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The Costs and Benefits of Tonal Centers for Chord Processing

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Harmonic priming studies have shown that a musical context, with its established tonal center, influences target chord processing. This study investigated costs and benefits of priming tonal centers for target processing by adding a baseline condition (sequences without a specific tonal center). Results confirmed harmonic priming, with faster processing for related than for unrelated and less related targets (tonic chord, out-of-key chord, subdominant chord). Comparing targets in baseline contexts with targets in sequences with well-established tonal centers revealed a benefit of processing for related targets but a cost of processing for unrelated and less related targets. Findings are discussed in terms of tonal knowledge activation and suggest that an activated tonal center gives rise to strong expectations for the tonic.

A musical context influences the perception and processing of a musical event. Depending on the beginning of a melody, the same tone is judged as fitting well and providing a good ending or not (e.g., Hébert, Peretz, & Gagnon, 1995; Krumhansl, 1990). Similarly, the same chord is processed faster and more accurately in a harmonically related context than an unrelated context (Bharucha & Stoeckig, 1986, 1987; Bigand, Madurell, Tillmann, & Pineau, 1999; Bigand & Pineau, 1997). The influence of a musical context is also reflected in neurophysiological data: The same musical event evokes a stronger late positive component (peaking around 500 and 600 ms) when it is unrelated to the context than when it is related (Besson & Faïta, 1995; Besson, Faïta, & Requin, 1994; Besson & Macar, 1987, for tones; and Janata, 1995; Patel, Gibson, Ratner, Besson, & Holcomb, 1998; Regnault, Bigand, & Besson, 2001, for chords). The present article explores the costs and benefits of a well-established harmonic context on the processing of related and unrelated target events by using a harmonic priming paradigm.

A musical context establishes a tonal center that contains and evokes tonal and harmonic hierarchies specific to this tonal center. The context plays a particularly important role in tonal music, as the tonal system is based on a restricted set of events (the 12 tones of the chromatic scale: C–C#–D–D#–E–F–F#–G–G#–A–A#–B). These tones are combined in several subsets of 7 tones that, depending on the combination, define major or minor scales. On the basis of each tone degree of a scale, chords (combinations of 3 tones; e.g., C–E–G for a C Major chord) can be defined. The degree on which the chord is built determines the functional importance of the chord—for example, the first degree (the tonic chord) is at the top of the harmonic hierarchy, followed by the fifth and fourth degrees (the dominant and subdominant chords). The tones in a scale and their associated chords define a higher level of organization in the tonal system: the keys (which can be either major or minor depending on the combination of tones and chords). The 7 tones that belong to the underlying scale are in-key tones; the remaining 5 tones are out-of-key tones. Similarly for chords, in-key chords (with their different functional importance) are differentiated from out-of-key chords. In a given musical piece, tones and chords belonging to one key are frequently associated and establish a tonal center. Tones and chords with higher musical functions (as, e.g., the tonic tone and tonic chord) are used more often than are tones and chords in lower positions of tonal and harmonic hierarchies (Francès, 1958; Krumhansl, 1990). Depending on the tonal center established by the context, the same chord can function as a tonic chord, serving an important referential role at the top of the harmonic hierarchy, or as a less important one (e.g., the subdominant chord), or it can turn into an out-of-key chord. In a musical piece, it is possible to change the tonal center over time. This change is associated with shifts in tonal and harmonic hierarchies reflecting the established tonal centers.

This presentation of some basic principles of the tonal system shows that understanding the context dependency of musical events is important for understanding the functions of musical events. Previous research has provided evidence that listeners are sensitive to tonal centers and to associated changes in the tonal functions of musical events depending on the tonal context (Bartlett & Dowling, 1980; Bharucha & Krumhansl, 1983; Cuddy & Badertscher, 1987; Cuddy & Thompson, 1992a, 1992b; Francès, 1958; Hébert et al., 1995; Krumhansl, 1979; Krumhansl, Bharucha, & Castellano, 1982; Krumhansl, Bharucha, & Kessler, 1982; Thompson & Cuddy, 1989). The influence of the musical context has been interpreted on a cognitive level. Listeners acquire knowledge about Western tonal regularities (e.g., frequencies of co-occurrence between musical events and frequencies of occurrence) through mere exposure to musical pieces in everyday life (Francès, 1958; Krumhansl, 1990; Tillmann, Bharucha, & Bigand, 2000). On the basis of this tonal knowledge, listeners develop expectations for further upcoming events depending on the actual context. A tonal center gives rise to expectations that tonally related events (tones, chords) will occur in the ongoing context, and these expectations then influence the perception of the actually occurring event (Bharucha & Stoeckig, 1986; Bigand et al., 1999;

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Boltz, 1993; Jones, Boltz, & Klein, 1993; Schellenberg, 1995; Schmuckler, 1989, 1990; Schmuckler & Boltz, 1994).

Harmonic priming research has focused on the investigation of the influence of a harmonic context on the processing of a target chord. In these studies, the harmonic relatedness between the prime context and the target chord is systematically manipulated. The prime context instills a tonal center against which a harmonically more or less related or even unrelated target chord occurs. The outcome of priming research has provided evidence that the processing of a target chord is influenced by the harmonic context, which can be as short as a single chord (Bharucha & Stoeckig, 1986, 1987; Tekman & Bharucha, 1992, 1998; Tillmann & Bharucha, 2002) or a longer sequence of several chords (Bigand & Pineau, 1997; Bigand et al., 1999; Bigand, Poulin, Tillmann, & D'Adamo, 2003; Tillmann & Bigand, 2001; Tillmann, Bigand, & Pineau, 1998). In the case of longer contexts (e.g., a sequence of eight chords), it is possible to distinguish the influence of the local context (e.g., the chord preceding the target) from the influence of the global context (e.g., the first six chords). When the local context is held constant, priming results show an influence of the global context on chord processing. Both musician and nonmusician listeners are sensitive to the tonal center established by the global context: The processing of the target chord is more accurate and faster when the target acts as the most referential tonic chord of the tonal center than when it is an out-of-key chord (Tillmann et al., 1998) or an in-key chord with a less important position in the harmonic hierarchy, the subdominant chord (Bigand et al., 1999; Bigand & Pineau, 1997; Bigand, Tillmann, Poulin, & D'Adamo, 2001).

Harmonic priming effects have been explained by a connectionist account of tonal knowledge activation (Bharucha, 1987; Tillmann et al., 2000). In the proposed model, the tonal knowledge of the listener is represented as a network of interconnected units that is organized in three layers, representing tones, chords, and keys. When a musical context is presented, tone units corresponding to the played tones are activated, and the activation reverberates among the layers until equilibrium is reached. For long contexts consisting of several events, activation patterns after each event are accumulated over time and weighted with a decay parameter to simulate recency. The emerging activation patterns reflect tonal and harmonic hierarchies of the established key: For example, units representing harmonically related chords are activated more strongly than are units representing unrelated chords. The context dependency of musical events in the tonal system is thus not stored explicitly for each of the different keys but emerges from activation spreading through the network. The strengths of activations are interpreted as relative levels of expectation for future events: The more a chord unit is activated, the more the represented chord is expected and the more its processing should be facilitated. Previous harmonic priming effects have been simulated by activation patterns of target chord units after a single prime chord (Bharucha & Stoeckig, 1987; Tekman & Bharucha, 1998; Tillmann & Bharucha, 2002) and after longer prime contexts containing 7 to 13 chords (Bigand et al., 1999; Tillmann & Bigand, 2001; Tillmann et al., 1998). The simulations suggest that harmonic priming results from activation that spreads through schematic knowledge of Western harmony and accumulates in short-term memory over the course of the chord sequence.

