continued the research into global context effects reported by Bigand and Pineau (1997). In all three experiments, target chords were more accurately and quickly processed when they were harmonically related to the previous context even though the immediate local context remained identical. According to Bharucha (1987, 1994), such a facilitation may be viewed as a robust demonstration of the anticipatory processing that underlies musical expectancies. The present findings therefore confirm that harmonic expectancies not only occur sequentially from chord to chord but also depend on the harmonic function of the chord in the extended temporal context.

Compared with Bigand and Pineau's (1997) study, the present research provides new evidence that the expectations created by an initial context may vary as a function of the larger context in which it is embedded. In cognitive theories of music, the importance of higher level structures has been underlined by L. B. Meyer (1956, 1973) as well as by Lerdahl and Jackendoff (1983). However, a number of studies have already questioned the importance of large-scale structures in music perception (Cook, 1987; Karno & Konecni, 1992; Tillmann & Bigand, 1996), and more recent research has focused primarily on the role played by local structures (Cuddy & Lunney, 1995; Narmour, 1989, 1990; Schellenberg, 1995). Experiment 3 demonstrates that harmonic expectancies also depend on an extended hierarchical temporal structure. The fact that this result was observed with an experimental task that forced participants to focus on information of an extremely local nature further emphasizes the impact of global harmonic structures on expectancy formation. In addition, Experiment 3 provides new evidence that priming effects occur at a cognitive level of representation and not at a peripheral level (see Bharucha & Stoeckig, 1987; Bigand & Pineau, 1997). In the unexpected and middle-expected conditions, the six chords prior to the target were identical. If sensory priming predominates over harmonic priming, no context effect should have been observed in these conditions. The present data clearly contradict this assumption.

Our final aim in the present study was to further investigate spreading activation accounts of global context effects. In Bharucha's (1987) neural net model, the locus of the facilitation effect is inside a long-term representation of Western harmonic relationships. Priming effects result from activation spreading via a stable cognitive structure that links related chords. Bigand and Pineau (1997) argued that such a model will encounter difficulties in accounting for global context effects because it confers too much importance on the most recent event. The present simulations do not support this claim. In all three experiments, the target chord received stronger relative activation in the expected condition than in the unexpected one, which suggests that global context effects result primarily from activations accumulated in the system when the target chord occurs. This finding provides evidence that Bharucha's model captures some dynamic characteristics of musical expectancies. The simulations conducted in Experiment 3 went one step further by showing that the model also accounts for expectancy derived at high and intermediate levels of musical structure: Stronger activations were observed when the target chord was expected at both high and intermediate levels. Lesser activations were observed when it was expected at the higher level only. The lowest activations were registered when the target chord was expected neither at the high level nor at the intermediate level. In other words, simulations derived from the model indicate that the strength of priming depends on the additive combination of expectancies generated at various levels of the hierarchical structure.

Only a few discrepancies between participants' performances and the simulations produced by the model were revealed by the present study. In Experiment 2, the model failed to predict the interaction between the length of the prime and the global context. In Experiment 3, the model failed to simulate the interactive effect of temporal and harmonic structures. Both discrepancies suggest that the incorporation of the temporal organization in the neural net remains a key consideration (Schmuckler & Boltz, 1994) that should be further addressed (Tillmann, Bigand, & Pineau, in press).

Conclusion

The processing of incoming events (words in language and chords in music) depends on the relationship of those events to the previous context. In language, several kinds of models have been proposed to account for global context effects on word processing (Hess et al., 1995). For intralexical activation models the source of the context effect is based on a fast-acting and automatic activation that spreads within the mental lexicon via the long-term connections between semantically related items. For discourse-based models, the locus of context effects is above the word level: Facilitation occurs for target words that are easily integrated into the ongoing discourse representation. For other models, activation of the lexical units occurs at a first stage and is followed by progressive integrative processes (Kintsch, 1988; Till et al., 1988).

In a similar way, the effect of global harmonic context in music may potentially be understood in the light of two theoretical frameworks. Effects of global context might result from activations spreading through a schematic knowledge set (as in Bharucha's, 1987, model) or from the ease with which participants integrate musical events into the overall structure of the piece (as in the model of Lerdahl & Jackendoff, 1983). The former model focuses on *tonal hierarchies* (i.e., a nontemporal schema of Western tonal hierarchies stored in long-term memory); the latter, on an *event hierarchy* (i.e., a hierarchy of specific pitch-time events inferred from the ongoing temporal sequence of musical events). An event hierarchy implies the activation of a tonal hierarchy plus the integration of the events in their specific temporal context (see Lerdahl & Jackendoff, 1983, for an extensive account). The present study reveals that global context effects on chord processing may result from the activation of tonal hierarchies alone. This means that it may not be imperative to consider a secondary integrative stage of processing.

