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Repetition priming: Is music special?

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Using short and long contexts, the present study investigated musical priming effects that are based on chord repetition and harmonic relatedness. A musical target (a chord) was preceded by either an identical prime or a different but harmonically related prime. In contrast to words, pictures, and environmental sounds, chord processing was not facilitated by repetition. Experiments 1 and 2 using single-chord primes showed either no significant difference between chord repetition and harmonic relatedness or facilitated processing for harmonically related targets. Experiment 3 using longer prime contexts showed that musical priming depended more on the musical function of the target in the preceding context than on target repetition. The effect of musical function was decreased, but not qualitatively changed, by chord repetition. The outcome of this study challenges predictions of sensory approaches and supports a cognitive approach of musical priming.

The processing of an event depends on the context in which it appears. Events that are related in some way to preceding ones are processed faster and more accurately than others. This facilitation effect can be caused by several contextual factors, such as associative and semantic relations between target and context or the occurrence of the target in the previous context (repetition). The purpose of our study was to investigate whether contextual priming effects that have been reported for various environmental stimuli (i.e., words, pictures, faces, environmental sounds) rely on general mechanisms and may thus be observed also for musical stimuli.

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Priming effects: Semantic relatedness versus repetition

In the language domain, semantic priming has been extensively investigated. The processing of a target word (*nurse*) is faster and more accurate when it follows a semantically related prime word (*doctor*) than when it follows an unrelated prime word (bread, D. E. Meyer & Schvaneveldt, 1971). Semantic priming occurs in short contexts, sentences, and discourse (Fischler & Bloom, 1980; Stanovich & West, 1979). Semantic priming also occurs for nonverbal stimuli, such as familiar faces (Bruce, 1983; Bruce & Valentine, 1986), pictures of common objects (Kroll & Potter, 1984; Palmer, 1975), and environmental sounds (Ballas & Mullins, 1991). According to spreading activation accounts of language (Collins & Loftus, 1975; Posner & Snyder, 1975), the presentation of a word activates a particular unit (or node) in semantic memory, and this activation spreads to adjacent, semantically related units, thereby facilitating the processing of these related words. Differently put, the activated units prime the processing of semantically related events. Semantic priming for nonverbal stimuli has been explained within similar spreading activation models that replace word or letter units with pictorial, face, or audiogen units (Bruce & Valentine, 1986, for faces; Schacter & Church, 1992; Srinivas, 1993, for pictures; Stuart & Jones, 1995, for environmental sounds).

Repetition priming designates another influence of the preceding context on the processing of a target event. It refers to the enhancing effect of a prior presentation of an item on its subsequent processing (Dannenbring & Briand, 1982; Durgunoglu, 1988; Wilding, 1986). The repetition effect is robust and has been demonstrated in a variety of experimental paradigms, such as recognition thresholds (Barlett, 1977), perceptual identification (Jacoby, 1983; Masson & MacLeod, 1992), completion of degraded target events (Bassili, Smith, & MacLeod, 1989), lexical decision (Jacobs, Grainger, & Ferrand, 1995), and naming (Ferrand, 1996). Furthermore, it has been observed with different event types, such as written letters (Haber & Hillman, 1966), written and spoken words (Jacobs et al., 1995; Meehan & Pilotti, 1996; Van Petten & Rheinfelder, 1995), drawings and pictures of common objects (Srinivas, 1993), environmental sounds (Chiu & Schacter, 1995; Stuart & Jones, 1995), and sinusoidal sounds (Farah & Smith, 1983). For example, studying a list of randomly selected words enhances participants' subsequent ability to identify these words even when presented very briefly or in fragmentary form (Jacoby, 1983; Jacoby & Dallas, 1981; Jacoby & Witherspoon, 1982; Tulving, Schacter, & Stark, 1982). Repetition priming is observed for immediate repetition and when prime and target are separated by several days (Jacoby, 1983; Jacoby & Dallas, 1981; Scarborough, Cortese, & Scarborough, 1977; Tulving et al., 1982) and even longer time periods (Kolers, 1976).

Explanations for repetition priming have focused on presentation and stimulus conditions and have referred to the implication of a perceptual representation system that mainly operates at a presemantic level (Church & Schacter, 1994; Tulving & Schacter, 1990). Even if repetition priming occurs despite changes of superficial features (i.e., changes of font, speaker, picture form) between prime and target (Biederman & Cooper, 1991; Kinoshita & Wayland, 1993), the strength of repetition priming depends on the extent of surface similarities between prime and target: The stronger the similarities, the stronger the priming—with maximum priming for identical primes and targets (Kirsner, 1998). These findings suggest that repetition priming results from memory traces formed by the prior presentation of the event (Jacoby, 1983; Jacoby & Dallas, 1981). The memory traces facilitate perceptual identification of the same event at a subsequent presentation (Chiu & Schacter, 1995; Kirsner & Speelman, 1996; Kolers & Roediger, 1984; McClelland & Pring, 1991; Morris, Bransford, & Franks, 1977; Roediger, 1990; Stuart & Jones, 1995). However, repetition priming is reduced or eliminated when the meaning of a word is changed by the new context, and this decrease in priming is enhanced with strong contextual binding of the words at their initial presentation (Bainbridge, Lewandowsky, & Kirsner, 1993; MacLeod, 1989; Masson & Freedman, 1990; Speelman, Simpson, & Kirsner, 2002). According to Jacoby (1983), repetition priming is the most effective when the initial encoding of words occurs without contextual restraints or specific semantic identifications.

Semantic priming and repetition priming represent two types of facilitatory effect that a context may have on event processing. These two priming forms presumably tap into two different processes (i.e., semantic knowledge activation vs. implicit memory of items with their superficial features). Some studies attempt to assess the respective strength of the two priming effects and their additive or interactive nature. Dannenbring and Briand (1982) presented pairs of words that were either identical (e.g., sea–sea) or semantically related (e.g., ocean–sea), and they manipulated the number of trials between prime and target from 0 to 16. Performance in lexical decision task showed stronger facilitation in the word repetition condition than in the semantic relatedness condition, and the semantic relatedness effect vanished with increasing time between prime and target. The influence of word repetition on word processing was thus considerably stronger and more persistent than the influence of semantic relations. Numerous studies provided corroborative evidence for additive effects between the two priming forms (Cronk, 2001; den Heyer, 1986; Durgunoglu, 1988; Wilding, 1986). According to Sternberg (1969), additivity supports the hypothesis that the mechanisms involved in the two priming forms are different. Repetition and semantic priming have rarely been compared for auditory stimuli, but available data suggest similar outcomes for spoken words (Hänze & Meyer, 1995). Up to now, comparisons between the two priming forms have not been made for musical stimuli.

Priming effects in music

Music is a complex acoustical and temporal structure in which musical events are primed by preceding ones. For listeners familiar with a given musical idiom, the sounding of a musical piece creates perceptual expectancies about events that are likely to follow. The building-up of musical expectations is crucial for musical experience. According to L. B. Meyer (1956, 2001), musical emotion is supposed to result from the way the composer does or does not satisfy listeners' expectations. Confirming musical expectation results in increased perceptual fluency, and delaying the resolution of expectation results in a variety of emotional responses. For composers, a key concern is to create some equilibrium between resolved and unresolved expectations. For music psychologists, a key concern remains to understand the cognitive bases of these anticipatory processes.

Although priming is supposed to play an important role in music perception, only a few studies have investigated its cognitive foundation. For music, contextual priming effects might be based on the repetition of identical events and on the strength of relatedness between events. Relatedness between musical events is based on the harmonic relations defined by the Western tonal system. Most of the published research has investigated the influence of harmonic relatedness between chords on musical priming effects. Western tonal music corresponds to most musical styles of occidental everyday life (e.g., serious music from J. S. Bach to R. Wagner, pop music, jazz music, Latin music). In this musical idiom, a restricted set of 12 pitch classes is combined in a highly constraint way to create subsets of seven tones—called major or minor diatonic scales. On the different degrees of the scale, seven diatonic chords can be defined, and, together with the tones of the scale, they define major and minor keys. The harmonic relatedness between chords, which is manipulated in musical priming research, is determined by (a) the key to which chords belong and (b) the chords' musical functions in their home key (i.e., the key they belong to). For example, chords that do not belong to the same key (i.e., C and F# major chords) are defined as harmonically weakly related or unrelated. In their home key, the musical functions of chords define the following hierarchy: The chords built on the first (I), fourth (IV), and fifth (V) scale degrees of major keys (referred to as tonic, subdominant, and dominant chords, respectively) are perceived as having more referential musical functions than chords built on other scale degrees—the tonic being the most referential chord of the key followed by the dominant and then the subdominant (see Bigand, Parncutt, & Lerdahl, 1996; Krumhansl, 1990; Lerdahl, 1988). Because of the context dependency of events in the musical system, the same chord can have different musical functions depending on the currently instilled context key. For example, the C major chord acts as the most referential tonic in the key of C major, as a less referential dominant in the key of F major, and as an even less referential subdominant in the key of G major. The succession of two referential chords (i.e., a dominant followed by a tonic) forms a musical cadence (i.e., an authentic cadence) that acts as a strong syntactic marker of ending in Western musical pieces. Accordingly, dominant and tonic chords are the most strongly harmonically related chords in Western tonal music (see Bharucha, 1987; Lerdahl, 1988).