In sum, previous harmonic priming research and simulations thereof have investigated the relative facilitation of processing by comparing more or less related targets following well-defined harmonic contexts. However, previous research has not addressed whether established tonal centers impart a cost or a benefit on the processing of target chords. A clear tonal center might cause different levels of facilitated processing of upcoming events, but it might also cause facilitation for some events (e.g., those belonging to the tonal center) and inhibition for others. Alternatively, it might not cause inhibition but simply create no advantage in processing when compared with a situation in which a tonal center has not been processed before.

The goal of our present study is to analyze facilitation and inhibition in harmonic priming effects. Specifically, is harmonic priming due to facilitation from related primes and/or inhibition from unrelated primes? To investigate how far the influence of the tonal center represents a cost or benefit for chord processing, we adopted a rationale that has been established in other domains showing context effects on the speed of event processing. The investigation of cost and benefit components has been operationalized by the introduction of a so-called *neutral baseline* context that is compared with related and unrelated contexts. In letter perception, Posner and Snyder (1975) compared target processing after a neutral cue as a warning signal with target processing after valid and invalid cues. In semantic priming research, the processing of a target word after semantically related and unrelated prime contexts is compared with processing after a semantically neutral context (de Groot, Thomassen, & Hudson, 1982; Neely, 1976, 1977; Stanovich & West, 1983). The neutral context was represented by a sequence of *XXXX* or the word *blank* in single word priming and by sentences such as "The next word is . . . " or "They said it was the . . . " in sentence priming (Hess, Foss, & Carroll, 1995; Stanovich & West, 1979). Similar rationales have been adopted for syntactic priming (Deutsch & Bentin, 1994; Friederici, Schriefers, & Lindenberger, 1998) and color priming (Rosch, 1975). The use of a neutral baseline condition leads to relative definitions of facilitation and inhibition, with facilitation being reflected in faster and more accurate processing than baseline (constituting the benefit component) and inhibition being reflected in slower and less accurate processing than baseline (constituting the cost component).

Psycholinguistic research on cost and benefit patterns underlines the importance of selecting an appropriate baseline condition, as inappropriate neutral conditions can create facilitation or inhibition artifacts (de Groot et al., 1982; Hess et al., 1995; Jonides & Mack, 1984; Neely, 1991; Page, 1999; Stanovich & West, 1983). If the neutral cue needs less processing capacity (e.g., it is seen more often during the experimental session or simply because it is perceptually less complex), facilitation might be underestimated and inhibition overestimated. The neutral cues should be matched as closely as possible to the informative cues, and, ideally, the cues should be identical with respect to all their effects on target processing except that of information specifically linked to the target. For example, neutral and informative cues should be equated in terms of their quality as warning signal and should not induce different levels of attentiveness and alertness in the participants.

In musical priming, a first attempt to investigate cost and benefit patterns on chord processing was restricted to single chord contexts (Arao & Gyoba, 1999). The influence of harmonically related and unrelated primes was compared with a noise burst as the baseline condition. Response times to the target chord were slower after an unrelated prime than after the noise burst, but response times were not faster after a related prime than after the noise burst. As the noise burst was repeated during the experimental session and was perceptually less complex than the prime chords, the noise burst baseline might have been processed faster than would have been a baseline more comparable to chord primes. Arao and Gyoba acknowledged in the discussion that the conclusion that chord priming does not involve facilitation is premature because decreased processing demands of the noise burst baseline might have led to underestimation of facilitation for related prime chords.

Our study focuses on harmonic priming in long contexts and investigates costs and benefits due to an established tonal center in chord sequences. For this purpose, the criteria for our baseline context were that it should not establish a tonal center yet should be as closely matched as possible to the tonal prime contexts in other regards. As harmonic priming investigates influences of harmonic expectations on musical event processing, the baseline condition should belong to the same stimulus class (i.e., musical material, preferably harmonic sequences)—in contrast to nonmusical stimuli that bear no relevance to harmonic expectancy formation. Rather than using noise bursts as the baseline context, we defined harmonic sequences in which the chords are combined in a way that does not allow the establishment of a clear, stable tonal center. In harmonic sequences that establish a tonal center, harmonically related chords that belong to the same key are used together. For the definition of the baseline sequences, this characteristic feature of tonal sequences was systematically broken: Harmonically unrelated chords were chained together, and chord repetitions were avoided. The baseline sequences differed in terms of chords used and voice leading characteristics to avoid the repetition of the same baseline context over the experimental session. The relative novelty of the different baseline sequences is thus closely matched to the original tonal sequences. We applied the key-finding algorithm of Krumhansl and Schmuckler (as cited in Krumhansl, 1990) to our sequences to test for the established tonal center and to confirm that the baseline contexts do not establish a tonal center. The outcome indicated that the original tonal prime sequences clearly establish a tonal center but that this tonal feature breaks down for the baseline sequences (see *Material* section of Experiment 1).

Using these baseline contexts, we studied costs and benefits of established tonal centers on the processing of in-key chords and out-of-key chords. Using baseline contexts enables us to build on our understanding of previously reported priming effects that directly compared target chord processing in more or less related contexts (Bigand et al., 1999; Bigand & Pineau, 1997; Tillmann et al., 1998). In light of previous priming research, we focus on the influence of the tonal center established by the global context of a chord sequence while holding constant the influence of the local context. Experiment 1 compares harmonic contexts that end on either the most referential in-key chord (the tonic) or an out-of-key chord with the baseline context. Experiments 2 and 3 concentrate on finer harmonic differences and compare the baseline context with two targets that belong to the established tonal center but that differ in their importance in the harmonic hierarchy (tonic vs. subdominant chords). We also ran simulations with the connectionist model of tonal knowledge activation using the stimulus material in our study and present the results in the General Discussion section. The simulations investigate the extent to which the modeled activation process can account for target processing in sequences without a tonal center and for the observed cost and benefit patterns. The proposed connectionist model is able to account for costs and benefits only in terms of relative differences in activation levels.[1]

Experiment 1: Related Versus Unrelated Versus Baseline Contexts

Experiment 1 studies the costs and benefits of an established tonal center on the processing of a target chord by comparing two harmonically distant contexts with a baseline context. The target chord was the last chord of eight-chord sequences. The local context was harmonically related and held constant over the three experimental conditions that modified the global context (Figure 1). In the related condition, the global context established a key in which the target functioned as the tonic chord. In the unrelated condition, the key of the global context was harmonically unrelated to the target chord and rendered the target an out-of-key chord in the global context while still being locally related to the preceding chord (the seventh chord). In addition to these two contexts that established a tonal center (either closely related or unrelated to the target), a baseline context that did not establish a tonal center with the first six chords was created, as described above. On the basis of previous priming research (Tillmann et al., 1998), we expected a facilitation effect for globally related targets (the tonic of the established global tonal center) over unrelated targets (out-of-key chords). The baseline sequence allowed the investigation of cost and benefit patterns attributable to the globally established tonal center. The hypothesis was that a tonal center primes the processing of chords that belong to the tonal center and that occur frequently in the established context, in contrast to out-of-key chords that belong to other nonestablished tonal centers. We thus expected facilitation for in-key chords in comparison with baseline targets and no difference or inhibition for out-of-key chords in comparison with baseline targets.

Method

Participants. Twenty introductory psychology students participated in this experiment for course credit. Number of years of musical training, as measured by years of instrumental instruction, ranged from 1 to 14, with a mean of 7.85 ($SD = 4.00$) and a median of 9.

Material. Twelve sequences of eight chords were selected from the material of Bigand and Pineau (1997) and Pineau and Bigand (1997). The sequences were transposed so that all 12 major keys were represented. The last chord of all sequences (the target) functioned as the tonic chord of the established key. These sequences defined the related condition. For the construction of unrelated and baseline conditions, the local context of the target (the seventh chord) was held constant and the global context (first six chords of the sequence) was modified. For the unrelated condition, the first six chords were transposed one semitone down, resulting in a harmonically unrelated key: For example, a global context in C Major was transposed to

[1] The terms *facilitation* and *inhibition* are used in comparison with the baseline without reference to excitatory and inhibitory mechanisms: If activation is stronger than baseline, the event is facilitated; if it is weaker than baseline, the event is inhibited. These definitions thus mirror the terminology for behavioral data, with facilitation denoting fewer errors and shorter response times than baseline (benefits) and inhibition denoting more errors and longer response times than baseline (costs).

