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Modularity in Musical Processing: The Automaticity of Harmonic Priming

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Three experiments investigated the modularity of harmonic expectations that are based on cultural schemata despite the availability of more predictive veridical information. Participants were presented with prime–target chord pairs and made an intonation judgment about each target. Schematic expectation was manipulated by the combination of prime and target, with some transitions being schematically more probable than others. Veridical information in the form of prime–target previews, local transition probabilities, or valid versus invalid previews was also provided. Processing was facilitated when a schematically probable target chord followed the prime. Furthermore, this effect was independent of all manipulations of veridical expectation. A solution to L. B. Meyer's (1967b) query "On Rehearing Music" is suggested, in which schematic knowledge contributes to harmonic expectation in a modular manner regardless of whether any veridical knowledge exists.

A paradox in the cognitive psychology of music is how a familiar piece of music can contain surprises. When listeners hear a sequence of music that they know well, there is no uncertainty about what to expect, and yet culturally atypical transitions still seem to violate expectations. This paradox is interesting because uncertainty and expectancy violation are thought to play a particularly important role in the aesthetics of music (Meyer, 1956, 1967a; see also Dowling & Harwood, 1986). In the Western musical system, expectations are created for the listener through a harmonic context and are then fulfilled or violated to varying degrees. Deviations of a musical sequence from the expected pattern create uncertainty and anticipation for the listener; this idea is consistent with broader speculations about the connection between schema disruption and emotional responses (Mandler, 1984).

If the degree to which expectation is fulfilled or violated is aesthetically important, then a musical work should lose some of its appeal when it becomes well-known to the listener. A frequently encountered work should be tedious and uninteresting because the listener already knows what to expect. However, this does not seem to be the case; an unusual harmonic progression can be interesting even when the listener knows exactly what to expect. In fact, even when someone overlearns a piece of music, as when a pianist performs from memory, unusual transitions are still in some sense surprising and aesthetically pleasing to the performer. In this article, we examine the automaticity of cultural expectations for chords (harmonic expectancy) even when they are in opposition to veridical expectations.

Schematic Expectation and Modularity

If the violation of expectations is important in musical aesthetics, then one must consider how such expectations are generated. One proposal is that harmonic schemata create expectations for sequential events typical of the musical environment. The mind is endowed with the ability to extract regularities from its surroundings, allowing an individual to process frequently encountered patterns more efficiently. Music is rich in regularities; most cultures have a highly structured system in which both the set of musical events and their temporal order are severely constrained. In Western music, the pervasive structure is called *tonality* or the *tonal-harmonic system,* and it has been prevalent for the past 400 years. Even though many composers of the past century abandoned traditional tonality for alternative forms, tonality is still ubiquitous; the older conventions are still found in most popular music genres, and these forms in turn have had their own influence on the contemporary music of non-Western cultures.

Given general cognitive principles, along with the highly structured and pervasive system of Western music, it is reasonable to propose the existence of mental representations of tonality in which general knowledge about regularities in this domain is stored. This knowledge may be the result of passive perceptual learning (Bharucha, 1991; Bharucha & Todd, 1989; Tillmann, Bharucha, & Bigand, 2000). We place an emphasis on the listener's knowledge of the sequential transition probabilities between chords in the Western idiom and the expectations generated from such knowledge. However, this is but one of many forms of

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knowledge in the musical schemata of Western listeners, with expectations deriving from higher level musical organization of pitch and rhythm as well (e.g., Krumhansl, 2000; Large & Jones, 1999; Lerdahl & Jackendoff, 1983; Narmour, 1999; for review, see Justus & Bharucha, in press).

Incidentally, it is important to distinguish between the implicit knowledge of Western tonality that could stem from passive exposure to this pervasive system and the explicit knowledge of someone trained in music theory or cognitive musicology. All speakers of a language can understand and manipulate complex grammatical structures by virtue of their implicit knowledge within that domain, without the benefit of formal training in generative linguistics. Similarly, people enculturated in an environment that includes the conventions of Western tonality will be able to comprehend and improvise within that style without having attended the conservatory. The tacit nature of this knowledge is also suggested by the fact that throughout the history of art and music, artists have not been explicitly aware of all of the conventions to which they adhered. Often, appealing patterns used increasingly often by artists are only later dubbed conventions by humanists who notice their history and are the first to explicitly conceptualize them (Meyer, 2000).

Such implicit, schematic representations offer a solution to the problem of rehearing music: Schematic expectations may be generated independently of one's knowledge of specific harmonic sequences (Dowling & Harwood, 1986). In other words, there may be musical *schemata,* representations of the harmonic events that are globally most likely to occur in Western music, and musical *memories,* representations of the harmonic events that actually do occur in a specific piece of music. Schematic representations generate *schematic expectancies* for harmonic events likely to occur in one's culture. Musical memories create *veridical expectancies* of the actual harmonic events that occur in a specific familiar piece of music (Bharucha, 1984, 1987a, 1994; Bharucha & Todd, 1989). In most cases, these two expectancies converge. However, for that familiar piece of music with unusual harmonic progressions, the two expectancies will diverge. The listener's veridical expectations for the unusual progression will be confirmed, but the schematic expectations for more probable harmonic events will be violated. Thus, even in a piece of music in which there is no harmonic uncertainty, harmonic expectations may be violated.

The idea of schematic expectation playing a role in music perception, no matter what other information the listener may know about the sequence, is reminiscent of the idea of mental modularity and input systems. Fodor (1983) has proposed a taxonomy of three fundamental psychological processes: compiled transducers, input systems, and central processors. Compiled transducers transform data from the environment, preserving all of its informational content. Input systems perform further domain-specific computations on this information, making unconscious inferences. Central processors can then perform more domain-general computations. Fodor's primary point is to characterize input systems as mental modules with particular characteristics including domain specificity, automaticity, unconsciousness, speed, and, most essentially, informational encapsulation (see also Fodor, 2000).