Previous studies on musical priming have shown that harmonic relations between chords determine chord processing. For example, facilitated processing was reported for chords that share a parent key (e.g., C and G major chords) in comparison to chords that do not (e.g., C and F# major chords; Bharucha & Stoeckig, 1986). In longer musical contexts, facilitated processing was reported for targets acting as a tonic rather than as a subdominant in the prime context (Bigand, Madurell, Tillmann, & Pineau, 1999; Bigand & Pineau, 1997; Bigand, Poulin, Tillmann, Madurell, & D'Adamo, 2003; Bigand, Tillmann, Poulin, D'Adamo, & Madurell, 2001; Pineau & Bigand, 1997). Harmonic priming was reported for both musically trained and untrained listeners. This finding suggests that priming reflects robust underlying processes than may be acquired without explicit learning of music (see Tillmann, Bharucha, & Bigand, 2000, for a formal account).

The specific nature of these processes has been a matter of debate. It has been argued that harmonic priming might simply occur at a sensory level. As quoted from Schmuckler (1989), "a chord sharing component tones, or overtones, with a preceding chord will be more highly anticipated than a continuation containing no overlapping frequencies with its predecessor" (p. 134). Therefore, increased processing times for an unrelated (i.e., unexpected) chord may be evoked solely by surprising discontinuities at the peripheral level, and stronger harmonic priming may be anticipated for stronger physical overlap between prime and target. In Western tonal music, this issue is crucial as theoretical accounts of Western harmony and psychoacoustical accounts of chordal dissonance are, to a large extent, intrinsically related (Bigand et al., 1996; Krumhansl, 1990; Parncutt, 1989): Harmonically related chords (e.g., C and G chords, respectively composed of the tones C–E–G and G–B–D) share more tones and overtones than do unrelated chords (e.g., C and F# chords, with the F# chord being composed of the tones F#–A#–C#). Harmonic priming may thus be conceived of as some form of repetition priming, with the amount of priming depending on the overlap in harmonic spectra between prime and target.

However, several data required minimizing the potential role played by sensory components in music. Harmonic priming was observed when prime and target chords did not share either pitches or overtones (Bharucha & Stoeckig, 1987), and it persisted for more than 2 s despite a noise mask introduced between prime and target (Tekman & Bharucha, 1992). According to Tekman and Bharucha (1998), "the processing of harmonic relationship continues independently of any involvement of an auditory sensory store, which would support the idea of a cognitive, rather than a sensory, basis for the priming effects" (p. 38). Recent studies compared the strength of sensory priming and harmonic priming by systematically manipulating sensory and harmonic relatedness. In Tekman and Bharucha (1998), the target was related to the prime on either a sensory level (e.g., C and E major chords, respectively composed of the tones C–E–G and E–G#–B) or a cognitive level (e.g., C and D major chords, with the D major chord being composed of the tones D–F#–A). The overlap in harmonic spectra is stronger in the first pair since the C and E major chords share the tone E. However, the C and D major chords do not share any tone. By contrast, the harmonic relatedness is stronger between the C and D chords that have a parent key (e.g., the G major key) than between the C and E chords that do not. Accordingly, a sensory account of priming predicts stronger priming for the chord pair C and E major, and a cognitive account of priming predicts stronger priming for the chord pair C and D major. The data support the prediction of the cognitive account for long stimulus onset asynchronies (SOAs, i.e., 500 to 2,500 ms), but sensory priming overrules cognitive priming at very short SOA (i.e., 50 ms). The finding suggests that cognitive priming needs some time to be efficient. Consistent findings were reported for longer musical contexts (Bigand et al., 2003): Processing facilitation was observed for a tonic target in comparison to a subdominant target, even when the subdominant occurred more often in the prime context and thus shared more overtones with the prime than did the tonic. As in Tekman and Bharucha (1998), this effect was modulated by the tempo at which the chord sequences were presented, with cognitive priming starting to vanish at extremely fast tempo only (i.e., 75 ms per chord).

The purpose of our present study was to further assess the respective strengths of sensory and cognitive components involved in musical priming by comparing priming effects due to chord repetition and to harmonic relatedness. Our present study was motivated by a pilot experiment, in which chord repetition (C–C) did not differ from harmonic relatedness (G–C) even if both conditions showed facilitated processing in comparison to harmonically unrelated chord pairs (i.e., F#–C).

PILOT EXPERIMENT

The aim of this pilot experiment was to investigate with single-chord primes the influence of different levels of harmonic relatedness on target chord processing. The levels of harmonic relatedness were defined by distances between prime and target on the cycle of fifths (i.e., a music theoretical representation of harmonic relations between chords that is conceived of spatially as a circle): The smaller the distance, as counted in number of steps on the circle, the stronger the harmonic relatedness. The following distances between prime and target were tested: 0, 1, 3, 4, 5, and 6 steps. A distance of 0 meant chord repetition (i.e., the same chord was presented as prime and as target). A distance of 1 referred to strongly related chords, defining an authentic cadence (i.e., corresponding to the harmonic relatedness condition in Experiments 1 and 2 here below). The distances 3 to 6 corresponded to harmonically unrelated conditions.

Method

A total of 18 nonmusicians (psychology students from introductory classes of the University of Burgundy) and 17 musicians (graduate students in the music department of the University of Burgundy) performed a speeded consonant/dissonant judgement on the target. For this task, half of the target chords were rendered acoustically dissonant. These dissonant foils acted as filler trials, and since they do not correspond to legal chords in Western tonal music their data were not reported. Our present study used this speeded intonation task because it is a well-established musical priming task (Bharucha & Stoeckig, 1986, 1987; Bigand et al., 1999; Bigand & Pineau, 1997; Bigand et al., 2003; Justus & Bharucha, 2001; Tekman & Bharucha, 1992, 1998; Tillmann & Bigand, 2001; Tillmann, Bigand, & Pineau, 1998; Tillmann, Janata, Birk, & Bharucha, 2003). It is worth noting that musical priming effects are not restricted to this specific task, but have been observed also with judgements requiring the detection of temporal asynchrony (Tillmann & Bharucha, 2002), or the discrimination of phonemes (Bigand et al., 2001), musical timbres (Tillmann, Bigand, Escoffier, & Lalitte, 2004a), or loudness (Poulin-Charronnat & Bigand, 2004).

Results

Table 1 represents the percentages of errors and correct response times, which were analysed separately by two 2 (musical expertise) × 6 (chord relatedness) analyses of variance (ANOVAs).

TABLE 1
Percentages of errors and correct response times as a function of chord relatedness and musical expertise in the pilot experiment

	Prime–target distance											
	Unrelatedness								*Relatedness*		*Repetition*	
	6 steps		*5 steps*		*4 steps*		*3 steps*		*1 step*		*0 step*	
Expertise	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
						% errors						
Musicians	15.69	4.40	6.86	2.50	9.80	2.50	2.94	2.14	0.98	0.98	3.92	1.56
Nonmusicians	43.52	4.69	43.52	5.07	33.33	4.86	25.00	3.87	21.30	4.63	14.81	2.50
						RTs[a]						
Musicians	874.70	41.83	885.23	44.18	864.38	23.39	805.45	38.87	773.90	46.15	810.56	45.10
Nonmusicians	979.76	73.72	906.67	59.55	899.13	59.76	923.75	77.22	878.22	65.15	889.84	64.81

[a]In ms.