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Appendix

Matlab (1997) Implementation of Bharucha's (1987) Model

```
% tones (t): A Ais B C Cis D Dis E F Fis G Gis
% chords (ch): Fis Cis Gis Dis Ais F C G D A E B dis ais f c g d a e b fis cis gis
% keys (k): Fis Cis Gis Dis Ais F C G D A E B
% number of tones, chords, keys
ntones=12;nchords=24;nkeys=12;
% W=links from tones to chords; Z=links from chords to keys
W=[0 0 0 0 0 1 0 0 1 1 0 0 0 0 0 0 0 1 1 0 0 1 0 0;1 0 0 1 1 0 0 0 0 0 0 0 1 1 0 0 1 0 0
0 0 0 0 0;0 0 0 0 0 0 0 1 0 0 1 1 0 0 0 0 0 0 0 1 1 0 0 1;0 0 1 0 0 1 1 0 0 0 0 0 0 0 1 1 0
0 1 0 0 0 0 0;1 1 0 0 0 0 0 0 0 1 0 0 0 1 0 0 0 0 0 0 0 1 1 0;0 0 0 0 1 0 0 1 1 0 0 0 0 0 0
0 1 1 0 0 1 0 0 0;0 0 1 1 0 0 0 0 0 0 0 1 1 0 0 1 0 0 0 0 0 0 0 1;0 0 0 0 0 0 1 0 0 1 1 0 0
0 0 0 0 0 1 1 0 0 1 0;0 1 0 0 1 1 0 0 0 0 0 0 0 1 1 0 0 1 0 0 0 0 0 0 ;10 0 0 0 0 0 0 1 0 0
1 1 0 0 0 0 0 0 0 1 1 0 0;0 0 0 1 0 0 1 1 0 0 0 0 0 0 0 1 1 0 0 1 0 0 0 0;0 1 1 0 0 0 0 0 0
0 1 0 0 0 1 0 0 0 0 0 0 0 1 1];
Z=[1 1 0 0 0 0 0 0 0 0 0 1;1 1 1 0 0 0 0 0 0 0 0 0;0 1 1 1 0 0 0 0 0 0 0 0;0 0 1 1 1 0 0 0
0 0 0 0;0 0 0 1 1 1 0 0 0 0 0 0;0 0 0 0 1 1 1 0 0 0 0 0;0 0 0 0 0 1 1 1 0 0 0 0;0 0 0 0 0 0
1 1 1 0 0 0;0 0 0 0 0 0 0 1 1 1 0 0;0 0 0 0 0 0 0 0 1 1 1 0;0 0 0 0 0 0 0 0 0 1 1 1;1 0 0 0
0 0 0 0 0 0 1 1;1 1 0 0 0 0 0 0 0 0 0 1;1 1 1 0 0 0 0 0 0 0 0 0;0 1 1 1 0 0 0 0 0 0 0 0;0 0
1 1 1 0 0 0 0 0 0 0;0 0 0 1 1 1 0 0 0 0 0 0;0 0 0 0 1 1 1 0 0 0 0 0;0 0 0 0 0 1 1 1 0 0 0
0;0 0 0 0 0 0 1 1 1 0 0 0;0 0 0 0 0 0 0 1 1 1 0 0;0 0 0 0 0 0 0 0 1 1 1 0;0 0 0 0 0 0 0 0 0
1 1 1;1 0 0 0 0 0 0 0 0 0 1 1];
%weights: w1 = tones to chords; w2 = major chords to keys; w3 = minor chords to keys
w1=.0122;w2=.244;w3=.22;
W=W*w1;
Z(1:(nchords/2),:)=Z(1:(nchords/2),:)*w2;
Z((nchords/2+1):nchords,:)=Z((nchords/2+1):nchords,:)*w3;
% initialisation (t=tones, ch=chords, k=keys)
t_p=zeros (1, ntones);ch_p=zeros (1, nchords);k_p=zeros (1, nkeys);
t=zeros (1, ntones);ch=zeros (1, nchords);k=zeros (1, nkeys);
delta_t=zeros (1, ntones);delta_ch=zeros (1, nchords);delta_k=zeros (1, nkeys);
% input pattern (mat_activ) : example of a Cmajor chord
mat_activ=[0 0 0 1 0 0 0 1 0 0 1 0];
[nc, nn]=size(mat_activ);
% time unit ti; decay.
ti=1;decay=0.4;
counter=0;hdelta=1;
for kk=1:nc;
        t=t_p+mat_activ(kk,:);
        while any ([delta_t'; delta_ch'; delta_k'; hdelta]>.005)
                counter=counter+1;hdelta=0;
                %compute the phasic activation
                delta_t=abs(t - t_p);delta_ch=abs(ch - ch_p);delta_k=abs(k - k_p);
                %actual activation becomes previous one
                t_p=t;ch_p=ch;k_p=k;
                %compute activation
                t=t_p+delta_ch*W';
                ch=ch_p+delta_t*W+delta_k*Z';
                k=k_p+delta_ch*Z;
        end
        hdelta=1;
        t_p=t_p*((1-decay)^ti);
        ch_p=ch_p*((1-decay)^ti);k_p=k_p*((1-decay)^ti);
        ch=ch*((1-decay)^ti);k=k*((1-decay)^ti);
end
```

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