If harmonic schemata had modular properties, then the expectations people generate when listening to music for the most probable harmonic events would be calculated quickly and unconsciously and would be done automatically even when other cognitive systems contain competing information (see Bharucha, 1987b). In this sense, the expectations would be analogous to compelling perceptual illusions such as the Ponzo illusion, which is still interpreted incorrectly by the modular inference mechanisms of the visual system even when the perceiver knows what the correct interpretation is, or to repeatedly encountered garden path sentences, such as *the horse raced past the barn fell,* in which the past participle *raced* is repeatedly mistaken for the main verb by a grammatical parser that does not remember reading the sentence before (see Jackendoff, 1992).

Harmonic Priming Studies and the MUSACT Model

In the laboratory, listeners' expectations can be inferred by using a response time paradigm. The more the participants expect to hear a certain musical event, the faster and more accurate they will be when processing that event. These expectations can be manipulated as a function of the preceding event or harmonic context. To the extent that the perception of the second event is facilitated by expectations derived from the first event, the first event has primed the listener for the second. In determining the relationships between the event sequences that do and do not demonstrate priming effects, inferences can be made about the participants' knowledge in the domain under investigation. The existence of schematic representations of chord transition probabilities has been supported by the experiments of Bharucha and colleagues that demonstrated such priming of chords (Bharucha & Stoeckig, 1986, 1987; Tekman & Bharucha, 1992, 1998). However, none of these studies has addressed what effect veridical knowledge has on chord priming, which is essential if one is interested in the modularity of these mechanisms. Given the importance of this paradigm for our experiments, a brief review is warranted.

In each trial of the original study (Bharucha & Stoeckig, 1986), the participants were presented with two chords, a prime and a target, and were required to respond to some aspect of the target. In the majority of these experiments, the task was to identify whether the target chord was in tune or mistuned. The variable of interest, however, was the harmonic relation between the two chords, which is related to the probability of these events occurring in sequence with each other. The results indicated that responses to tuned target chords that were in a close harmonic relation with the prime (referred to as *related* or *close*) were faster and more accurate than responses to such chords distantly related to the prime (referred to as *unrelated* or *distant*). This pattern of results is hereinafter referred to as a *priming effect.* The data also revealed a response bias in that participants were more likely to judge a related target chord as more consonant; in an intonation task, a close target is likely to be judged as tuned, whereas a distant target is likely to be judged as mistuned. This bias adds to the observed priming effect for the tuned targets, because participants will be faster to identify a closely related target as tuned as their bias suggests. However, the bias reduces the priming effect for the mistuned targets (also referred to as *foils*), because participants will be faster to identify a distantly related foil as mistuned, again because this is congruent with their bias.

In a later study (Bharucha & Stoeckig, 1987), expectancies were shown to be generated at a cognitive level, by activation spreading through a representation of harmonic relationships (*spreading activation hypothesis*) rather than by perceptual priming of specific frequencies (*overlapping spectra hypothesis*). In one experiment, the priming effect was replicated using prime–target pairs in which no component tones were shared. In addition, the priming effect was also observed in a subsequent experiment in which all non-octave harmonics of the tones were stripped, eliminating all overlapping frequencies between the prime and target. The fact that the prime chords could still facilitate processing of harmonically related target chords in the absence of common frequencies provides strong support in favor of the spreading activation hypothesis, in which representations of musical regularities give rise to harmonic expectations, rather than the overlapping spectra hypothesis, in which expectations are due to lower level perceptual priming.

The MUSACT model (Bharucha, 1987a) is a connectionist model of musical harmony that accounts for the results of these priming experiments and is a specific account of a spreading activation explanation. This three-layered system of units representing pitch classes, chords, and keys, along with differentially weighted connections between them, represents the internalized knowledge of the regularities in Western music. The model can learn these regularities by passive exposure through self-organization, which is essential given that explanations of musical priming involve the passive internalization of regularities in the auditory environment (see Tillmann et al., 2000). The action of the model, briefly stated, is as follows. Pitch input provided to the tone layer sends activation through the network, which reverberates until it reaches equilibrium. The final state of the network represents both the expectations for other musical events that will follow and also the consonance with which these events will be perceived if they do in fact occur. Specifically, the activation of key units represents how established a given key is, and the activation of chord units represents the expectation for the chords that will follow.

Following the presentation of a major chord to the model, the relative activation of the other chord units will be monotonically related to their harmonic distance from the presented chord, with distance measured by their relative placements on the circle of fifths (see Figure 1). The circle of fifths, in addition to being a representation of similarity between musical keys, is also a rough representation of the transition probabilities between major chords in the Western tonal-harmonic system, with chords near each other on the circle being likely to occur in sequence with each other. For example, a C major chord is likely to be followed by an F major or G major chord, and unlikely to be followed by a G-flat major chord. Thus, in the MUSACT model, after the presentation of tones C, E, and G to the model, the C major chord will be the most highly activated, followed by F major and G major. Activation decreases around the circle of fifths with G-flat major, which is directly opposite C major on the circle and has the lowest activation. This activation represents how likely that chord is to occur next in the Western tonal-harmonic system.

To investigate the time scale of chord priming, Tekman and Bharucha (1992) varied the duration of the prime and the stimulus onset asynchrony (SOA) between the prime and target. They found that priming in both cases can occur within 50 ms and remain until at least 2,500 ms. In addition, they also provided further evidence for the spreading activation hypothesis (Experiment 4). By presenting a noise mask between the target and prime, auditory sensory memory and perceptual processing of the prime were eliminated. The fact that the usual pattern of harmonic priming was retained despite such masking supports the idea that the priming is facilitated by a cognitive representation rather than by perceptual mechanisms.

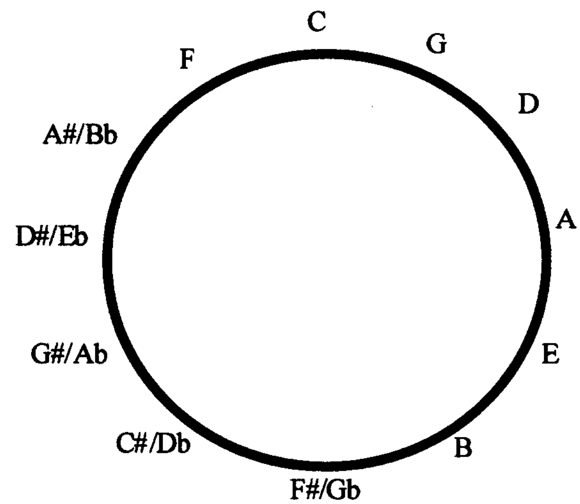

Figure 1. The circle of fifths, a representation of similarity between musical keys or of the transition probabilities between major chords in Western tonal-harmonic music.