For both dependent variables, the main effect of chord relatedness was significant, $F(5, 165) = 11.59$, $p < .0001$, $MSE = 202.45$ for errors and $F(5, 165) = 3.70$, $p = .003$, $MSE = 11{,}964.20$ for response times. Overall, processing was facilitated with closer harmonic relatedness. More specifically, the comparison between six-step and one-step distances (i.e., F#–C and G–C) replicated previous findings (Bharucha & Stoeckig, 1986, 1987; Tekman & Bharucha, 1992, 1998), with less numerous errors, $F(1, 33) = 30.95$, $p < .0001$, $MSE = 192.61$, and faster response times, $F(1, 33) = 14.19$, $p < .01$, $MSE = 12{,}607.20$, for the harmonically related condition. Given the repetition priming effects reported in other domains, the facilitated processing in the repeated condition (C–C) over the unrelated condition (F#–C) was predictable: This difference was significant for both errors and response times: $F(1, 33) = 34.77$, $p < .0001$, $MSE = 205.88$, and $F(1, 33) = 9.32$, $p < .01$, $MSE = 11{,}135.00$, respectively. However, this pilot experiment failed to reveal any significant difference between the repetition condition (C–C) and the harmonically related condition (G–C) for both errors and response times (Fs < 1). For completion, let us note that for errors the effect of chord relatedness was modulated by musical expertise, $F(1, 33) = 3.13$, $p < .01$, $MSE = 202.45$, but the pattern of contrast analyses reported above was replicated for the two groups considered separately. In addition, nonmusicians committed overall more errors than did musicians, $F(1, 33) = 78.04$, $p < .0001$.

Discussion

The facilitated processing of related and repeated conditions over unrelated conditions was convergent with previous data patterns in music and other domains. However, the failure to obtain any significant differences between related and repeated conditions was rather surprising in the light of the strong repetition priming effects observed in other domains. One possible explanation might be based on the experimental situation of this pilot experiment. The multiple presentations of harmonically unrelated chord pairs (i.e., which sounded particularly surprising) might have dissolved or even annihilated a potentially weak difference in priming due to repetition and harmonic relatedness. Experiments 1 and 2 of the present study were thus designed to focus exclusively on chord repetition and harmonic relatedness condition in short contexts.

EXPERIMENT 1

The goal of Experiment 1 was to compare chord repetition and harmonic relatedness priming effects directly to each other (i.e., C–C vs. G–C). This comparison aimed to assess the influence of perceptual similarity between prime and target on chord processing. To further investigate this influence, the fundamental frequencies of the component tones of the prime in chord repetition and harmonic relatedness conditions were manipulated to create either small or large pitch intervals between the sequentially presented chords (Figure 1, left vs. right). Changing the chordal disposition of the component tones changes the physical overlap of prime and target, but does not alter the musical identity nor the musical function of the prime. For the repetition condition (Figure 1a), this manipulation created either a complete repetition (i.e., prime and target are identical) or a partial repetition (i.e., fundamental frequencies of component tones of prime and target are far apart in pitch). For the

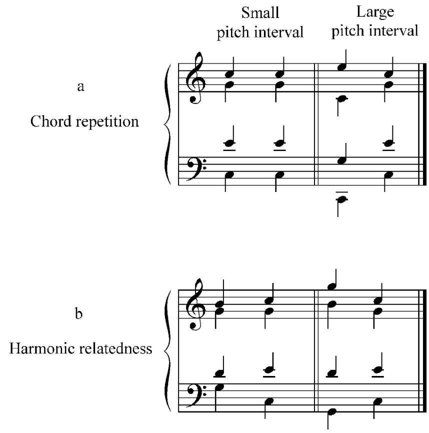

Figure 1. Examples of stimuli used in the first two experiments.

harmonic relatedness condition, chordal dispositions were manipulated similarly to obtain larger pitch intervals covered by each voice when passing form one chord to the other (Figure 1b). According to accounts of repetition priming based on materials other than music, target processing should be facilitated in the chord repetition condition in comparison to the harmonic relatedness condition, with the strongest facilitation for complete repetition. This overall goal was addressed in Experiments 1a and 1b differing in the interstimulus interval (ISI) between prime and target: The target directly followed the prime (i.e., ISI of 0 ms) in Experiment 1a and was slightly delayed (i.e., ISI of 50 ms) in Experiment 1b to render more salient the onset of the target in the repetition priming condition (notably for identical repetition).

Method

Participants

A total of 40 students from an introductory course in psychology at the University of Burgundy participated in this experiment. None had received formal musical training or had learned a musical instrument; 21 participated in Experiment 1a (without ISI) and 19 in Experiment 1b (with ISI).

Materials

Sixty-four pairs of chords were presented. In each pair, the first chord was the prime, and the second was the target. The two chords were either strongly harmonically related and could be analysed as an authentic cadence (i.e., V–I), or were identical and represented a chord repetition. The chordal disposition of the prime was manipulated in order to create either small or large pitch intervals between prime and target (see Figure 1). In one condition, the size of pitch intervals covered by each voice when moving from prime to target was null or as small as possible (small pitch interval condition), resulting in an identical repetition of the prime in the repetition condition. In the other condition, the chord disposition of the prime was modified so that all voices changed between prime and target (large pitch interval condition).

In Experiment 1a (without ISI), the prime chords sounded for 670 ms and target chords for 1,330 ms. The ISI was set to 0. For the experimental task, the target was rendered dissonant in 32 pairs by adding either an augmented octave (i.e., C2–E3–G3–C4–C#4) or an augmented fifth (i.e., C2–E3–G3–G#3–C4) to the root. The added tones were played more quietly to temper the salience of the dissonance.

In Experiment 1b (with ISI), the following aspects differed from Experiment 1a, aiming to correct potential problems encountered in Experiment 1a. A silent ISI of 50 ms was introduced between prime and target, which sounded for 750 ms and 2,000 ms, respectively. With the goal of simplifying the task, the velocity of the added dissonant tone was tempered less strongly than in Experiment 1a. Finally, each trial was separated by a melodic arrangement of 12 sine-wave tones randomly chosen among the 12 chromatic tones. The random melodies were added to eliminate traces in sensory memory buffer of a previous trial carrying over to the current trial.

Apparatus

All stimuli were played with sampled piano sounds produced by an ETM 10 Yamaha Sound Expander. The Yamaha sampler was controlled via a MIDI interface by a Macintosh computer running Performer software. Velocity, a parameter related to the force with which a key is struck, was constant for all pitches, except for the added dissonant tones that were played at lower velocity. The sound stimuli were recorded by SoundEditPro software at CD quality (16 bits and 44 kHz). The experiment was run on PsyScope software, and response times were recorded with a PsyScope button box clock with a time accuracy of 1 ms (Cohen, MacWhinney, Flatt, & Provost, 1993).

Procedure

The experimental procedure was split into two phases. During the first phase, participants were trained with 48 trials to differentiate between consonant and dissonant chords played in isolation. They had to make a consonant/dissonant judgement as quickly and accurately as possible. During the course of this training session, the velocity of the added dissonant tone was decreased to the velocity value used in the experimental material. The chords used in the training session were randomly chosen among all targets of the experimental material. During the second phase, participants were asked to perform the same task on the chord (target) that followed the prime. In both phases, a feedback signal sounded for incorrect responses.

Design

Crossing the manipulation of the priming condition (chord repetition vs. harmonic relatedness) and pitch interval size (small vs. large) produced 32 items (8 items per experimental condition), which were presented with consonant targets and dissonant foils. The resulting total of 64 trials was presented in random order for each participant. Priming condition and pitch interval size thus defined within-subject factors. Experiments 1a and 1b were captured by the between-subject factor presentation (without ISI vs. with ISI).

Results

The first dependent variable involved the percentages of errors (Table 2). Percentages of errors were less numerous (a) in the harmonic relatedness condition than in the repetition condition, (b) in the small pitch interval condition than in the large pitch interval condition, and (c) in the presentation with ISI than in the presentation without ISI. A 2 (priming

TABLE 2
Percentages of errors and correct response times as a function of priming condition, pitch interval size, and presentation in Experiment 1

Priming condition	*Without ISI*				*With ISI*			
	Small		*Large*		*Small*		*Large*	
	M	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
	% errors							
Repetition	12.75	3.69	23.41	3.64	8.55	2.54	12.50	3.45
Relatedness	10.06	2.69	15.57	3.13	5.92	1.75	7.24	2.76
	RT[a]							
Repetition	868.79	27.38	860.83	29.40	662.52	25.29	708.48	30.97
Relatedness	860.63	35.77	869.22	28.75	674.14	33.33	687.08	22.07

Note: ISI = interstimulus interval. Small = small pitch interval. Large = large pitch interval.
[a]In ms.

condition) × 2 (pitch interval size) × 2 (presentation) ANOVA indicated that all main effects were significant: priming condition, $F(1, 39) = 4.31$, $p < .05$, $MSE = 200.39$, pitch interval size, $F(1, 39) = 6.46$, $p < .05$, $MSE = 181.28$, and presentation, $F(1, 39) = 7.20$, $p < .05$, $MSE = 269.41$. There were no significant interactions. The second dependent variable was correct response times (Table 2) and showed only a significant main effect of presentation, $F(1, 39) = 542.95$, $p < .001$, $MSE = 29{,}600{,}000$, with faster response times for the presentation "with ISI" than for the presentation "without ISI".