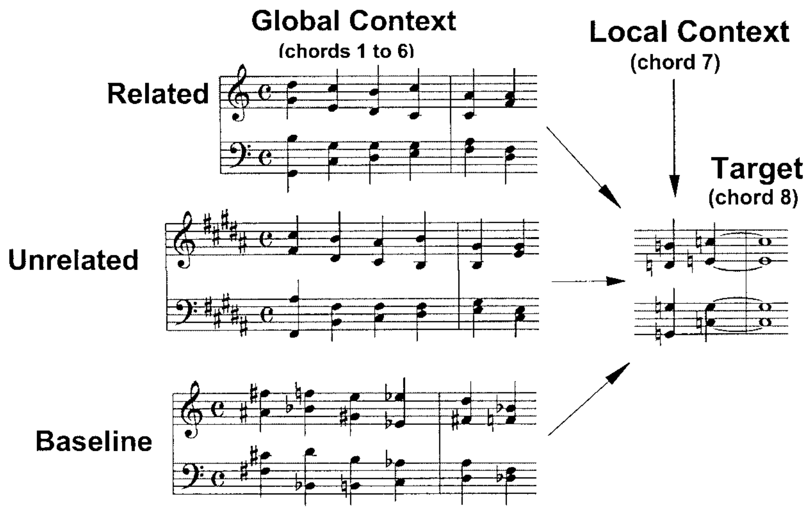

Figure 1. One example of the chord sequences used in Experiment 1 for the three experimental conditions: the related context, the unrelated context (transposed a semitone down into a harmonically distant key), and the matched baseline context. The last chord of the sequence is the target chord, and the local context (the chord preceding the target) is held constant.

B Major (see Figure 1). For the baseline condition, the first six chords were chosen in such a way that they were harmonically unrelated from one chord to the next. The chords were chosen on the basis of two constraints: (a) Two neighboring chords in the sequence had to be separated by a minimum distance of three steps on the cycle of fifths,[2] and (b) chord repetitions were not allowed. In addition, the chords chosen for the baseline context were matched closely to the original (related) sequence concerning chord types (e.g., major, minor, diminished), their inversions, and their position in the sequence. We composed the baseline sequences with the aim to respect as far as possible Western tonal rules of voice leading, notably by creating contrary motions, avoiding large intervals in voices between successive chords, and avoiding parallel fifths or octaves.

We used the key-finding algorithm proposed by Krumhansl and Schmuckler (cited in Krumhansl, 1990) to analyze the strength of tonal centers established by the global contexts. The tones used in the first six chords of related contexts and baseline contexts were correlated with the tone profiles of 12 major and 12 minor keys, respectively. The tone profiles reflect the functional hierarchy defined by tonal theory for a given key (with highest values for the tonic tone, followed by tones on the fifth and third scale degrees, then by the remaining in-key tones, and, finally, the out-of-key tones). The profiles result from subjective judgments of listeners on how well a probe tone fits with a preceding tonal context (Krumhansl & Kessler, 1982). The maximum positive correlation provides an indication of the most strongly established key, and the maximum negative correlation indicates the least likely key. The maximum positive and negative correlations averaged over the 12 sequences clearly indicated that the related contexts strongly established a tonal center, whereas the baseline contexts showed weaker correlations (cf. Table 1, left). The positive and negative correlations were significantly higher for the related sequences than for the baseline sequences, $t(22) = 12.25$, $p < .0001$, and $t(22) = 3.30$, $p < .01$, respectively. As the unrelated sequences had been obtained by transposition of the related sequences, the result of related contexts was valid also for unrelated contexts that established a different key. For related sequences, the highest correlation was followed by a marked decrease in correlation for the next most strongly correlated key. For baseline sequences, several keys reached similarly high positive correlations. When correlations were ordered as a function of their strengths, the mean difference between the first and second, the second and third, and the third and fourth strongest correlations was .13 for related sequences but .06 for baseline sequences.

For all sequences, the last chord defined the target chord. To create dissonant target chords for a priming task using speeded intonation judgments,[3] we altered the sensory consonance of all targets by adding an augmented fifth (G#3) to the root (i.e., C2–E3–G3–G#3–C4).

Apparatus. The stimuli were created with Performer 5.3 software (Mark of the Unicorn, Cambridge, MA) using Musical Instrument Digital Interface (MIDI) and played with sampled piano sounds produced by a Korg (Melville, NY) New SG-1D. Velocity, a MIDI parameter related to the sound level, was constant for all tones except for the added augmented fifth, whose velocity was decreased to temper the salience of the dissonance and adjusted for comparable salience among dissonant targets. Each of the first seven chords sounded for 500 ms, the target sounded for 2,000 ms, and the interchord interval was set to zero. The stimuli were recorded with SoundEdit 16 Software (MacroMedia, San Francisco, CA) and the experiment was run on PsyScope software (Cohen, MacWhinney, Flatt, & Provost, 1993).

Procedure. The experiment contained two phases. In the first phase, participants were trained to differentiate between consonant and dissonant chords with single chords first, then with chord sequences. In this speeded

[2] The cycle of fifths is a music theoretical representation of keys (and their tonic chords) that is conceived of spatially as a circle. The number of steps separating two keys on this circle (whatever the direction of rotation) defines their harmonic distance. Modulating tonal musical pieces generally change keys going step by step to the next key on the circle. The *x* axes of Figures 3 and 5 (introduced later) are organized following the order on the circle and thus represent increasing harmonic distances from C Major on either side.

[3] Harmonic priming effects for both short and long contexts have been observed not only with intonation judgments (Bharucha & Stoeckig, 1986, 1987; Bigand et al., 1999; Bigand & Pineau, 1997; Tekman & Bharucha, 1992, 1998) but also with a phoneme-monitoring task (i.e., participants decide whether the target is sung on the phoneme /i/ or /u/; Bigand, Tillmann, Poulin, & D'Adamo, 2001), a temporal asynchrony task (i.e., participants decide whether all notes in the target are played at the same time or whether one note is late; Tillmann & Bharucha, 2002), and a timbre discrimination task (i.e., participants decide whether the target is played with timbre A or B; Tillmann & Bigand, 2002).

Table 1
Maximum Positive and Negative Correlations Between Tone Profiles of All Major and Minor Keys and the Tones of the First Six Chords in Related/Unrelated, Less Related, and Baseline Contexts (Averaged Over the 12 Sequences) for Experiments 1 and 2

	Experiment 1		Experiment 2	
Maximum correlation	Related/ unrelated	Baseline (R)	Less related	Baseline (LR)
Positive	.91	.55	.92	.59
Negative	−.67	−.55	−.66	−.57

Note. R = baseline contexts matched to related sequences; LR = baseline contexts matched to less related sequences.

intonation task, participants were asked to judge as quickly and accurately as possible whether the isolated chord or the last chord of the chord sequence was acoustically consonant or dissonant by pressing one of two keys. In the second phase, participants judged the consonance/dissonance of the target chord for chord sequences only. Presenting the 36 sequences (12 related, 12 unrelated, 12 baseline) with both consonant and dissonant targets resulted in 72 trials that were presented in random order for each participant. In both phases, the target chord was followed by a 250-ms noise mask, and the next trial started when participants pressed a third key. To encourage participants to answer as quickly and accurately as possible, an incorrect response was accompanied by an alerting feedback signal, and a correct response stopped the target.