A later study by Tekman and Bharucha (1998) clarified these findings. This study tested a prediction of the MUSACT model that at very short SOAs shared tones between the prime and target would be the primary basis of any perceptual facilitation, whereas at longer SOAs, after which the network's activation has reached an equilibrium, knowledge of harmonic relations would drive the priming effect. Target–prime pairs were chosen such that the closely related pair did not contain any pitches in common, whereas the more distantly related pairs did. If the prime was C major, the close target was D major (two places away around the circle of fifths), whereas the distant target was E major (four places away around the circle of fifths), with C major and E major sharing the pitch E. The results were that at a 50-ms SOA the distant targets were processed more efficiently, whereas at a 500-ms or longer SOA the close targets were favored. A second experiment in which neither close nor distant targets shared a tone with the prime showed that no significant priming occurred at 50 ms; but the close targets were primed at longer SOAs, providing further support that it was the common tone between the distantly related pairs that created a priming effect by 50 ms in the first experiment. In the earlier study (Tekman & Bharucha, 1992), it was the closely related pair that contained common pitches, and thus the priming effect observed at 50 ms was likely due to psychoacoustic similarity, whereas with longer SOAs it was due to implicit knowledge of harmonic relations.

These priming studies demonstrated chord priming from a local harmonic context, one chord. Global harmonic context has also been shown to influence the processing of musical events even when the local context is precisely the same. Pineau and Bigand

(1997, Experiment 2; Bigand & Pineau, 1997, Experiment 3) created pairs of eight-chord sequences in which the final two chords were identical for each pair. The first six chords, however, established two different harmonic contexts, one in which the final chord was highly expected (a tonic following a dominant) and the other in which the final chord was less highly expected (a subdominant following a tonic). In an intonation task, participants were faster and made fewer errors when the target chord was more highly expected given the global harmonic context. This result is also in accord with the MUSACT model, in which the activation of a unit (and thus expectation for it to be perceived) is a function of decaying activation from previous harmonic events, of bottom-up activation from the current stimulus, and of top-down activation from the network in response to the current stimulus.

As might be expected, the differences in the processing of a target chord embedded in a context in which it is expected, compared with one in which it is unexpected, become larger when the context's length is increased (Bigand, Mandurell, Tillman, & Pineau, 1999, Experiment 2). Furthermore, different contexts can be established by the harmonic structure of past events. Bigand and colleagues (Experiment 3) found that target chords are processed more efficiently when they are more closely related to the overarching harmonic context (as determined by the harmonic structure of a preceding phrase), even when all of the chords in the second phrase are identical.

An Experimental Investigation of Automaticity in Harmonic Priming

All of the above studies are concerned with musical expectations derived only from schematic representations. In the current experiments, we wished to examine what effect, if any, veridical knowledge about specific harmonic events would have on harmonic priming. If the solution to the problem of rehearing music is that schematic expectations for harmonic events are generated in a modular manner and operate independently of veridical expectations, then harmonic expectation should show some schematic component (a harmonic priming effect) even when veridical expectations are present. In other words, participants should still be faster and more accurate at processing harmonically related chords relative to unrelated chords, even when they have explicit expectations for the particular chord about to be heard. If this is true, then it would suggest that at some level we still expect the resolutions most probable for our culture even when we are familiar with the progression and know otherwise.

In each of the three experiments of the current study, we modified the priming paradigm of Bharucha and Stoeckig (1986, 1987) by introducing a different source of veridical information. In the first experiment, a preview was provided of the harmonic relation about to be perceived, and along with it a veridical expectation for a specific target chord. In the second experiment, the local transition probabilities of the experiment favored the more distant schematic relationship, thus creating another kind of veridical expectation within the study. Finally, in the third experiment, the full crossing of the fulfillment and violation of schematic expectation and veridical expectation was examined by using a valid–invalid preview design (see Table 1).

Table 1
The Fulfillment and Violation of Schematic and Veridical Expectations in Experiments 1, 2, and 3

Type of trial	Schematic expectation	Veridical expectation
	Experiment 1	
Close standard	Fulfilled	None
Distant standard	Violated	None
Close preview	Fulfilled	Fulfilled
Distant preview	Violated	Fulfilled
	Experiment 2	
Close	Fulfilled	None → Violated
Distant	Violated	None → Fulfilled
	Experiment 3	
Close invalid	Fulfilled	Violated
Distant invalid	Violated	Violated
Close valid	Fulfilled	Fulfilled
Distant valid	Violated	Fulfilled

Note. In the case of schematic expectation, fulfillment and violation are relative terms. The arrows indicate the accumulation of veridical expectation.

Experiment 1

The type of veridical information introduced in Experiment 1 was a preview of the chord transition. In the standard condition, participants heard a prime chord followed by a target chord. The prime and target had either a high or a low transition probability in Western tonality, representing a close or distant harmonic relationship. However, both transitions were equally probable within the experiment. On half of the trials, the target chord was mistuned. Participants were to decide as quickly as possible whether the target was tuned or mistuned.

In the preview condition, the prime–target pair was previewed in each trial, eliminating uncertainty about whether the final target was going to be close or distant. Uncertainty remained, however, regarding whether the target was tuned or mistuned. The preview established a veridical expectation that was always fulfilled, whereas the prime chord established a schematic expectation that was fulfilled to a greater extent in the close trials, because the close relationship is culturally more probable than is the distant relationship. The two kinds of expectancy were more convergent in the close trials than in the distant trials.

We predicted that schematic priming effects would still be observed in both conditions. That is, participants would have lower response times and fewer errors when making the intonation judgment for closely related tuned targets, as determined by their schematic expectations.