Discussion

Experiment 1 revealed influences of priming condition and of pitch interval size on chord processing. The delayed presentation of the target (i.e., with ISI) only improved overall performance, but did not interact with the other effects. In the following, we discuss first the influence of interval size and then the results of the priming conditions.

Experiment 1 provided evidence for facilitated processing of small interval differences between prime and target: Errors were less numerous, and correct response times were shorter for small interval sizes than for large interval sizes. This finding is consistent with the effect of chordal disposition on perceived musical tension reported in music theory (Lerdahl, 2001) and empirical research (Bigand et al., 1996). It is also consistent with a recent harmonic priming study showing that chord processing in longer musical contexts is facilitated for contexts involving small intervals between the four voices of successive prime chords (Poulin-Charronnat, Bigand, & Madurell, in press). Taken together, these studies provide an empirical basis for rules of Western harmony treatises recommending composers to avoid large pitch intervals between component tones of successive chords. Small pitch intervals, indeed, define smoother progressions in the musical stream, and this feature might allow enhanced processing of musical structures. It might be argued that facilitated processing for small-interval progression can be interpreted as an indication for sensory priming, with stronger priming for more similar frequencies. However, this interpretation would predict an interaction with priming condition leading to the strongest facilitation for identical chord repetition. Since overall harmonic relatedness led to less numerous errors than did repetition, we propose that the effect of pitch interval size on musical priming might be understood in the light of Bregman's (1990) stream segregation theory. Large pitch intervals between the four component tones of chords might render more complex the integration of musical tones into coherent auditory streams. As a consequence, the musical scene analysis is more difficult to achieve, and this difficulty influences event processing. Perceptual stages of processing, which are generally conceived of to occur before abstract knowledge activation (see McAdams & Bigand, 1993), thus influence harmonic priming. The observed influence of interval size represents a serious difficulty for models of music perception that do not integrate chordal disposition; we come back to this point in the General Discussion section.

The main purpose of Experiment 1 was to compare priming effects of chord repetition and harmonic relatedness. Contrary to typical outcomes in other domains, processing the same event again (i.e., target repetition) did not result in facilitated processing when compared to processing two different events (i.e., harmonically related prime and target). For errors, a significant opposite difference was reported, with more accurate performance in the harmonic relatedness condition. For correct response times, the two priming forms did not differ.

Given this unexpected finding, the comparison of both priming forms was further investigated in Experiment 2. Three alternative explanations of data of Experiment 1 were addressed. The first explanation was linked to the structure of the experimental session. As targets and primes were different (at least in terms of chordal dispositions) in three of the four experimental conditions, the experimental design might have encouraged participants to expect differences between prime and target chords resulting in longer and less accurate processing for less frequent identical repetitions. To address this criticism, only pairs with small pitch intervals were used in Experiment 2, and, consequently, identically repeated pairs occurred as often as harmonically related pairs. The second alternative explanation of data of Experiment 1 was based on the hypothesis that the strength of each priming type depends on the SOA between prime and target. Given that cognitive priming is likely to take more time to occur than sensory priming (Bigand et al., 2003; Tekman & Bharucha, 1998), the long SOAs of Experiment 1 might have provided enough time for harmonic priming to be active and to compete with repetition priming. Consequently, differences between the two priming types were presumably decreased at this long SOA. At shorter SOAs, however, repetition priming might have a stronger influence on chord processing than has harmonic priming.

Finally, it might also be argued that forward masking acted against target processing in the repetition condition. Forward masking illustrates some limitations of the auditory system to integrate or resolve temporal information. It results in an increased threshold for the second sound and usually occurs at short ISIs (i.e., 20 to 50 ms). Forward masking suggests that recently stimulated sensors are not as sensitive as fully rested sensors. In Experiment 1, forward masking might have occurred for both repetition and harmonic priming conditions. However, its effect is supposed to be stronger in the repetition condition as forward masking depends on the qualitative similarity between masker and signal: The more qualitatively alike the masker and the signal, the stronger the effect of forward masking (Moore, 1980; Weber & Moore, 1981). Forward masking might thus diminish the facilitation created by chord repetition, and this process might explain the advantage of harmonic relatedness reported in Experiment 1.[1] In order to assess the potential influence of forward masking on chord priming, Experiment 2 also manipulated the ISI between prime and target. If forward masking is occurring in the present material and mainly with chord repetition, the advantage of harmonic relatedness over chord repetition should disappear with long ISI.

The main purpose of Experiment 2 was thus to compare the two priming forms at short and long SOAs (i.e., 100 and 500 ms) and at short and long ISIs (i.e., 50 and 450 ms). In addition, given that the time course of sensory and cognitive priming was shown to depend on musical expertise (Bigand et al., 2003), two groups varying by their extent of musical training participated in Experiment 2. In the light of Bigand et al.'s (2003) finding, harmonic priming for musically trained listeners was expected to be less influenced by changes of SOA and ISI.

EXPERIMENT 2

Method

Participants

A total of 58 students participated in this experiment: Of these, 31 had never received formal musical training or learned to play a musical instrument (referred to below as *nonmusicians*), and 27 had studied music theory, received ear training, and learned how to play a musical instrument (referred to below as *musicians*); 18 of them were graduate students in the music department of the University of Burgundy.

Materials and apparatus

The material was identical to the material of the small pitch interval condition of Experiment 1b, except for the following modifications: For the SOA condition, the SOA was set to either 100 ms (with a 50-ms prime) or 550 ms (with a 500-ms prime), with the ISI always set to 50 ms. For the ISI condition, all primes sounded for 50 ms, and the ISI was set to either 50 ms or 450 ms. The apparatus was as described in Experiment 1.

Procedure and design

The procedure was as described in Experiment 1. All chord pairs were presented with both SOAs and both ISIs, but in two blocks separating short and long SOAs for 22 participants and short and long ISIs for 36 participants. The order of blocks was counterbalanced over participants for both SOA and ISI conditions. Crossing the manipulation of priming condition (chord repetition vs. harmonic relatedness) and duration (short vs. long) produced 32 items (8 items per experimental condition), which were presented with consonant targets and dissonant foils, leading to a total of 64 trials for each block. Priming condition and duration defined the within-subject factors. Timing condition (SOA vs. ISI) and musical expertise (musicians vs. nonmusicians) defined the between-subject factors.

[1]However, it should be emphasized that forward masking usually involves long maskers (200 ms) and short signals (less than 50 ms). Experiments 1 and 2 displayed the opposite relation with short primes (i.e., 50 ms to 750 ms) and long targets (i.e., 1,330 and 2,000 ms).

TABLE 3
Percentages of errors and correct response times as a function of priming condition, duration, timing condition, and musical expertise in Experiment 2

		SOA				*ISI*			
		Short		*Long*		*Short*		*Long*	
Expertise	*Priming condition*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
		% errors							
Musicians	Repetition	4.17	2.08	4.17	2.95	2.08	1.13	2.08	1.52
	Relatedness	8.33	4.17	4.17	2.08	0.00	0.00	2.08	1.52
Nonmusicians	Repetition	12.50	3.74	6.73	2.69	13.89	2.45	17.79	3.03
	Relatedness	5.77	2.29	3.85	1.66	13.89	3.18	12.50	3.03
		RT[a]							
Musicians	Repetition	712.27	51.39	701.78	56.24	660.43	41.31	650.30	44.98
	Relatedness	679.42	46.63	635.87	37.00	670.03	43.48	626.19	39.99
Nonmusicians	Repetition	1005.04	71.90	964.38	63.63	839.15	55.83	893.82	73.04
	Relatedness	972.82	63.08	934.98	57.11	803.44	56.78	840.16	68.52

Note: SOA = stimulus onset asynchrony. ISI = interstimulus interval.
[a]In ms.

Results

Percentages of errors and correct response times are displayed in Table 3 and are analysed by two separate 2 (musical expertise) × 2 (timing condition) × 2 (priming condition) × 2 (duration) ANOVAs. Percentages of errors were very low overall. The ANOVA on percentages of errors revealed a two-way interaction between priming condition and musical expertise, $F(1, 54) = 4.13$, $p = .047$, $MSE = 58.40$. Errors were more numerous for the repetition condition than for the harmonic relatedness condition in nonmusicians only, $F(1, 54) = 7.18$, $p < .01$, $MSE = 58.40$. There was a main effect of musical expertise with fewer errors for musicians than for nonmusicians, $F(1, 54) = 19.67$, $p < .001$, $MSE = 152.16$, and this difference was more pronounced in the ISI condition than in the SOA condition, $F(1, 54) = 10.54$, $p < .01$, $MSE = 152$. No other effects were significant.

The ANOVA on correct response times revealed a main effect of priming condition, $F(1, 54) = 10.50$, $p < .01$, $MSE = 5{,}556.70$, with faster responses for the harmonic relatedness condition than for the chord repetition condition, and a main effect of musical expertise, $F(1, 54) = 18.52$, $p < .001$, $MSE = 165{,}932.70$, with musicians responding faster than nonmusicians. No other effects were significant.