Results

Performance in the speeded intonation task was high overall, with 4.0% errors for consonant trials and 4.3% errors for dissonant trials. As dissonant targets represented filler trials to define the priming task and as our hypotheses concerned only consonant chords, dissonant targets were not further analyzed.

For consonant targets, fewer errors were committed in the related condition than in the unrelated condition (Table 2). In comparison with the baseline condition, fewer errors were committed in the related condition, but more errors were committed in the unrelated condition. This pattern of error rates mirrors the pattern of correct response times, with the shortest response times for related targets, followed by baseline targets and by unrelated targets (Table 2).

Correct response times were analyzed by a one-way analysis of variance (ANOVA) with context (related/unrelated/baseline) as a within-subject factor, and differences between contexts were analyzed by planned comparisons. The main effect of context was significant, $F(2, 38) = 17.90$, $MSE = 3{,}230.6$, $p < .0001$. Response times were faster for related targets than for unrelated targets, $F(1, 19) = 51.16$, $p < .001$. Response times for baseline targets were longer than for related targets, $F(1, 19) = 7.65$, $p < .05$, but shorter than for unrelated targets, $F(1, 19) = 8.02$, $p < .05$. For the pairwise comparisons, the differences in response times did not correlate with the number of years of musical training, $r(18) = .25$ for related versus unrelated, $r(18) = .06$ for related versus baseline, and $r(18) = -.14$ for unrelated versus baseline. An additional ANOVA with chord sequences as random variable confirmed the main effect of context, $F_2(2, 22) = 21.33$, $p < .001$. All three comparisons among conditions were significant, with shorter response times for related than for unrelated targets, $F_2(1, 11) = 47.84$, $p < .001$, shorter response times for related than for baseline targets, $F_2(1, 11) = 18.10$, $p < .01$, and longer response times for unrelated than for baseline targets, $F_2(1, 11) = 6.41$, $p < .05$.

Discussion

Experiment 1 compares the processing of strongly related targets and out-of-key targets with the processing of targets in a baseline context that did not establish a tonal center. Results confirm previously reported global context effects, with faster processing for a tonic chord than for an out-of-key chord (Tillmann et al., 1998). The comparison of tonic and out-of-key targets with targets in baseline sequences reveals a facilitation effect for the tonic chord but an inhibition effect for the out-of-key chord. Processing a tonal center in the global context resulted in a benefit for processing a related chord but a cost for processing an unrelated chord. The fact that the cost of global unrelatedness was not eliminated by the local relatedness of the seventh chord underlines the influence of the global context on chord processing.

The results suggest that an established tonal center represents preparatory processes for incoming events that belong to this tonal center. The musical context activates possible musical events that are coherent with the tonal center and that, in Western tonal music, are frequently associated. This activation linked to the tonal center creates in listeners the expectation that subsequent events belong to the established tonal center. When an expected event occurs, the established tonal center (i.e., the global context) imparts a benefit and the processing of the event is facilitated. When, however, an unexpected event outside the current tonal center occurs, the established tonal center is inappropriate and induces a processing cost, relative to a situation in which the preceding context has not established a clear tonal center. This cost–benefit pattern is an example of an adaptive process in perception. If, in a musical piece, the tonal center is changed over time, the modulation develops over closely related keys, but radical key shifts to a very distant key (as in the unrelated context between the sixth and seventh chords) are rare. In light of these results based on an extreme opposition in harmonic relatedness, the question arises as to the nature of cost–benefit patterns for events that belong to the established tonal center but that differ in their relative position in the harmonic hierarchy of the tonal context.

Table 2
Percentages of Errors and Correct Response Times (RTs; in Milliseconds) for Related, Unrelated, and Baseline Contexts (Averaged Over the Sequence Set) in Experiment 1

Variable	Related	Unrelated	Baseline
% error			
M	2.5	5.4	4.2
SE	1.1	1.8	2.1
RT			
M	562.9	670.3	620.2
SE	32.8	39.7	33.8

Experiment 2: Related Versus Less Related Versus Baseline Contexts

Experiment 2 investigates cost and benefit patterns of harmonic priming that are more subtle than those explored in Experiment 1. Previous studies have reported priming effects while comparing target chords that all belong to the established tonal center but differ in their position in the harmonic hierarchy (Bigand et al., 1999; Bigand & Pineau, 1997). In their harmonic priming study, Bigand and Pineau (1997) varied the functional importance of the target chord (the last chord of eight-chord sequences) by changing the harmonic context created by the first six chords. Both contexts (related, less related) clearly established a tonal center in which the target chord defined an in-key chord, but the harmonic function of the target differed between the two contexts. In the related context, the target was a harmonically stable tonic chord. In the less related context, the target was a contextually congruent but less stable subdominant chord. Results showed faster and more accurate processing for the tonic chord in the related context than for the subdominant chord in the less related context. The goal of Experiment 2 is to investigate the costs and benefits of the tonal center for the processing of two in-key chords (tonic vs. subdominant) that differ in their position in the established harmonic hierarchy (first vs. third position). The related and less related contexts were compared with a baseline context that was defined as in Experiment 1.

Method

Participants. Sixteen introductory psychology students participated in this experiment for course credit; none had participated in Experiment 1. Number of years of musical training, as measured by years of instrumental instruction, ranged from 0 to 12, with a mean of 7.69 ($SD = 3.16$) and a median of 7.5.

Material. The 12 related sequences that ended on the tonic chord and their matched baseline sequences of Experiment 1 were used. The related sequences had been selected from the material of Bigand and Pineau (1997) and Pineau and Bigand (1997). From this material were now selected the 12 less related sequences that were matched to the original related sequences. These sequences ended on the same two chords as the related sequences, but the global context (first six chords) had been modified so that the target chord functioned as a subdominant chord. As the chords of these less related sequences ending on the subdominant were not obtained by transposition as in Experiment 1, an additional set of 12 baseline sequences was constructed. These baseline sequences were defined with the same criteria as were the baseline sequences matched to related sequences in Experiment 1 (see Figure 2 for an example) and were analyzed with the Krumhansl and Schmuckler (cited in Krumhansl, 1990) key-finding algorithm. The averaged maximum positive and negative correlations of the less related sequences and their matched baseline sequences are displayed in Table 1 (right). The tonal center was clearly established in the global context of the less related sequences, but not for the baseline sequences. The positive and negative correlations were significantly higher for the less related contexts than for the baseline contexts, $t(22) = 11.89$, $p < .0001$, and $t(22) = 2.78$, $p < .05$, respectively. For normal sequences, related and less related contexts did not differ significantly. For baseline sequences, the sequences matched to related and to less related contexts did not differ significantly. The less related sequences and their matched baseline sequences were recorded as described in Experiment 1, and the experiment was run using PsyScope software (Cohen et al., 1993).

Procedure. The two phases of the experiment proceeded as described in Experiment 1. The baseline sequences, matched to related and less related sequences, were divided into two sets of 6 sequences, respectively.

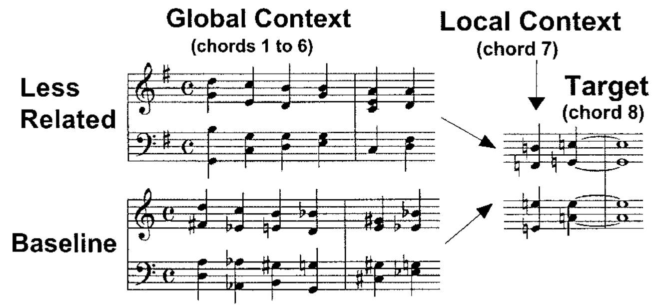

Figure 2. One example of chord sequences used in Experiment 2 for the less related context and its matched baseline context. The related context and its matched baseline context in Figure 1 complete one chord sequence example in the four experimental conditions.