Method

Participants. Eighteen students at Dartmouth College (including author TJ) participated in the study, representing a wide range of musical experience. Musical training, as measured by the amount of formal study on an instrument, ranged from 0 to 16 years with a mean of 8 years and a median of 9 years. Seven participants reported having studied music theory, and 3 reported having some degree of absolute pitch. The ages of the participants ranged from 18 to 28 with a mean of 21. Four participants were members of the Dartmouth Symphony Orchestra, 7 were graduate students in the Department of Psychological and Brain Sciences (TJ overlapping both categories), and 8 were introductory psychology students who participated for class credit.

Apparatus. Chords were synthesized by an Apple Power Macintosh 7500/100 computer and presented using PsyScope (Version 1.1; Cohen, MacWhinney, Flatt, & Provost, 1993) to participants through Sony MDR-V600 headphones in a sound-attenuating chamber.

Stimuli. An equal tempered tuning system (in which one semitone corresponds to a factor of $2^{1/12}$) was used to construct the chord stimuli. Thus, a major chord consisted of three frequency chromas in the ratio $1{:}2^{4/12}{:}2^{7/12}$. Each component chroma of a chord was represented by five tones, with the loudness tapering to the threshold of hearing in the highest and lowest octaves (Krumhansl, Bharucha, & Kessler, 1982; Shepard, 1964). We used this method because it maximizes the sense of chroma and minimizes the effect of pitch height.

The mistuned chords were created in the same manner with the exception that the frequencies were in the ratio $1{:}2^{4/12}{:}2^{6.75/12}$ In other words, the fifth degree of the chord was lowered by an eighth tone (a quarter semitone, or a factor of $2^{1/48}$).

The two harmonic relationships chosen were the same as those used by Tekman and Bharucha (1998, Experiment 1). The close targets were two semitones (a major second) above the prime, whereas the distant targets were four semitones (a major third) above the prime. Thus, on the circle of fifths, the close targets were two places away from the prime and the distant targets were four places away. For these choices, perceptual priming due to overlapping frequency spectra and harmonic spreading-activation priming are in opposition. Perceptual priming speeds the processing of the distant targets, which in this case share frequencies with the prime. It would not affect the processing of the close pairs, which in this case do not share any frequencies at all. In contrast, priming due to the spreading of activation in a network of harmonic relationships facilitates the processing of the close targets relative to the distant targets.

Procedure. Participants were first given examples of the stimuli, and then they underwent an identification test to see whether they could correctly identify the tuned and mistuned chords. On each of 48 trials, a chord was played for 1,000 ms and participants responded *tuned* or *mistuned* by pressing an appropriately marked button. Then they pressed a third button to continue to the next trial. This practice set was repeated until at least 80% accuracy (39 correct responses) was achieved, at which point the main experiment began. All participants met this criterion; the majority met it in one session.

In each trial of the standard condition, the prime chord and target chord were each presented for 1,000 ms with a separation of 50 ms between the two. Participants were asked to respond as quickly as possible once they knew whether the second chord was tuned or mistuned. Feedback was provided after each response as to whether the answer was correct or incorrect, and the participants proceeded to the next trial when they were ready by pressing a third button.

In each trial of the preview condition, four chords were presented. The prime–target pair was presented twice, with each prime and target separated by 50 ms and the two pairs separated by 1,000 ms. The target chord was always tuned in the first presentation but was either tuned or mistuned in the second. The specific chords used (and thus the relationship between prime and target) were always the same for each of the two prime–target pairs. Thus, after hearing the first presentation of prime and target, the participant knew what chord to listen for when making the intonation judgment but received no information regarding whether it would be tuned or mistuned. The participants were told that in each trial the chord pairs would be repeated and that they should decide as quickly as possible if the fourth chord was tuned or mistuned. Again, feedback was provided after each response.

Within each condition (standard and preview), each of the 12 major chords occurred as the prime on four trials for each participant, followed by four different types of targets—close tuned, distant tuned, close mistuned, and distant mistuned (see Figure 2). Each participant thus received two sets of 48 trials, which were presented in random order for each participant. The order of the two conditions was counterbalanced across participants.

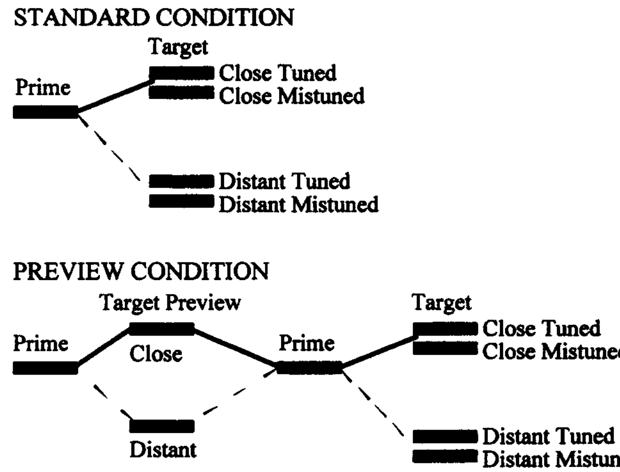

Figure 2. A representation of the trials in Experiment 1. In the standard condition, the prime is followed by a target that is either closely or distantly related to the prime and is either tuned or mistuned. In the preview condition, the target preview is predictive of whether the target is close or distant with respect to the prime but is not predictive of the target's intonation.

Prior to each condition, participants were given an opportunity to practice the task (with randomly selected trials) until they understood the instructions. The entire experiment lasted about 40 min. Participants then filled out a musical background questionnaire and were debriefed.

Results

Figure 3 presents the response time and error rate data as a function of the harmonic relation between the prime and target (close vs. distant), the intonation of the target (tuned vs. mistuned), and the condition (standard vs. preview). For the response time data, only trials in which the correct answer was given were analyzed.

Consistent with earlier chord priming studies (Bharucha & Stoeckig, 1986, 1987), close targets were processed faster than distant targets when they were tuned and more slowly than distant targets when they were mistuned, as suggested by a highly significant interaction between relation and intonation for the response time data, $F(1, 17) = 20.47$, $p < .001$. Separate analyses of the tuned and mistuned chords confirm these effects of relation: tuned, $F(1, 17) = 19.26, p < .001$; mistuned, $F(1, 17) = 11.11, p = .004$. This same interaction between relation and intonation was found in the error data as well, although this effect did not reach significance at the .05 level when the error rates were analyzed without first being transformed. However, when the percentages were corrected for unequal variance using the function $y = 2 \arcsin \sqrt{X}$ (Winer, 1971), this interaction was significant, $F(1, 17) = 6.23$, $p = .02$.