Discussion

The findings of Experiment 2 are consistent with those of Experiment 1: Even with both priming conditions occurring equally often in the experimental session, chord repetition did not result in facilitation over harmonic relatedness. Moreover, Experiment 2 confirmed the opposite difference and provided evidence for faster processing (and more accurate processing for nonmusicians) in the harmonic relatedness condition than in the chord repetition condition. Even when the SOA was extremely short, repetition did not result in a processing advantage. The ISI condition provided new evidence that the advantage of harmonic priming cannot be explained by forward masking, as even with longer ISI between prime and target chord (i.e., reduced forward masking) repetition priming did not gain in impact. It remains to be specified why harmonic relatedness results in stronger priming than does chord repetition. A cognitive account of musical priming posits that the musical function of a chord influences chord processing more strongly than do memory traces formed by prior presentations of that chord. Accordingly, differences in harmonic function of the target should result in different priming strengths. How does the musical function of the target chord differ between harmonic relatedness and chord repetition conditions?

In the harmonic relatedness condition, the two related chords (e.g., G–C in the key of C major) can be analysed as the most relevant harmonic progression of Western tonal music: the authentic cadence (Schenker, 1935). The first chord is thus likely to be perceived as a dominant chord that anticipates a tonic chord. In other words, the first chord primes the processing of the tonic target, and this priming is driven by abstract knowledge of Western tonal harmony. The expectation developed after the dominant resulted in greater facilitation when the tonic actually occurred (harmonic relatedness condition) rather than when it did not (chord repetition condition). In the repetition condition, the fact that the target was identical to the prime did not compensate the harmonic expectation instilled by the first chord.

However, this interpretation rests on a musical analysis of chord functions that can be questionable. Indeed, an extremely short musical context (i.e., one chord in the present case) does not permit conferring straightforward musical functions to a chord. As a consequence, the chord pairs of the harmonic relatedness condition may also be analysed, in theory, as a tonic-to-subdominant progression (e.g., G–C in the key of G major) and not as a dominant-to-tonic progression. Experiment 3 was designed to address this criticism by using longer musical contexts.

Experiment 3 manipulated simultaneously the musical function and the immediate repetition of the target in order to further assess their respective influences on chord processing. The target acted as either a tonic chord or a musically possible but less referential chord (i.e., dominant or subdominant) and was immediately repeated or not (Figure 2). If musical priming is determined by sensory traces formed by the prior presentation of the target in memory, stronger priming should be obtained in the repetition condition, irrespective of the musical function of the target. If, however, musical priming is governed by the harmonic function, facilitation should be obtained for tonic targets over nontonic targets (i.e., dominant and subdominant), irrespective of a repetition of the target. If both forms of priming tap into different mechanisms, additive effects should be observed, with the strongest facilitation for the repeated tonic chord. The nontonic targets were composed of dominant and subdominant chords (i.e., the repeated nontonic target and the nonrepeated nontonic target, respectively). These two chord types have different musical functions, but are both less referential than the tonic chord and are even considered as being almost equally referential (see Bharucha, 1987; Bigand et al., 1996; Krumhansl, 1990; Lerdahl, 1988, 2001).

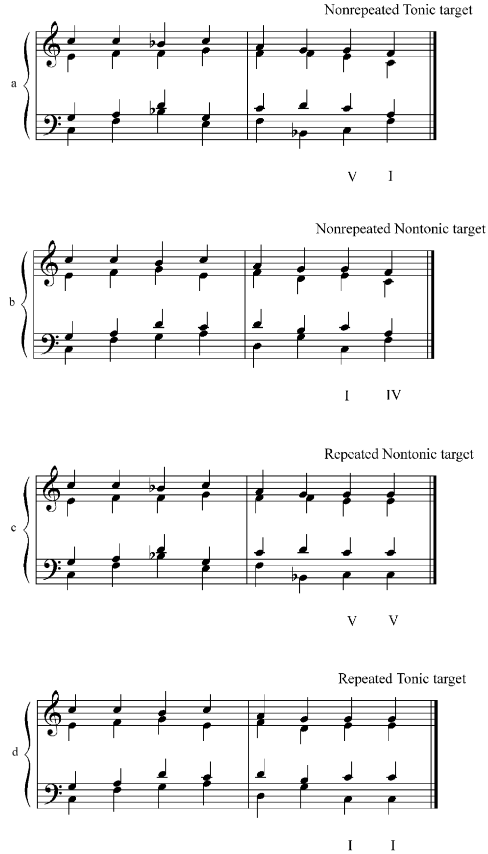

Figure 2. One example of the 20 chord sequences used in Experiment 3 in the four experimental conditions. Tonic, dominant, and subdominant targets are represented by roman numerals I, V, and IV, respectively.

EXPERIMENT 3

Method

Participants

A total of 41 students participated in this experiment: 22 psychology students without formal musical training or practice of a musical instrument (referred to below as *nonmusicians*), and 19 students finishing their studies in music theory, ear training, and instrumental practice at the Conservatory of Troyes (referred to below as *musicians*).

Materials

A total of 20 eight-chord sequences from Bigand and Pineau (1997) and Pineau and Bigand (1997) were used. Figure 2 illustrates, with one example, the manipulation of musical function and target repetition. The last chord defined the target. The roman numerals below targets represent their musical functions in the contexts, with I representing a tonic, IV a subdominant, and V a dominant. The chord sequence a ended on a tonic (i.e., F major chord in this example) without repetition. In order to manipulate the musical function of the target, some component tones of the first six chords of these sequences were shifted one semitone up or down in Sequence b, while keeping constant the last two chords (see Bigand & Pineau, 1997, for details). These pitch changes modified the key of the context by one step clockwise on the cycle of fifths (e.g., the F major key shifting toward the C major key). As a consequence, the target does not act as a tonic in Sequence b, but as a subdominant (without repetition). These two conditions were strictly identical to conditions tested in Bigand and Pineau (1997), and replication of previous findings was expected. For the repetition conditions, the penultimate chord of Sequences a and b was repeated, and this resulted in Sequences c (repeated dominant chord) and d (repeated tonic chord). These manipulations were applied to all 20 sequences. Crossing musical function and target repetition produced four possible versions for each of the 20 initial sequences, resulting in 80 sequences.

For the experimental task, in half of the trials the target (i.e., the last chord of each sequence) was rendered dissonant by adding either an augmented octave (i.e., C2–E3–G3–C4–C#4) or an augmented fifth (i.e., C2–E3–G3–G#3–C4) to the root. The added dissonant tone was played more quietly to temper the salience of the dissonance. In order to reduce the number of trials per participant, the 20 original sequences were split into two blocks of 10. One block of sequences was presented with consonant targets and the other block with dissonant targets for half of the participants. The type of target (consonant/dissonant) for each block was reversed for the other half of participants. Each participant thus heard 80 sequences presented in different random order (i.e., 10 items per experimental condition presented with consonant targets).

Apparatus

All stimuli were played with a sampled piano sound produced by an EMT10 Yamaha Sound Expander. Velocity was constant for all pitches except the added dissonant tone that was played at half velocity. The tempo of the sequences was set to 90 quarter notes per minute (i.e., 666 ms per chord). The sound stimuli were captured by SoundEditPro software at CD quality (16 bits and 44 kHz). The experiment was run on PsyScope software (Cohen et al., 1993), and response times were recorded using PsyScope's button box.

Procedure

The experimental procedure was split into three phases. During the first phase, participants were trained to differentiate between consonant and dissonant chords presented in random order. They had to make a consonant/dissonant judgement as quickly and accurately as possible by pressing one of two buttons. During the second phase, the eight-chord sequences were presented, and participants made the consonant/dissonant judgement for the last chord of each sequence. In both phases, participants were alerted by a feedback signal for incorrect responses, and the next trial began when they pressed a third button. During the third phase, participants made the consonant/dissonant judgement to all targets of the experimental sequences, but the targets were presented without preceding context. This last phase was added to test whether targets of repeated and nonrepeated conditions were processed with the same accuracy and speed without context. Even if targets of repeated and nonrepeated conditions were acoustically very similar (i.e., perfect major chords with roughly the same chordal dispositions), they were not strictly identical. The data of the present control phase revealed no differences between target types for percentages of errors and correct response times, $F\text{s} < 1$.

Design

Musical function (tonic vs. nontonic target) and target repetition (repeated vs. nonrepeated) defined within-subject factors. Musical expertise (nonmusicians vs. musicians) defined a between-subject factor.