Half of the participants listened to 6 related and 6 less related baseline sequences presented with a consonant target and to the other two sets of baseline sequences presented with a dissonant chord. For the other half of the participants, the mapping was reversed. In the experimental phase, participants heard 72 sequences: 12 related sequences, 12 less related sequences, and 12 baseline sequences (6 matched to related, 6 to less related sequences), each presented with a consonant target and with a dissonant chord. The division of baseline sequences in sets of 6 was necessary to present sequences of the three conditions (related, less related, baseline) with the same frequency of occurrence (i.e., one third for each) over the experimental session, as was done in Experiment 1.

Results

Performance level was high overall, with an error rate of 2.6% for both consonant and dissonant targets. For consonant targets, the fewest errors were committed in the related sequences when the target functioned as a tonic chord. Percentages of errors were higher for the less related sequences than for the related sequences and slightly higher than for the baseline sequences. This pattern of error rates mirrors the pattern of response times, with shorter response times for related targets than for baseline targets and than for less related targets (Table 3).

Response times for correct responses were analyzed by a one-way ANOVA with context (related/less related/baseline) as a within-subject factor. The main effect of context was significant, $F(2, 30) = 16.65$, $MSE = 4{,}681.62$, $p < .0001$. Response times were faster for related than for less related sequences, $F(1, 15) = 28.45$, $p < .0001$. The comparison with the baseline sequences showed that response times were faster for the related sequences, $F(1, 15) = 9.47$, $p < .01$, but slower for the less related sequences, $F(1, 15) = 8.81$, $p < .01$. The pairwise differences between the three conditions did not correlate with years of musical training, $r(14) = .05$ for related versus less related; $r(14) = .32$ for related versus baseline, and $r(14) = .23$ for less related versus baseline. To investigate differences between the two sets of baselines, we separated percentages of errors and response times for baseline sequences matched to related sequences and those matched to less related sequences (cf. Table 1, Table 3). Percentages of errors were equivalent for both baseline types, and response times were as fast for the baselines matched to related sequences as for those matched to less related sequences.

An additional ANOVA on response times was performed with chord sequences as random variable and sequence set (related/less

Table 3
Percentages of Errors and Correct Response Times (RTs; in Milliseconds) for Related, Less Related, and Baseline Contexts in Experiment 2

Variable	Related	Less related	Baseline	Baseline (R)	Baseline (LR)
% error					
M	0.5	4.2	3.1	3.1	3.1
SE	0.5	2.2	2.1	2.3	2.3
RT					
M	661.4	800.9	728.8	728.1	730.1
SE	42.5	54.8	46.1	48.3	46.1

Note. In Experiment 2, baseline targets were averaged over baseline sequences matched to related and less related sequences (participants worked on six related and six less related baseline sequences). Results were also analyzed separately for the two matched baseline sequences: baseline (R) and baseline (LR). Baseline (R) = baseline matched to related sequences; baseline (LR) = baseline matched to less related sequences.

related/baseline related [B(R)]/baseline less related [B(LR)]) as within-item factor. The main effect of sequence set was significant, $F_2(3, 33) = 13.15$, $MSE = 3{,}515.79$, $p < .0001$. Planned comparisons confirmed that response times were faster for related than for unrelated sequences, $F_2(1, 11) = 25.53$, $p < .001$. Response times for related sequences were faster than for the matched related baseline sequences, $F_2(1, 11) = 11.31$, $p < .01$, and response times for less related sequences were slower than for the matched less related baseline sequences, $F_2(1, 11) = 8.47$, $p < .05$. Response times for the two sets of baseline sequences, however, did not differ significantly ($F_2 = 0.01$).

Discussion

Experiment 2 replicates previously reported priming effects with facilitation of the tonic relative to the subdominant target chord (Bigand et al., 1999; Bigand & Pineau, 1997). The comparison with the baseline condition confirms the benefit of processing for the tonic target that had been observed in Experiment 1. The comparison with the baseline condition, however, reveals a 70-ms cost of processing for the subdominant target. Even though the target belonged to the key of the global context, the processing of this less related chord was slower than the processing of targets in the baseline sequences. This inhibition effect for the less related targets is a surprising outcome, as these targets belong to the established tonal center and function as the subdominant chord—the third most important chord of the harmonic hierarchy.

It might be argued that because of the artificial, atonal baseline sequences used, participants developed listening and answering strategies over the course of the experimental session that caused a shift in reaction times. At the outset, the processing of the less related target might have been facilitated in comparison with the baseline, but, over the course of the experiment, targets in the baseline conditions might have been processed faster and created a cost for the subdominant. To investigate changes of observed priming effects between the beginning and the end of the experimental session, we performed an additional analysis on response times for the first three and last three instances of each condition with correct responses. Response times were analyzed with a 3 × 2 ANOVA with context (related/less related/baseline) and position (first/last) as within-subject factors. The only significant effect was a main effect of context, $F(2, 30) = 6.31$, $MSE = 13{,}693$, $p < .01$. No main effect of position and, more important, no interaction of position with context ($F = 0.37$), was observed. The inhibition effect for the subdominant target over the baseline target was observed from the beginning of the experimental session, and the priming pattern did not change between the two temporal positions: The processing of the tonic target was the fastest, followed by the baseline target, and with the slowest response times for the subdominant target.

An alternative explanation for the observed cost of processing for the less related targets might be based on the overall dynamics of the experimental session. In Experiments 1 and 2, related, unrelated/less-related, and baseline conditions each represented one third of the experimental trials. When viewed in terms of context validity, only one third of the contexts thus produced a completely valid prediction. The relative proportion of valid contexts to invalid contexts (Experiment 1) or to less valid contexts (Experiment 2) might have been the basis for inhibition effects for unrelated and less related targets. This concern is based on psycholinguistic research in which semantic context effects have been analyzed for influences due to the characteristics of the total set of experimental stimuli (Becker, 1980; Sanocki & Oden, 1984; Tweedy, Lapinski, & Schvaneveldt, 1977). Sanocki and Oden (1984) reported that the validity of the context across the entire experimental session influences the observed context effects. When sentence contexts were incongruous with the target words as often as they were congruous, the congruous context had a slight inhibitory effect in comparison with a baseline condition. However, when the context was always congruous with the target word, a large facilitation effect was observed. For harmonic priming, a facilitation of related targets and an inhibition of less related targets was observed, but in light of Sanocki and Oden's (1984) results, the question arises as to how far the cost of the less related context would be altered if only the less related context was opposed to the baseline context.

To test whether the overall dynamics of the experimental session were the primary determinant of the cost–benefit pattern observed in Experiment 2, we compared directly the less related sequences and their matched baseline sequences in Experiment 3. Omitting the related condition allowed us to present less related and baseline conditions each on 50% of the trials and to eliminate the possibility that interference due to the related condition affects the observed inhibition of the subdominant chord.

Experiment 3: Less Related Versus Baseline Contexts

Method

Participants. Seventeen introductory psychology students participated in this experiment for course credit; none had participated in Experiment 1 or 2. Number of years of musical training, as measured by years of instrumental instruction, ranged from 0 to 14, with a mean of 7.09 (SD = 3.58) and a median of 8.

Material. The less related sequences ending on the subdominant chord and their matched baseline sequences selected from Experiment 2 were used.

Procedure. The experimental procedure was as described in Experiment 1, but the experimental phase contained 48 trials. Participants listened to 12 less related sequences and 12 baseline sequences matched to these less related sequences, presented once with a consonant target chord and once with a dissonant chord.

Results

Overall percentages of errors were 7.35% for consonant targets and 5.64% for dissonant targets. The percentage of errors for consonant targets was slightly higher for the subdominant sequences than for the baseline sequences (Table 4). The response times for the less related condition were significantly longer than for the matched baseline condition, $t(16) = 2.23$, $p < .05$, two-sided, and confirm the outcome of Experiment 2. The difference between the two conditions did not correlate with the level of musical expertise, $r(15) = -.08$. In an analysis with chord sequences as random variable, the difference between less related and baseline contexts failed to reach significance, $t(11) = 1.55$, $p = .15$. An additional analysis was run on the first and last three instances of each experimental condition, with position (first/last) and context (less related/baseline) as within-subject factors. As in Experiment 2, position was not significant and did not interact with context ($F = 0.12$). The main effect of context, however, was significant, $F(1, 16) = 7.35$, $p < .05$, with longer response times for subdominant targets than for baseline targets.