Processing was faster and more accurate in the preview condition: response time, $F(1, 17) = 4.62$, $p = .05$; error rates, $F(1, 17) = 5.56, p = .03$. However, there were no interactions between condition and either of the other two variables. Additionally,

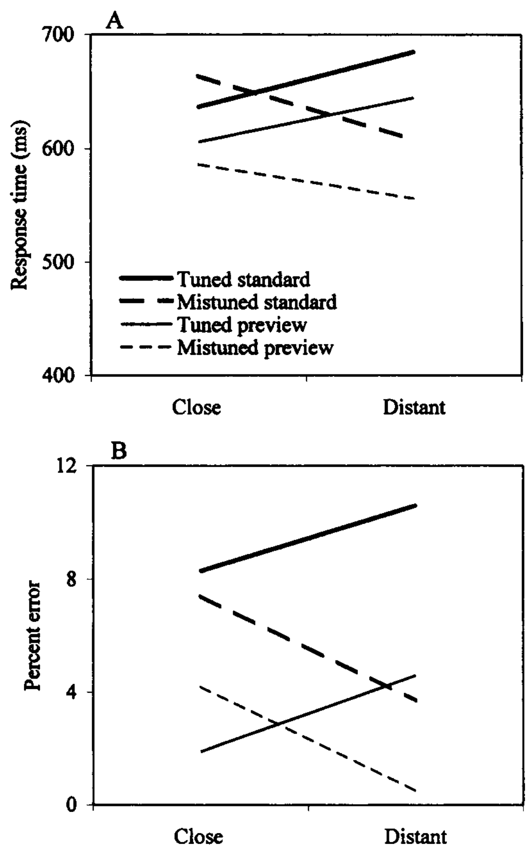

Figure 3. Results of Experiment 1. Mean response time (A) and mean error rate (B) as a function of relation (close or distant), intonation (tuned or mistuned), and condition (standard or preview).

mistuned chords were processed faster than tuned chords, $F(1, 17) = 8.86$, $p = .008$, replicating another effect found in previous priming studies (Bharucha & Stoeckig, 1986, 1987).

Fifteen out of the 18 participants showed priming effects in the standard condition. The average size of the priming effect (the mean response time for distant-tuned targets minus that for close-tuned targets) was 50 ms, indicating that on average participants were able to respond 50 ms faster to the close-tuned targets than to the distant-tuned targets. In the preview condition, 13 participants showed priming effects, and this difference was 39 ms on average.

The size of an individual's priming effect was not, however, correlated with the amount of musical training, $r(17) = .18$, $p = .5$. Musical training was a predictor of mean response time, $r(17) = -.52$, $p = .03$, and also of the total number of errors, $r(17) = -.61$, $p = .007$; people with musical experience made faster responses and fewer errors.

Unlike previous studies (e.g., Bharucha & Stoeckig, 1986) in which there was a strong bias to judge targets to be in tune when related and out of tune when unrelated, only the latter was replicated in Experiment 1. The proportion of targets judged in tune was not significantly different from chance when closely related (.50) but was significantly less than chance when distantly related (.47), $t(17) = 2.25$, $p = .04$, two-tailed.

Discussion

The standard condition replicated the schematic priming effect that has been previously reported: The processing of tuned target chords is facilitated when the target is culturally more likely to follow from the prime and thus is in a close harmonic relationship with it (Bharucha & Stoeckig, 1986, 1987). For the mistuned targets, the reverse is true; distant mistuned targets are processed more efficiently. The latter effect can be explained by an observed bias to judge distantly related chords as mistuned.

Moreover, the pattern of results was the same for both the standard and preview conditions, in which the latter provided veridical information about the harmonic relation. Participants were faster and more accurate at processing closely related tuned targets regardless of their veridical expectation. Additionally, participants were faster and more accurate overall in the preview condition, suggesting that veridical expectation does play a significant role in generating harmonic expectation. But this improvement in the preview condition was uniform across all of the other variables. The absence of any significant interaction of condition with either relation or intonation in any statistical analysis shows that the schematically based priming effect remained the same in both conditions; the presence of a veridical expectation did not eliminate the differences in the processing of schematically close targets relative to schematically distant targets.

Experiment 2

In Experiment 1, the critical comparison was between a condition in which there was no veridical expectation and another in which a veridical expectation was present and was always fulfilled. In Experiment 2, we wished to examine how another type of veridical expectation, one that was not always fulfilled, might alter the priming effect.

In previous musical priming experiments, the likelihood of the prime chord being followed by either of the two targets, one closely related and the other distantly related, was equal. In this way, one can be assured that any observed processing advantage for closely related chords is based on a musical schema, an internalization of the global musical transition probabilities of the listener's culture, and is not due to any veridical expectations based on regularities extracted from the experiment itself. In Experiment 2, we deliberately created a situation in which there was the potential for listeners to accumulate such a veridical expectation throughout the course of the experiment.

In each trial of Experiment 2, participants heard a prime chord followed by a target chord and made an intonation judgment for the target. On 25% of the trials, the target chord was closely related to the prime, and on 75% of the trials, the target chord was distantly related to the prime. In this way, a veridical expectation for the distant relation accumulated during the experiment. We chose to examine this particular combination of probabilities because in this case the veridical expectation generated is in opposition to schematic harmonic expectation. If this veridical expectation were to influence priming, we would expect to see a different priming effect at the end of the experiment, when the transition probabilities of the experiment have been internalized, relative to the beginning. To test this, participants listened to two blocks of stimuli, and priming effects were compared between the first and second blocks.

Method

Participants. Eighteen students at Dartmouth College participated in the experiment, none of whom had participated in Experiment 1. Musical training, as measured by the amount of formal study on an instrument, ranged from 0 to 11 years with a mean and median of 5 years. Two participants reported having studied music theory, and 1 reported having absolute pitch. The ages of the participants ranged from 18 to 21 with a mean of 19. All of the students in this experiment were introductory psychology students who participated for class credit. Given that no differences in the priming effect were found as a function of training in Experiment 1, musicians were not specifically recruited.