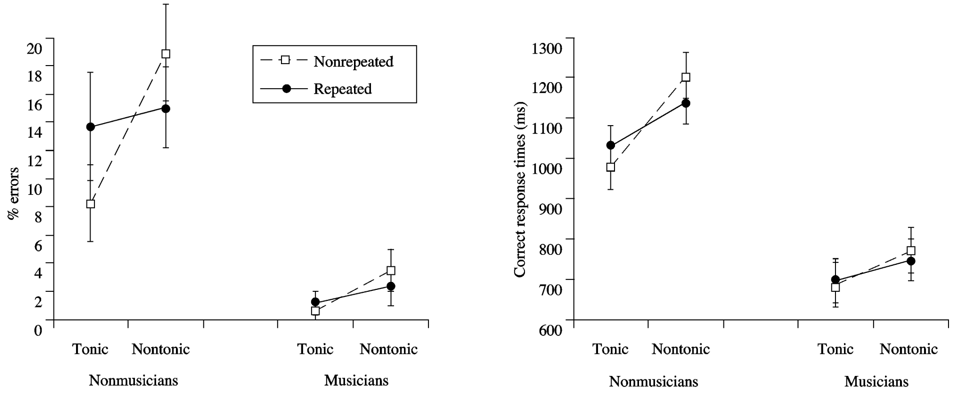

Figure 3. Percentages of errors (left) and correct response times (right) observed in Experiment 3 for both groups of participants, for nonrepeated and repeated conditions and for tonic and nontonic targets. Note that the nonrepeated nontonic target functioned as a subdominant chord (IV) and the repeated nontonic target as a dominant chord (V; see Figure 2).

Results

Percentages of errors and correct response times are displayed in Figure 3 and are analyzed by two 2 (musical expertise) × 2 (musical function) × 2 (target repetition) ANOVAs. For percentages of errors (Figure 3, top), a significant main effect of musical function was observed: Percentages of errors were less numerous for tonic than for nontonic targets, $F(1, 39) = 4.81$, $p < .04$, $MSE = 137.80$. The two-way interaction between musical function and target repetition was significant, $F(1, 39) = 7.47$, $p < .01$, $MSE = 42.01$, indicating that the effect of musical function was significantly more pronounced when the target was not repeated. In addition, there was a significant main effect of musical expertise, $F(1, 39) = 19.61$, $p < .001$, $MSE = 303.50$, with more errors for nonmusicians.

Correct response times mirrored percentages of errors (Figure 3, bottom). Response times were significantly shorter for tonic than for nontonic targets, $F(1, 39) = 63.87$, $p < .001$, $MSE = 9{,}110.50$. This difference was stronger for nonrepeated than for repeated targets, as expressed by a significant interaction between musical function and target repetition, $F(1, 39) = 6.05$, $p < .02$, $MSE = 9{,}567.30$. Response times were overall shorter for musicians, $F(1, 39) = 24.48$, $p < .001$, $MSE = 218{,}466.00$. In addition, the analysis also indicated a more pronounced effect of musical function in nonmusicians, $F(1, 39) = 11.54$, $p < .005$, $MSE = 9{,}110.50$.

A post hoc analysis of the experimental material revealed that in 20 of the 80 sequences the tonic targets tended to occur more often in the first six chords of the sequences than did the dominant or subdominant targets (i.e., the nontonic targets). This difference might create a potential confound between musical function and frequency of occurrence, notably that the strength of priming increased with the frequency of occurrence of the target in the prime. For the remaining 60 sequences, the frequencies of occurrence of tonic and nontonic targets were identical in the prime sequences. Even if Bigand and Pineau (1997) rejected the criticism of a potential confound for tonic and subdominant targets in the nonrepeated conditions with post hoc analyses, we performed two additional ANOVAs on percentages of errors and correct response times for the 60 sequences only. The results mirrored the results of all 80 sequences. This outcome suggests that the frequency of occurrence of the target was unlikely to account for the observed differences in chord processing. This post hoc analysis is consistent with a recent study that simultaneously manipulated the musical function of the target (tonic vs. subdominant) and its frequency of occurrence in the musical context (Bigand et al., 2003): Facilitation was observed for tonic over subdominant targets, even when the subdominant target occurred more often in the prime context.

Discussion

Experiment 3 confirmed the importance of contextual information on chord processing, which has already been reported in previous studies (Bigand & Pineau, 1997; Tillmann et al., 2000, for a review). In the nonrepeated conditions, tonic targets were processed faster than subdominant targets even though the local context was held constant. This finding demonstrates that harmonic priming not only occurs from chord to chord but also depends on the musical function of the target in the extended temporal context. The critical point of Experiment 3 was to compare this contextual effect of harmonic relatedness to the effect of chord repetition.

The data provided further evidence that chord processing is more strongly influenced by the musical function of the chord in the overall prime context than by the immediately preceding chord. Independently of repetition, the tonic always remains the chord that is processed the fastest.[2] In other words, the effect of chord repetition does not overcome the effect of musical function. Chord repetition actually did not result in processing facilitation per se, but found expression only in a two-way interaction with musical function. Chord repetition increased processing times for tonic targets, but decreased processing times for less referential dominant targets (i.e., the repeated nontonic target) in comparison to nonrepeated subdominant targets (i.e., the nonrepeated nontonic target). This difference between repeated and nonrepeated nontonic targets might also be due to differences in tonal stability, although some music-theoretical models claim that there are no hierarchical differences between these dominant and subdominant chords (Lerdahl, 2001). In a recent priming study (Tillmann, Janata, Birk, & Bharucha, 2004b) focusing on tonic, dominant, and subdominant targets (i.e., without investigating the influence of chord repetition), processing times reflect a hierarchy between the three chords: Dominant targets were processed faster than subdominant targets, and tonic targets were processed the fastest. In the light of this data set, the comparison between repeated and nonrepeated targets should mainly focus on the tonic chords: With constant tonal stability, a processing advantage is observed for the nonrepeated tonic targets.

The observed data pattern (i.e., the interaction between chord repetition and musical function) is different from result patterns observed in psycholinguistic studies of semantic and repetition priming. Indeed, most psycholinguistic research reported additive effects with stronger priming for both semantically related and repeated target words (Cronk, 2001;

[2] An additional contrast decomposing the interaction between target repetition and musical function confirmed that response times in the repeated condition were significantly shorter for tonic targets than for nontonic targets, $F(1, 39) = 13.22$, $p < .001$, $MSE = 10{,}311.90$.

den Heyer, 1986; Durgunoglu, 1988; Wilding, 1986). The interaction observed with musical material might be understood in connection with typical chord progressions of Western tonal music: Notably, a tonic occurring after a dominant at the end of a musical sequence acts as a marker of ending (i.e., authentic cadence). Given the shortness of our sequences (i.e., 8 chords), the repetition of a marker of ending (i.e., repetition of the tonic) is unnecessary and rather unexpected.[3] By contrast, a dominant chord at the end of a short musical piece acts as a temporary ending in Western tonal music. Repeating a dominant chord can be perceived as less surprising since the musical piece has not definitely ended yet.

GENERAL DISCUSSION

The main purpose of our study was to further investigate the processes that govern musical priming. Three experiments were designed to distinguish two forms of priming: chord repetition and harmonic relatedness. Repetition priming refers to performance facilitation that is gained from a prior presentation of the same stimulus. The degree of repetition priming is determined by the extent to which the processes employed during encoding are reactivated in identification or recognition of the same stimulus. Priming due to harmonic relatedness refers to the facilitatory effect that a musical context (i.e., one chord or more) has on target processing when the target is related to the context according to musical rules that the listeners are familiarized with. Harmonic priming thus involves schematic long-term memory: The context is supposed to activate an abstract knowledge of musical rules that is culturally determined. Target chords that fit well with this context according to these rules are processed faster and in a more accurate way than target chords that violate these rules.

Up to now, repetition and relatedness priming have never been investigated with musical stimuli, except in our pilot experiment contrasting pairs of identical chords (i.e., a C major chord followed by a C major chord) to pairs of musically unrelated (i.e., F# and C major chords) and related chords (i.e., G and C major chords). Chord repetition resulted in stronger facilitation than harmonic unrelatedness, but surprisingly, no difference was observed between repeated chords and harmonically related chords. Experiments 1 to 3 were designed to further investigate priming based on repetition in comparison to priming based on harmonic relatedness. Moreover, given that both forms of priming presumably tap into different processes, it was of interest to address whether they combine in an additive or interactive way.