Discussion

Experiment 3 confirms the inhibition effect for subdominant targets in comparison with baseline targets. The longer response times for subdominant targets in comparison with the baseline targets cannot be explained by the dynamics of the experimental session. The tonal center established by the global context represents a cost of processing for the subdominant chord. Even if the subdominant chord belongs to the tonal center and occupies a high rank in the harmonic hierarchy (third position), the establishment of a tonal center is detrimental to its processing when it is compared with a context that does not establish a tonal center.

General Discussion

Harmonic priming research has provided evidence that the global context of a chord sequence influences the processing of a target chord (Bigand et al., 1999; Tillmann et al., 1998). Our study investigates whether the tonal center established by the global context causes a cost or benefit for the processing of the target. Following a rationale used in other domains (Neely, 1977; Posner & Snyder, 1975; Rosch, 1975), we compared baseline contexts that did not establish a tonal center with prime contexts that established variously related tonal centers. The baseline contexts were compared with related contexts ending on a tonic chord (Experiments 1 and 2), unrelated contexts ending on an out-of-key chord (Experiment 1), and less related contexts ending on a subdominant chord (Experiments 2 and 3). Results provide evidence for a facilitation of the tonic chord over the baseline target but an inhibition of both an out-of-key chord and the subdominant chord relative to the baseline target. The comparisons with the baseline contexts show a cost and benefit pattern due to the tonal center: If the context establishes a tonal center and the tonic chord occurs, the processing of this chord benefits from the tonal center. However, if another event occurs—an out-of-key chord or even another chord belonging to the key (the subdominant)—then the established tonal center causes a cost in chord processing. The present outcome suggests that an established tonal center gives rise to strong expectations for the tonic chord that—when fulfilled—selectively facilitate the processing of the tonic.[4] The tonic chord and the tonic tone reside at the top of harmonic and tonal hierarchies. For the listener, with mere exposure to musical pieces in everyday life, the tonic has taken the role of a reference point to which other musical events are anchored and referred (Bharucha, 1984; Krumhansl, 1979). A tone, for example, heard in isolation is interpreted in most of the cases as the tonic tone for a beginning melody (Francès, 1958, Experiment 4). The specific status of the tonic as the reference element in a given key might cause the facilitation observed for tonic processing, especially in contrast to subdominant processing. The processing cost for subdominant targets suggests that differences between in-key and out-of-key events are not directly reflected in relative facilitation of processing when compared with a condition without an established key. This hypothesis can be further investigated by testing cost and benefit patterns for the dominant chord, which is the second highest position in the harmonic hierarchy. Harmonic priming research up to now analyzed in-key chord relations only by comparing the tonic with the subdominant (i.e., first and third positions in the harmonic hierarchy), and even if higher order organizational levels have been analyzed (Bigand et al., 1999, Experiment 3), the effect of global context on the processing of the dominant chord has not been investigated yet. Further studies are necessary to compare the processing of the dominant chord with tonic and baseline targets (Tillmann, Janata, Birk, & Bharucha, 2003).

The data of the present study constitute the first available evidence for facilitation effects involved in harmonic priming, because Arao and Gyoba (1999) reported inhibition without facilitation for single chord contexts. In Arao and Gyoba (1999), noise bursts were used as the neutral baseline condition. The authors restricted the interpretation of their data by questioning the adequateness of the used baseline:

Table 4
Percentages of Errors and Correct Response Times (RTs; in Milliseconds) for Less Related Contexts and for Baseline Contexts Matched to Less Related Sequences in Experiment 3

Variable	Less related	Baseline (LR)
% error		
M	7.8	6.8
SE	2.5	2.2
RT		
M	832.8	790.1
SE	65.2	71.4

Note. LR = baseline matched to less related sequences.

[4] Schematic expectations for musical events might be influenced not only by the level of tonal stability but also by the typicality of sequential chord progressions (Bharucha & Todd, 1989). Our material focuses on the influence of tonal stability, as progressions created by the last two chords in related and less related sequences (V-I and I-IV, respectively) are both deemed as highly probable root progressions in Western tonal music (Piston, 1978, p. 21). Estimations of transition probabilities (Piston, 1978) might, however, raise the hypothesis that, depending on the preceding chord function, the tonic should not always be the most expected chord in a tonal context (e.g., the sixth degree is followed the most often by the second or fifth, sometimes by the third or fourth, but less often by the tonic).

> If the noise prime, which presumably has little information, consumes less processing capacity or takes less time to encode than does the chord prime, faster responses can be expected in the noise-prime control condition, thereby implying a possible underestimation of the facilitation effect. (p. 244)

In our study, we observed a facilitation effect for the tonic chord, an outcome that suggests that the baseline sequences we used were more equated in processing demands to the contexts with a tonal center than a series of noise bursts would have been. Even if the studies differ in the length of prime contexts (one chord vs. seven chords), the observed difference underlines how crucial the definition of the baseline condition is. Jonides and Mack (1984) called for caution when interpreting cost and benefits relative to neutral conditions and proposed that (a) neutral cues should be matched "on physical appearance, on potential to alert subjects generally, and on ease of encoding" (p. 41) and (b) to seek for converging measures, including the use of multiple neutral cues, the manipulation of strategies, the use of secondary tasks, and so on.

In our study, we aimed to equalize baseline sequences to tonal sequences by defining them on the basis of musical material (i.e., chords with coherent melodic lines) and creating several instances to avoid repeated occurrence of the same neutral trial. The chosen baselines represent a first step in analyzing cost and benefit patterns due to tonal centers established by global contexts. To further the understanding of costs and benefits, converging evidence should be obtained with different definitions of musical baselines without tonal center. In a related vein, additional studies might analyze the contribution of the local context to processing costs and benefits by systematically manipulating the strength of local relatedness or by introducing silent intervals preceding the target (as in Tekman & Bharucha, 1992, for one-chord primes). Future research along this line should also analyze the influence of strategies or secondary tasks (as detailed below).

One criticism against our baseline sequences and the observed cost and benefit patterns might be linked to an alternative explanation based on sensory priming. If related contexts share more tones (and their octave equivalents) with the tones of the target chord than do baseline contexts and these in turn more than unrelated and less related contexts, differences in response times might be explained solely on the basis of differences in sensory priming—with facilitated processes for targets with previously frequently occurring tones. An additional analysis of the experimental material counted pitch classes (target tones and their octave equivalents) in the prime contexts of all conditions. These target-matching tones were either simply summed up or weighted with a slight temporal decay to mimic decay of sensory memory (i.e., after each chord, the sum was weighted by 0.8 before being added to the next chord). The outcome of these analyses (Table 5) provides evidence that the frequency of target-matching tones in the global context cannot predict the observed cost and benefit patterns, especially in Experiment 2. For the material of Experiment 1, more target-matching tones were present in related contexts than in baseline contexts, and slightly fewer were present in unrelated contexts than in baseline contexts. The weak difference between baseline and unrelated contexts further decreased when the temporal decay was applied. These patterns mirror the relative benefit pattern observed in human listeners but underestimate the cost of out-of-key contexts. For the material of Experiment 2, more target-matching tones were present in related and less related contexts than in baseline contexts. Contrary to the observed behavioral data, the number of target-matching tones would predict (with and without temporal decay) that related and less related targets are facilitated over baseline targets (with stronger facilitation for related targets).[5]

Table 5
Number of Pitch Classes Shared Between the Target Chord and the Preceding Context Averaged Over the Sequence Set: Summed Over the Prime Context and Weighted by a Temporal Decay for Related, Unrelated, Less Related, and Baseline Contexts

Version	Related	Unrelated	Less related	Baseline (R)	Baseline (LR)
Sum					
M	16.67	4.25	13.41	5.75	6.42
SE	0.66	0.35	0.53	0.49	0.50
Decay					
M	9.15	3.18	7.10	3.64	4.08
SE	0.46	0.22	0.29	0.21	0.27

Note. R = baseline matched to related sequences; LR = baseline matched to less related sequences.