Apparatus and stimuli. Chords were synthesized and presented in the same manner as in Experiment 1.

Procedure. As in Experiment 1, participants were given examples of the stimuli and repeated an intonation identification test until they achieved at least 80% accuracy, at which point the main experiment began. Unlike Experiment 1, several participants could not meet this criterion and were dismissed from the experiment. Those who did meet the criterion often took two or three practice sessions before they achieved 80% accuracy.

In each trial, the prime chord and target chord were each presented for 1,000 ms with a separation of 50 ms between the two. Participants were asked to respond as quickly as possible once they knew whether the second chord was tuned or mistuned. Feedback was provided on the accuracy of the responses. After a few practice trials, the participants completed the first block of 96 trials. After this, they were informed that they had finished half of the experiment, the instructions were repeated, and the remaining block of 96 trials was completed. Within each of two blocks, each of the 12 major chords occurred as the prime on eight trials for each participant, followed by four different types of targets—close tuned, distant tuned, close mistuned, and distant mistuned—in the ratio 1:3:1:3 (see Figure 4). Each block of 96 trials was presented in a different random order for each participant. Participants then filled out a questionnaire and were debriefed.

Results

Figure 5 presents the response time and error rate data as a function of the harmonic relation between the prime and target (close vs. distant), the intonation of the target (tuned vs. mistuned), and the block (first vs. second). For the response time data, only trials in which the correct answer was given were analyzed.

Again, close targets were processed faster than distant targets when they were tuned and more slowly than distant targets when they were mistuned, as suggested by the significant interaction between relation and intonation for the response time data, $F(1, 17) = 5.52$, $p = .03$. A separate analysis of the mistuned chords also suggested this effect of relation, $F(1, 17) = 9.33$, $p = .007$. This same interaction between relation and intonation was found in

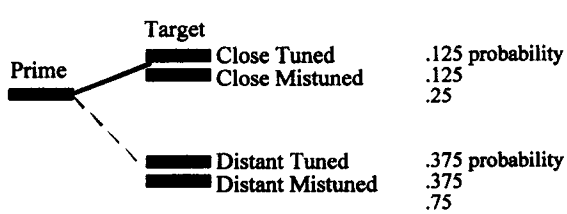

Figure 4. A representation of the trials in Experiment 2. The prime is followed by a target that is either closely or distantly related to the prime and is either tuned or mistuned. The transition probability for close targets is 25%, whereas that of distant targets is 75%. The tuned and mistuned chords occur with equal probability.

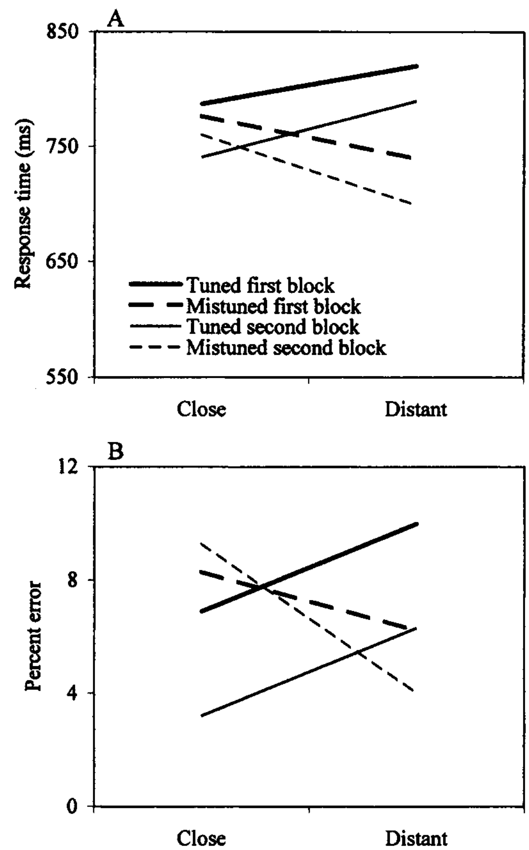

Figure 5. Results of Experiment 2. Mean response time (A) and mean error rate (B) as a function of relation (close or distant), intonation (tuned or mistuned), and block (first or second).

the error data as well, although this effect did not reach significance at the .05 level regardless of whether or not the data were transformed.

Processing was faster and more accurate in the second block: response times, $F(1, 17) = 7.13$, $p = .02$; untransformed error rates, $F(1, 17) = 4.22$, $p = .06$; transformed error rates, $F(1, 17) = 4.80$, $p = .04$. However, there were no interactions between block and either of the other two variables, indicating that the priming effect did not change over the course of the experiment. Unlike the previous experiment, the effect of intonation did not reach significance for the response time data or for the error rate data, although there was a trend for the mistuned chords to be processed faster than the tuned chords.

Twelve participants demonstrated a priming effect in the first block, and 13 participants did so in the second block. The mean size of priming for tuned chords (response time for distant-tuned targets minus that for close-tuned targets) was 33 ms in the first block and 49 ms in the second. This effect is the processing savings for the close-tuned targets relative to the distant-tuned targets.

There was a tendency in both blocks for participants to judge close targets as in tune and distant targets as mistuned. However, these proportions did not differ significantly from chance at the .05 level for either close targets or distant targets in either block.

Discussion

In Experiment 2, the unequal probability of the distant and close transitions was designed to create an expectation for the former over the latter. Given that the experimental situation was far removed from the typical musical situations in which transition probabilities would normally be encoded, as well as the relatively brief period of exposure to this set of stimuli, this expectation was regarded as a type of veridical expectation rather than a modification of the harmonic schema of the listener.

When we compare the priming effects from the first half of the experiment to the second, we see that the pattern was virtually unchanged; the processing of tuned targets was facilitated when they were closely related to or schematically more likely to follow from the prime, and the processing of mistuned targets was facilitated when they were distantly related to or schematically less likely to follow from the prime. This was despite the fact that the participants had more experience with the unequal probabilities of the experiment during the second set of trials than the first. If this veridical knowledge had interacted with schematic knowledge in determining harmonic expectation, a change in the priming effect would have been observed in the second half of the experiment. But as seen from Figure 5, in the case of both tuned and mistuned targets the differences between close and distant targets were comparable throughout the course of the experiment.