The critical outcome of our study was to provide evidence that in the music domain chord repetition did not result in stronger facilitation than harmonic relatedness. Moreover, significant advantages of harmonic relatedness were reported in Experiment 1 for percentages of errors, and in Experiments 2 and 3 for both percentages of errors (nonmusicians only in Experiment 2) and correct response times. The present data thus showed stronger target facilitation due to harmonic relatedness than to chord repetition. Interestingly, this outcome was observed for musically trained and untrained listeners, suggesting that harmonic priming rests on robust cognitive processes that do not require formal learning of the Western

[3] This explanation is likely to be modulated by the length of the musical piece, notably when we consider that it is very usual for symphonic masterworks to end with numerous repetitions of the tonic (as in Beethoven's symphonies, for example).

musical idiom. This finding has several implications for music cognition as well as for priming research using different materials.

The present data challenge current models of music perception. Sensory and cognitive models can be distinguished in music psychology, with each providing different accounts of musical priming. The sensory models emphasize the influence of sensory-driven processes: Harmonic relationships between chords are predicted without either music theoretic constructs (e.g., key, harmonic hierarchy) or psychological constructs (e.g., abstract knowledge of Western musical rules). In the sensory model of Parncutt (1989), the harmonic relatedness of two chords is entirely based on the pitch commonality of successive chords. Pitch commonality is the degree to which chords have pitches in common, taking into account the relative perceptual salience of each pitch pair. For example, pitch commonality is greater between the C and G major chords (.32) than between the C and F# major chords (−.12) (see Bigand et al., 1996, for more details; Parncutt, 1989). In longer musical sequences, the sensory traces associated to each musical event are accumulated over time in sensory memory, weighted according to recency. A sensory account of musical priming predicts that the strength of priming depends on the amount of component tones and virtual pitches that the target shares with component tones and virtual pitches of the prime context, stored in sensory memory and decaying over time. Consequently, stronger facilitation is predicted for repeated than for harmonically related chords.

In contrast to sensory accounts of music perception, cognitive models emphasize the importance of knowledge-based processes. In Western tonal music, the combination possibilities between pitches are considerably constrained by rules of harmony and counterpoint. The pitch regularities induced by these constraints are supposed to be implicitly internalized by Western listeners through mere exposure (Francès, 1958; Krumhansl, 1990; Tillmann et al., 2000). A cognitive account of harmonic priming stipulates that a musical context activates the listener's knowledge of Western harmony, resulting in faster processing of a target that is harmonically related to the context. Cognitive priming effects in music share similarities with semantic priming for words and sentences (Tillmann & Bigand, 2001, 2002). In both cases, the processing of a target event is mediated by the activation of an abstract mental representation: The more the target is related to the previous context in the light of this abstract representation, the more its processing is facilitated.

The role of knowledge-driven processes in Western harmony perception has been questioned by several authors (Butler, 1989; Huron & Parncutt, 1993; Leman, 1995, 2000; Parncutt & Bregman, 2000). It has been argued that some data usually referred to as support for the cognitive foundation of music perception do not necessarily reflect an abstract knowledge of Western musical rules but can be more simply explained by psychoacoustic models integrating sensory memory decay. For example, key differences in listeners' perception of tones (i.e., represented in Krumhansl & Kessler's, 1982, key profiles) can emerge from an echoic memory model based on pitch salience (Huron & Parncutt, 1993; see also Parncutt & Bregman, 2000), and from a short-term memory model based on echoic images of periodicity pitch (Leman, 2000).

Our present study compared sensory and cognitive approaches of music perception in the case of harmonic priming. A sensory account predicts stronger priming for chord repetition. A cognitive account predicts stronger priming for harmonic relatedness. In Experiments 1 and 2, the harmonic priming condition was defined by harmonically related chords, which create a dominant-to-tonic progression. This progression represents a highly meaningful cadence (i.e., authentic cadence) in Western music. As explained above, the contrast between sensory and cognitive accounts is better achieved with longer musical contexts in Experiment 3. For this material, a sensory account predicts stronger priming for repeated targets irrespective of function, and a cognitive account predicts that priming depends on the musical function of the target in the context irrespective of repetition. Consistent with other recent findings (Bigand et al., 2003), the data supported more strongly the cognitive account of harmonic priming.

The cognitive account of music perception has been formalized in two different frameworks: Bharucha's (1987) connectionist model MUSACT and Lerdahl's (1988) tonal pitch space theory (TPST). In the following, we want to discuss how far these frameworks might account for the present findings.

In Bharucha's (1987) connectionist model, the knowledge of Western harmonic hierarchy is conceived of as a network of interconnected units. These units are organized in three layers that correspond to tones, chords, and keys. Each of the 12 tones is connected to six chord units representing the three major chords and the three minor chords of which that tone is a component. In the same way, each chord unit is connected to three major key units representing the keys of which that chord is a component. This connection pattern constitutes a knowledge representation of Western harmony that generates automatic and schematic expectations (Bharucha, 1987, 1994). When a triad (i.e., a chord consisting of three tones) is sounded, the three corresponding tone units are activated, and phasic activation (i.e., change of activation) spreads via connections toward chord units. The chord unit connected to all three tones receives the strongest activation. For example, if the triad includes the tones C, E, and G, the chord unit representing the C major chord is the most activated. Phasic activation spreads from chord to key units (bottom-up activation) and reverberates toward tone units (top-down activation) and back to chord and key units, and so on. After several cycles of reverberation, MUSACT reaches equilibrium (i.e., reverberating phasic activation is inferior to a given threshold), and the pattern of activation reflects tonal and harmonic hierarchies (i.e., with stronger activation for more stable events). In long chord sequences, activations due to each chord are accumulated, and their pattern of activation decays over time (according to recency). The global pattern of activation in the units at the end of the sequence represents the influence of the overall context. The activation levels are interpreted as levels of expectation for subsequent events (Bharucha, 1987; Bigand et al., 1999; Tekman & Bharucha, 1998; Tillmann et al., 1998) and predict harmonic priming: After the presentation of the prime context, the activation of a target chord unit is, for example, stronger for a tonic chord than for a subdominant chord (Bigand et al., 1999).

To date, harmonic priming studies have provided strong support for this model, with either short contexts (Bharucha & Stoeckig, 1987; Tekman & Bharucha, 1998; Tillmann & Bharucha, 2002) or long contexts (Bigand et al., 1999; Tillmann & Bigand, 2001; Tillmann et al., 1998; Tillmann et al., 2003). Our present study, however, raises two major problems for this model. The first problem concerns the influence of chordal disposition on chord priming observed in Experiment 1. Since the input units of MUSACT correspond to the 12 pitch classes, the model does not represent the pitch height of the chord's component tones. As a consequence, the current form of MUSACT does not have any possibility of accounting for the chordal disposition effect (i.e., small vs. large intervals).

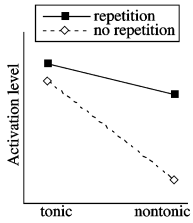

Figure 4. Relative activations for target chord units in the four experimental conditions crossing musical function (tonic vs. nontonic target) and target repetition (repetition vs. no repetition). The simulations were run with all sequences used in Experiment 3, and relative activation patterns were averaged over the sequence set. According to Bharucha (1987), the more a chord unit is activated, the stronger the expectation for the represented chord to follow next and the stronger the predicted facilitation of processing.

The second problem for MUSACT is its simulation of stronger activations for repeated chords. After a single prime chord, reverberating activation is the strongest for the chord unit representing the prime (see Bharucha, 1987). In two-chord priming experiments, the model thus makes predictions similar to sensory models of music perception: Strongest priming effects are expected for repeated chords. For the chord sequences used in Experiment 3, we ran neural net simulations: The first seven chords of each sequence were presented one by one to the model, and the activation of the target chord units was read off after the seventh chord.[4] As shown in Figure 4, MUSACT anticipated an effect of chord repetition and an effect of musical function, with stronger activation for repeated chords and for tonic targets. Consistent with the observed data, the model also predicted interactive effects between chord repetition and harmonic relatedness, with the difference between tonic and nontonic targets being less pronounced in the repetition condition. However, the model predicts strongest facilitation for repeated tonic and weakest for nonrepeated nontonic target. Overall, the model simulates correctly the effect of musical function, but overestimates the influence of repetition and fails to account for reduced facilitation for repeated tonic over nonrepeated tonic and increased facilitation for repeated nontonic over nonrepeated nontonic (Experiment 3).

Lerdahl's TPST (1988, 2001) provides another (though less formal) cognitive account of music perception. The TPST was not designed to account for priming effects, but prediction about priming can be derived from the theory in a straightforward way (Bigand, 2003), and these predictions account for complex tonal context effects in long chord sequences (Bigand, 2003; Bigand & Parncutt, 1999). In this theory, musical events are conceived of as being dispatched in a three-dimensional space. The tonal stability of musical events and the syntactical relationships in Western music are expressed in terms of distances that separate musical events from the most referential event of the main key, which is the tonic chord.