Simulations With a Connectionist Model of Tonal Knowledge Activation

Previous priming data with an established tonal center have been modeled by the activation of tonal knowledge representation and the accumulation of activation patterns over time (e.g., Bharucha, 1987; Bigand et al., 1999). When a tonal context is presented to the model, the underlying harmonic hierarchy of the tonal center emerges and the relative facilitation of chords is simulated by the relative activation of chord units. The comparison of activation patterns arising from well-defined harmonic contexts with those arising from the baseline contexts tested whether a spreading activation model can account for the observed cost and benefit patterns.

We ran simulations with the experimental material (related, unrelated, less related, and baseline sequences) used in the present

[5] The analyses also revealed that the tonal sequences used in the present study (Bigand & Pineau, 1997; Pineau & Bigand, 1997) did not control for target tone frequency in the prime contexts. The differences in target-matching tones suggest that the facilitation of the tonic target in comparison with subdominant and out-of-key targets might be explained on the basis of sensory priming. This criticism on contributions of acoustic factors of the prime context was addressed in the original study with regression analyses showing that harmonic function of the target (tonic vs. subdominant) was the sole variable explaining response times (Bigand & Pineau, 1997). Recent harmonic priming studies that systematically manipulated frequencies of target tone occurrence in prime contexts provide evidence that cognitive priming prevails over sensory priming (Bigand et al., 2003; Bigand, Tillmann, Manderlier, & Poulin, 2001; Poulin, Bigand, D'Adamo, Madurell, & Tillmann, 2000). For example, the processing of the tonic target was facilitated in comparison with the subdominant target even if the subdominant target (but not the tonic target) was part of the prime context (Bigand et al., 2003).

study.[6] Figure 3 displays relative activations of all major chord units after the first seven chords for the different contexts. For related sequences, activations reflected the harmonic hierarchy of C Major, with the tonic chord (C Major) being the most activated and activation levels decreasing with increasing harmonic distance. For less related sequences, the activation curve was shifted in comparison with related sequences, with G Major being at the top. For unrelated sequences, the activation pattern almost reversed and reflected the key of B Major, with some influence of the local context (i.e., the G Major chord preceding the C Major target). All three contexts that establish a tonal center reflected—despite some local influence of the preceding chord—the harmonic hierarchies of the respective tonal centers, with strong differences in activation levels depending on the key memberships of the chords. However, after the baseline contexts, which did not establish a tonal center, the activation levels did not show strong differences between the 12 major chords, and all units were more or less uniformly activated, with some local influence of the G major chord.

Only the activation levels of the target chord unit were relevant for the simulation of the priming effects (Figure 4). Following related contexts, the target chord unit was more strongly activated than when it followed the unrelated contexts (Figure 4, left) and the less related contexts (Figure 4, right). This activation pattern simulates the relative facilitation of target processing by directly comparing events after contexts establishing a tonal center (cf. also Bigand et al., 1999; Tillmann & Bigand, 2001; Tillmann et al., 1998). The comparison with the baseline target showed stronger activation for the related target but weaker activation for the unrelated target and slightly weaker activation for the less related target. The targets in the two baseline sequences were similarly activated.

The activations of the target chord unit in the two experimental situations simulated the behavioral data as a pattern of relative differences: The model predicts a benefit for the tonic chord and a cost for unrelated and less related targets. The simulations suggest

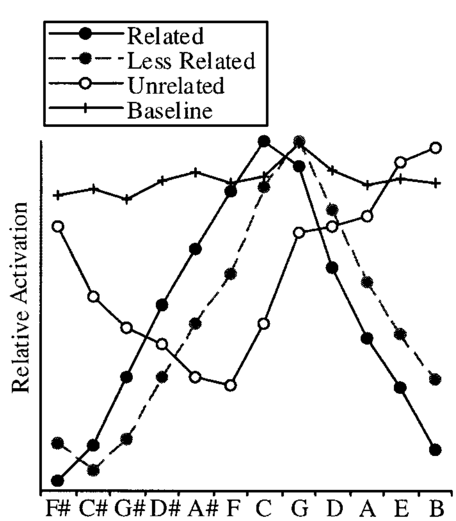

Figure 3. Relative activations for all major chord units after the first seven chords of all sequences in each experimental condition. The simulations were run with all sequences, and relative activation patterns were then centered with the C Major chord as target chord.

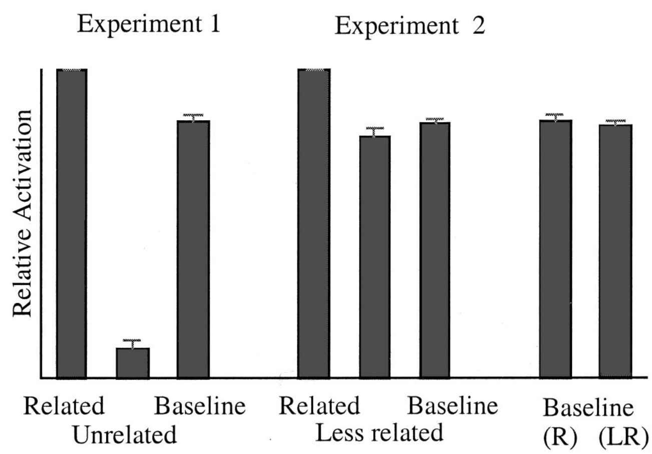

Figure 4. Relative activations for the target chord units in the experimental conditions of Experiment 1 (related, unrelated, baseline) and Experiment 2 (related, less related, baseline). R = baseline sequences matched to related sequences; LR = baseline sequences matched to less related sequences. Error bars represent standard errors.

that the observed relative patterns of behavioral costs and benefits can be explained in terms of accumulated activation in tonal knowledge structures. The strong activation differences established by a tonal context result in a benefit of processing for the event at the top of the tonal context profile but in a cost of processing for an out-of-key chord and for the subdominant chord, both of which have a lower position in the profile.

Activation profiles in the chord units arise from activation reverberating through excitatory links followed by a final scaling (i.e., normalization) of the output unit activations. A discussion of the scaling step is relevant because the choice of the scaling factor influences the relative chord unit activations and because normalization implicitly introduces inhibitory mechanisms into the model. Both of these issues are addressed in more detail below.

In previous work, the output of the chord units has been based on strength of activation relative to the most strongly activated unit in the layer (Bharucha, 1987; Tillmann et al., 2000). Thus, the activation r of a major chord unit i is defined as

$$r(i) = \mathbf{a}(i)/\max(\mathbf{a}), \qquad (1)$$

with **a** being a vector of absolute activations of all major chord units. One likely consequence of scaling by the most strongly activated unit in the chord layer is that the normalized output values are uniformly high for situations in which the absolute activation differences between units are small, as was the case for the baseline sequences.

[6] Simulations were run for all sequences with an implementation of Bharucha's (1987) model on Matlab (see Bigand et al., 1999). For each sequence, the first seven chords were presented to the model. Given that the interstimulus interval between chords was set to zero 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 in the reported simulations. The activation patterns of the major chord units were centered to C Major as target chord and averaged over all sequences in Figures 3, 4, and 5.