The one difference between the first and second blocks was that processing was easier during the second. As in Experiment 1, this may be an effect of veridical expectation that is independent of the effect of schematic expectation. Just as the preview manipulation in Experiment 1 yielded a uniform advantage in processing and did not interact with the effects of relation and intonation, the improvement in performance by the end of Experiment 2 was similar across the other two variables. However, given that the schematic and veridical expectations were in opposition in Experiment 2, a leveling or reversal of the priming effect would have resulted from combining these two effects even if they were independent. With this in mind, the lack of change between the first and second blocks suggests that the transition probabilities of the experiment may not have created a veridical expectation in this particular experiment; the probability ratio may not have been strong enough and/or the period of exposure not long enough. If the lower response times and error rates of the second block are reflective of an effect of veridical expectation, then it would suggest that any veridical expectation, regardless of whether or not it is accurate, facilitates processing.

An alternative cause of the main effect of block might have been a practice effect, with the benefit of previous experience making the task more intuitive for the participants. Given that the design of the experiment did not allow for counterbalancing between conditions, as was done in Experiment 1, it was not possible to eliminate the effects of practice. To distinguish between these two possibilities, it was necessary to investigate the importance of the validity of veridical expectations, and this was done in Experiment 3.

Experiment 3

Table 1 lists the various trial categories in the three experiments of this study with respect to the types of harmonic expectation introduced and their subsequent fulfillment or violation. In the first two experiments, a comparison between the presence and absence of veridical expectations is made. In Experiment 1, either a veridical expectation is present and is fulfilled (preview condition), or there is no veridical expectation at all (standard condition). In Experiment 2, the veridical expectation accumulates during the course of the experiment (as indicated by the arrows in Table 1), and it is always for the distant relationship. However, in this case, schematic and veridical expectations are somewhat confounded (intentionally) in that whenever the schematic expectation is fulfilled, the veridical expectation is violated, and vice versa. In Experiment 3, we wished to create a situation in which a relatively strong veridical expectation could be created on a trial-by-trial basis and then systematically violated in certain trials. This manipulation, based on the cue-validity method (e.g., Posner, 1980), allowed us to see whether the fulfillment and the violation of veridical expectation interacts with the fulfillment and violation of schematic expectation.

In each trial of Experiment 3, participants heard four chords consisting of a prime preview, a target preview, a prime, and a target. For 75% of the trials (the valid trials), the harmonic relationship between the prime and target in the preview was the same as in the final prime–target pair. For the remaining 25% of the trials (the invalid trials), the harmonic relationship of the prime–target preview was not the same as in the final prime–target pair; when the preview predicted the close relationship, it was followed by the distant relationship, and vice versa. Therefore, the veridical expectation is fulfilled in one type of trial and violated in the other type of trial. After combining this with the variable of harmonic relation (close vs. distant), we now had every possible combination of the fulfillment and violation of schematic and veridical expectations, as illustrated in Table 1.

We predicted that the validity of the veridical expectation would not interact with the schematically based harmonic priming effect, again suggesting that harmonic expectancy is based on schematic and veridical expectation independently. Participants should still show the same interaction between relation and intonation, regardless of whether or not their veridical expectations are accurate. We also predicted an effect of validity, in which trials accurately predicted would be processed better than those inaccurately predicted. This latter effect would support the conclusion that only a practice effect and not an effect of veridical expectation was observed in Experiment 2.

Method

Participants. Eighteen students at Dartmouth College participated in the study, none of whom had participated in Experiments 1 or 2. Musical training, as measured by the amount of formal study on an instrument, ranged from 0 to 15 years with a mean and median of 8 years. Eleven participants reported having studied music theory, and none reported having absolute pitch. The ages of the participants ranged from 18 to 20 with a mean of 19. All of the students in this experiment were introductory psychology students who participated for class credit. Despite having been recruited in precisely the same manner as Experiment 2, the musical background of these participants more closely resembled that of Experiment 1, in which some musicians were specifically recruited.

Apparatus and stimuli. Chords were synthesized and presented as in Experiments 1 and 2.

Procedure. As before, participants were first given examples of the stimuli and then tested for their ability to identify correctly the tuned and mistuned chords. This practice set was repeated until at least 80% accuracy (39 correct responses) was achieved, at which point the main experiment began. The majority of the participants met this criterion within two practice sessions.

Four chords were presented in each trial. The prime–target pair was presented twice, with each prime and target separated by 50 ms and the two pairs separated by 1,000 ms. The target chord was always tuned in the first presentation but was either tuned or mistuned in the second. For 75% of the trials, the specific chords used (and thus the relationship between prime and target) were the same for each of the two prime–target pairs. Thus, after hearing the first presentation of prime and target, the participant would expect to hear a certain chord when making the intonation judgment but would have no expectation regarding whether or not it would be tuned or mistuned. For the remaining 25% of trials, the two prime–target pairs of the trial were not congruent; when the close relationship was previewed, it was followed by the distant relationship, and vice versa. When the preview was invalid, (a) the final target chord was different from the preview and the two prime chords were always the same and (b) the trials were labeled close or distant with respect to the relationship between the final prime and target. The participants were told that they would hear four chords in each trial, that the majority of the time the fourth chord would follow from the third chord in the same way that the second followed from the first, and that they should decide as quickly as possible if the fourth chord was tuned or mistuned. Feedback on accuracy was provided after each response.

After practicing with randomly selected trials, the participants proceeded through the 192 trials of the experiment, with small pauses after every 24 trials. Each of the 12 major chords occurred as the prime on 16 trials for each participant, followed by four different types of targets (close tuned, distant tuned, close mistuned, and distant mistuned) each of which occurred four times, being preceded three times by a valid preview and one time by an invalid preview (see Figure 6). After they had finished, participants filled out the musical background questionnaire and were debriefed.