[4] Simulations were run with an implementation of Bharucha's model on Matlab. Given that the ISI between chords was set to 0 and that all chords were played with the same duration, the time transpired since the last offset (*t*) was identical for each chord and was set to 1. The rate at which activation decays (d) was set to .02. Figure 4 represents the activation level of target chord units averaged over the sequence set. When the decay was set to .04 (i.e., representing a stronger decay over time), the activation pattern of target units was similar to Figure 4, except that the difference between tonic and nontonic targets was further decreased for the repetition condition only.

Harmonically less related chords in a given context are far away from the tonic chord of that context. According to Lerdahl (1988, 2001), the distance between the dominant chord and the tonic chord equals the distance between the subdominant chord and the tonic chord (a value of 5 in both cases). This distance is smaller than distances between other chords and the tonic since dominant and subdominant chords are syntactically important chords in Western tonal music. This distance, however, is greater than the distance between two instantiations of the tonic chord, since in this case the distance is null. Table 4 indicates these tonal stability values of the TPST (i.e., distance in pitch space to the tonic of the context key) computed for the last two chords of the sequences in each condition. The predictions for the target chord encounter some difficulties in accounting for the data obtained with chord sequences in Experiment 3. It predicts a tonal pitch space distance of 0 for the tonic chord and a distance of 5 for dominant and subdominant chords—with and without repetition (the repetition of the target is analysed as a prolongation that inherits the values of the chord to which it is prolonged to: 0 for tonic repetition and 5 for dominant repetition). The model thus anticipates an effect of musical function with tonic chords being more expected than nontonic chords, an outcome consistent with the observed behavioural data. However, the model is not able to anticipate a significant interaction between both factors (harmonic relatedness and repetition), with the harmonic relatedness effect being reduced for repeated chords in comparison to nonrepeated chords.

The predictions of the cognitive models are thus in agreement with the observed effect of musical function in the behavioural priming data, but they encounter difficulties in predicting its exact combination with the chord repetition effect. Both cognitive models take into consideration the differences in tonal stability between chords. In the light of the behavioural data showing that listeners' expectations differ with the influence of chord repetition, the outcome of our study might suggest that processes involved in music perception integrate other features, which are characteristic for the compositions of the Western tonal musical system. One of these features might thus concern the avoidance of direct repetition

TABLE 4
Predictions of the tonal pitch space theory and its proposed extension for the four experimental conditions

		Nonrepeated		*Repeated*	
		Tonic (V–I)	*Nontonic (I–IV)*	*Tonic (I–I)*	*Nontonic (V–V)*
1. *TPST values of tonal stability*	*7th Chord*	5	0	0	5
	Target	0	5	0	5
2. Tension/relaxation of progression		−5	+5	0	0
3. Sum: Target's TPST values + (2)		−5	10	0	5

Note: 1. Stability values of the tonal pitch space theory (TPST) for penultimate chords (i.e., 7th chord of the sequence) and target chords. 2. Distances separating the target from the penultimate chord in terms of tension (positive values) and relaxation (negative values). 3. Sum of the calculated values of the target in (1) and (2), reflecting the combination of two aspects of dynamic music listening (cf. text for further explanations).

(except for stylistic purposes) and the preferred use of continuation and progression (also allowing the musical pieces to be made more interesting). In the following, we propose an extension of Lerdahl's TPST that aims to integrate the dynamic aspect of music listening. The values based on Lerdahl's model in Section 1 of Table 4 (i.e., tonal stability values of TPST) represent a rather static aspect: the distance of the target chord to the tonic of the context's key at a given time point. This prediction is thus independent of the preceding chord (i.e., in sequences without tonal modulation). However, music listening is a dynamic progression and based on structures of tension and relaxation, with tension and relaxation being illustrated as distances to the tonic. As developed in Lerdahl and Jackendoff (1983), the Western tonal music rests on the alternation of departure from the tonic (which creates musical tension) and the return to the tonic (which creates relaxation). The alternation of tension and relaxation is definitely the most basic feature of Western tonal music, and it has been compared to Chomsky's deep structures (subject–verb–object; see Deliège, 1984; Lerdahl & Jackendoff, 1983; Sloboda, 1985). Therefore, it is reasonable to assume that once a tension has been created in a given musical context, Western listeners expect musical events that resolve this tension (i.e., that minimize the distance toward the tonic chord of the context key). In other words, Western listeners are likely to anticipate paths in the pitch space leading toward the most referential event of the key (i.e., the tonic). To capture this dynamic, Section 2 of Table 4 expresses the distance that separates the target chord from the penultimate chord in terms of tension and relaxation (i.e., always in reference to the tonic chord of the context key as formalized in the TPST). A reduction of distance (negative value) corresponds to a relaxation, and an increase of value to a musical tension. This computation partly fits with our data since it can account for the facilitation of V–I over IV–I and I–I; however, it fails to account for the observed difference between I–I and V–V. A way to adjust the extension of the TPST to our data would be to combine tonal stability values of the target chord with the change in distance between penultimate chord and target chord by simple addition (Table 4).

From a psychological point of view, combining the two values integrates two factors of music perception: (a) the change of tonal stability due to the change between penultimate and last chord (i.e., distance travelled through in the tonal pitch space) and (b) the tonal stability of the target chord (i.e, formalized as distance of the target to the tonic in the TPST). This combination expresses the fact that Western listeners expect an event at the end of a sequence that minimizes most strongly the distance toward the tonic chord (i.e., small values reflecting strong stability), and this expectancy is even stronger when the penultimate chord is far from the tonic (cf. Section 2 in Table 4). As a consequence, repeating the dominant chord at the end of the sequence does not fit with this expectation since listeners, presumably, anticipate a motion toward the tonic chord. The addition of these factors provides values that fit the behavioural data pattern obtained in Experiment 3: strongest expectation for the tonic after the dominant (i.e., V–I in the nonrepeated tonic condition) because of strong tonal stability and the created movement of relaxation, followed by the repeated tonic condition (I–I), the repeated dominant condition (V–V), and finally the nonrepeated nontonic condition (i.e., I–IV) because of weak stability and the created movement of tension.

At a more general level, musical priming experiments challenge the traditional view predicting that event repetition systematically results in stronger priming (see Tillmann & Bigand, 2004, for converging evidence). Even if the immediate repetition of a target chord results in larger priming than harmonic unrelatedness, it results in smaller priming than harmonic relatedness. At first glance, the weakness of repetition priming suggests some kind of repetition deafness in music perception. This musical repetition deafness might be compared to repetition blindness, which has been largely documented in psycholinguistics (Bavelier, Prasada, & Segui, 1994; Humphreys, Besner, & Quinlan, 1988; Kanwisher, 1987; Mozer, 1989) and to repetition deafness in speech, which is studied less extensively (Miller & MacKay, 1994, 1996; Soto-Faraco & Sebatian-Galles, 2001; Soto-Faraco & Spence, 2001). Repetition blindness occurs when a target is immediately repeated, when the temporal lag between its two occurrences is small, and when its presentation rate is extremely fast. In the present study, none of these conditions was necessary to reveal the advantage of harmonic relatedness over chord repetition. Given that repetition priming is observed in auditory domain with spoken words (Meehan & Pilotti, 1996; Van Petten & Rheinfelder, 1995) and environmental sounds (Stuart & Jones, 1995), our present finding points to a possible specificity of musical stimuli.

The question remains to understand the characteristics that cause music to be different from these other auditory structures of our environment. Although this question calls for future research, we want to suggest that one of the most important differences that might modulate the effect of repetition priming is related to the balance between syntactic and semantic features in the three auditory structures (i.e., speech, music, environmental sounds). In environmental sounds, the most important aspect for the listener is related to the meaning of the sound source (i.e., identification). Environmental sounds usually do not occur in sequences that are temporally structured with constraints as strong as those in language and music (i.e., syntactic organizations). In short, semantic is more predominant in environmental sounds than is syntax. For language, the respective strengths of semantic and syntactic structures have largely been discussed, and numerous research has provided evidence for considerable influences of both structures on word processing. In contrast to environmental sounds and language, there is no semantic in musical units: Musical events (i.e., tones, chords) do not refer to external objects, but are self-referential, at least for nonmusician listeners. As a consequence, the most predominant feature of music rests on the temporal (syntactic) relationships between musical events. Of course, the nature of these temporal relationships depends on the considered culture. In Western tonal music, the basic temporal relations involve the tension-relaxation schemes, as described above. According to Lerdahl and Jackendoff (1983), the alternation of tensions and relaxations is the “normative structure” that underlies every piece of Western tonal music. Western listeners are thus likely to strongly expect (a) changes between events rather than repetition of events and (b) that these changes result in strong relaxations at the end of a piece. This music-specific feature allows us to explain why repetition is not an expected phenomenon in music and, as such, does not necessarily result in processing facilitation.

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