Other definitions of relative activation strength have been proposed in the connectionist modeling literature. One measure of relative strength is based on the Luce (1963) ratio (Cleeremans, 1993; McClelland & Elman, 1986; McClelland & Rumelhart, 1981), which divides the activation of a target unit by the sum of activations of all output units:

$$r(i) = \mathbf{a}(i)/\mathrm{sum}(\mathbf{a}). \quad (2)$$

Simulations with our experimental material based on Luce's (1963) ratio scaling (Figure 5) indicate that only the baseline sequences were sensitive to the change in scaling. For sequences that establish a tonal center, the activation patterns were insensitive to the scaling, and the predictions for the target remained as before: stronger activation for the tonic target than for the subdominant target and the out-of-key target. However, for the baseline sequences, the scaling based on the Luce ratio placed the flat activation curve at a lower level. The outcome still predicted a cost for out-of-key targets in comparison with baseline targets, but the change in activation level incorrectly predicted a benefit for less related targets. Thus, normalization by max(**a**) afforded a better match of the model to the behavioral data than did normalization using sum(**a**). The simulations with two scaling definitions allow us to gain further insight into the type of inhibitory processes that captures more closely behavioral patterns.

Although the model based on the maximum scaling simulated the relative differences from baseline, it did not simulate the magnitudes of differences observed for human listeners. For Experiments 1 and 2, the magnitudes of response time differences between unrelated and baseline and between less related and baseline contexts were comparable to the response time difference between related and baseline contexts. However, the model grossly overestimated the cost for the unrelated target and underestimated the cost for the less related target. These discrepancies suggest supplementary processes for human listeners that are not captured by the spreading activation model in its present form. This outcome can be linked to recent simulations of harmonic priming, for which observed discrepancies with behavioral data suggested further developments of the model (i.e., integration of in-layer links among chord units; Bigand et al., 2003).

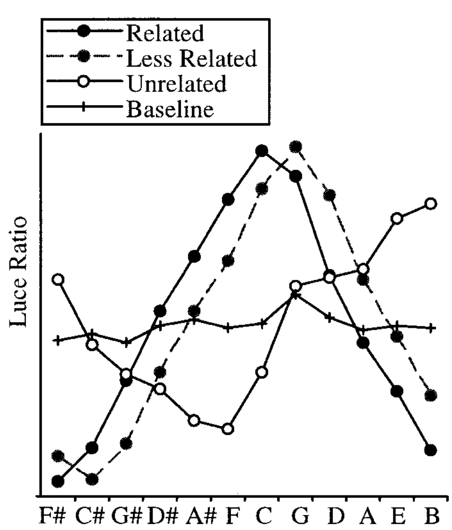

Figure 5. Relative activations based on Luce ratio for all major chord units after the first seven chords of all sequences in each experimental condition.

One long-term goal of this research on costs and benefits is to establish a mapping between behavioral and modeling results that simultaneously explains the relationships among underlying cognitive and neural processes and equivalent computational operations. In establishing this mapping, terminologies used across the cognitive, modeling, and neural domains must be heeded. For example, in a cognitive approach, the concepts of costs and benefits refer to facilitation and inhibition relative to a baseline state. These terms map loosely onto the neural principles of excitation and inhibition, which themselves are manifested as increased and decreased neural firing rates, respectively, relative to a baseline firing rate. Computations in neural network models, such as the one we used, map more directly onto neural mechanisms (i.e., summation across positively weighted inputs reflects excitatory mechanisms, whereas normalization by a scaling factor reflects inhibitory mechanisms; Levine, 1991). Given our current model and behavioral data, we may conclude that an activation model, which incorporates computational elements that have been linked to both excitatory and inhibitory neural processes, exhibits patterns of activation that resemble patterns of cognitive facilitation and inhibition observed in the behavioral data. However, we do not conclude that cognitive facilitation and inhibition map directly onto excitatory and inhibitory mechanisms (computational and neural), respectively.

Automatic Activation Versus Attentional Processes

Our study investigates for the first time the cost and benefit patterns in long musical contexts by comparing in-key and out-of-key chords and two levels of in-key chords. The simulations with the connectionist model suggest that facilitation and inhibition involved in harmonic priming are based on activation spreading and accumulating in a tonal knowledge representation, with the caveat that absolute magnitudes of response time differences have not been replicated. To further the investigation of processes underlying harmonic priming, we integrate our experiments in a framework that has motivated a large pool of psycholinguistic research analyzing costs and benefits in semantic and syntactic priming (e.g., Deutsch & Bentin, 1994; Neely, 1977; Stanovich & West, 1979; West & Stanovich, 1982). On the basis of inhibition and facilitation patterns, Posner and Snyder (1975) proposed a two-process theory distinguishing a fast-acting automatic spreading activation component from the controlled attentional processes of expectancy formation. A benefit in processing can be based on both automatic and attentional processes, but inhibition is supposed to develop slowly under the control of the individual and to require the capacity of a limited attentional system. These postulated characteristics lead to predictions for the time course of cost and benefit patterns and their susceptibility to strategies and instructions. Manipulating the time between prime and target or manipulating the probability that the prime is a valid cue should vary the degree of active attention that participants commit to the prime. If little processing capacity is committed to the prime, then there should be automatic pathway activation that brings benefit but no cost. If participants are actively attending to the prime, then there should be benefits from both automatic activation and conscious attention that should be accompanied by costs. Manipulating stimulus onset asynchronies (SOAs) between prime and target has provided support for Posner and Snyder's theory—for example, with single word primes: With decreasing SOA (2,000 ms to 250 ms), facilitation remained constant but inhibition decreased and disappeared at the shortest SOA (Neely, 1977). The automatic spreading activation component was further supported by the finding that facilitation effects were not altered by strategic manipulations, notably by the proportion (33% to 66%) of congruous trials (e.g., Stanovich & West, 1983).

In musical priming up to now, the distinction between automatic and attentional processes has not been made. Context effects were generally interpreted as expectancy based, and automatic activation of tonal knowledge was proposed as a possible underlying mechanism (Bharucha, 1987). For the data of the present study, the simulations with the connectionist model indicate that activation spreading in a tonal knowledge representation may underlie relative patterns of costs and benefits in harmonic priming. The activation levels of target chord units simulated a facilitation of the tonic chord and an inhibition of the out-of-key target with both types of scalings and an inhibition for the subdominant target with the scaling based on the maximum. The explanation of the benefit of a tonal center based on the tonal knowledge activation process can be integrated in the framework of Posner and Snyder (1975). However, the fact that the cost of the tonal center for out-of-key targets (and for subdominant targets based on the maximum scaling) can be explained solely with automatic activation processes is incompatible with Posner and Snyder's framework. Interestingly, some results in psycholinguistic studies do not support the assumption of inhibition being solely under attentional control: Strategic manipulations by explicit instructions (Fischler & Bloom, 1979) or presentation of congruent and incongruent trials in separate blocks (Deutsch & Bentin, 1994) did not eliminate inhibition effects. These studies suggest that expectations causing inhibition not only are under strategic control but can be produced by automatic processes as well as by attentional processes (de Groot et al., 1982). Further research will be necessary to investigate the hypotheses of automatic inhibition in harmonic priming and whether additional processes involved in inhibition are under attentional control. This research line will follow the rationale of cost and benefit research in psycholinguistics that is linked to the theoretical framework of Posner and Snyder and the postulated characteristics of cost and benefit components. Manipulating the SOA between prime context and target, the frequencies of occurrence of the different prime contexts, and the instructions to participants will shed more light on the underlying processes in harmonic priming, notably to determine to what extent these processes (involved in both inhibition and facilitation) are automatic or under attentional control. In our study, the cost and benefit patterns in harmonic priming were observed with a fixed SOA between prime and target and without biasing instructions. A first step to manipulate the proportion of less congruent primes can be found in the comparison between Experiments 2 and 3. Despite the increase of less congruent contexts from 33% to 50%, the inhibition of subdominant targets persisted in Experiment 3—an outcome hinting that automatic processes are involved in the observed inhibition.

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