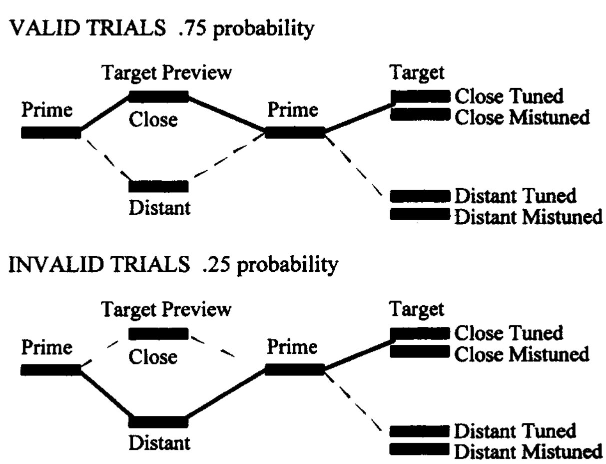

Figure 6. A representation of the trials in Experiment 3. As before, the prime is followed by a target that is either closely or distantly related and is either tuned or mistuned. For 75% of the trials, the target preview is predictive of whether the target is close or distant with respect to the prime. For the remaining 25%, the harmonic relationship between prime and target is opposite of that predicted by the preview. Neither the valid nor the invalid previews are predictive of the target's intonation.

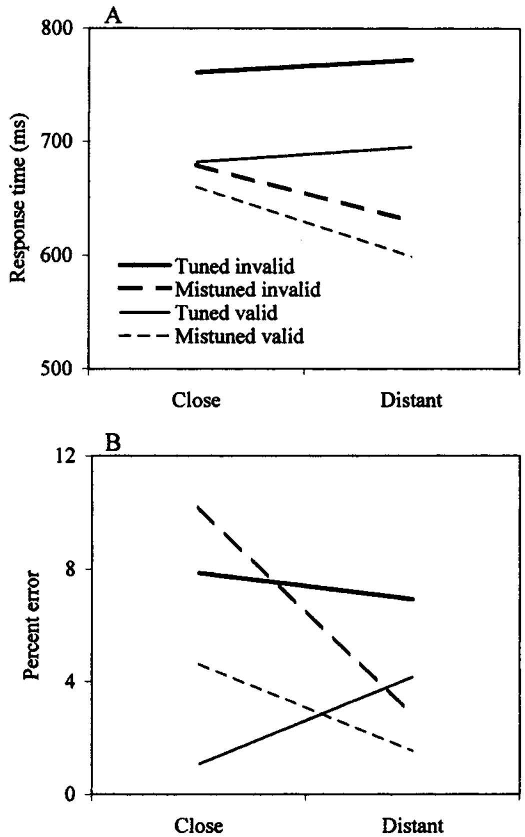

Figure 7. Results of Experiment 3. Mean response time (A) and mean error rate (B) as a function of relation (close or distant), intonation (tuned or mistuned), and preview validity (valid or invalid).

Results

Figure 7 presents the response time and error rate data, respectively, as a function of the harmonic relation between the prime and target (close vs. distant), the intonation of the target (tuned vs. mistuned) and the validity of the preview (invalid vs. valid). For the response time data, only trials in which the correct answer was given were analyzed.

As in Experiments 1 and 2, close targets were processed more efficiently than distant targets when they were tuned, whereas the reverse was the case for the mistuned targets. This is supported by the significant interaction between relation and intonation for the response time data, $F(1, 17) = 11.51$, $p = .003$. A significant effect of relation for the mistuned chords alone also supports this interaction, $F(1, 17) = 23.45$, $p < .001$. A similar interaction was observed in the error rate data as well, although it was carried largely by the mistuned chords. This interaction was significant after the error data were corrected using Winer's (1971) function, $F(1, 17) = 7.50$, $p = .01$.

Valid trials were easier to process than invalid trials; these trials were faster, $F(1, 17) = 12.08$, $p = .003$, and more accurate, $F(1, 17) = 9.93$, $p = .006$, than invalid trials. No significant interactions were observed between the validity of the trial and the other two factors. A significant effect of intonation was also found, with mistuned chords being processed faster than tuned chords, $F(1, 17) = 19.02$, $p < .001$, and with a similar but insignificant trend in the errors.

Ten participants demonstrated a priming effect for tuned chords on trials with invalid previews, whereas 12 participants did so on trials with valid previews. The mean priming effect for tuned chords (response time for distant-tuned targets minus that for close-tuned targets) was 11 ms for the invalid trials and 13 ms for the valid trials.

Discussion

Every trial in Experiment 3 introduced at least two kinds of harmonic expectation. The prime chord in each trial introduced a schematic expectation for chords likely to follow in the system of tonal-harmonic music. The target preview in each trial introduced a veridical expectation for the specific harmonic transition that the participant had just heard. Both types of expectation were then violated independently of each other. The schematic expectation was fulfilled in the close trials and violated in the distant trials, whereas the veridical expectation was fulfilled in the valid trials and violated in the invalid trials.

The results suggest that the fulfillment and violation of these two types of expectation work independently. The fulfillment and violation of veridical expectation is suggested by the differences between the valid and invalid trials, independent of the effects of schematic expectation generated by the listener's harmonic schema. The fulfillment and violation of schematic expectation is suggested by the differences between the close and distant trials, independent of the effects of veridical expectation generated by the listener's memory of the preview.

In light of the results of Experiment 3, it now seems that no effect of veridical expectation was observed in Experiment 2. Because veridical expectations must be correct if they are to facilitate processing, a veridical expectation for the distant relation would have changed the priming effect in Experiment 2. As this was not the case, the overall difference between the first and second blocks in that experiment was probably due to a practice effect.

General Discussion

In the preceding experiments, we examined how the presence of veridical information about harmonic events influences schematic chord priming. Schematic knowledge of the transition probabilities of our culture is thought to generate schematic expectations for the events most typical in any musical context, whereas veridical knowledge of specific transitions may generate veridical expectations for the events in a particular familiar sequence.

Schematic expectation was manipulated in the same manner for all three experiments, by changing the harmonic relationship (transition probability in Western tonal-harmonic music) between the prime chord and the target chord. Target chords that are closely related to the prime (following from it with a high transition probability) were processed more easily than those more distantly related to the prime (following from it with a lower transition probability), demonstrating an effect of schematic expectation.

Veridical information was presented in three different ways. In Experiment 1, some trials were previewed so that the participant would know the particular transition about to be heard. In Experiment 2, the schematically improbable transition occurred more often than the schematically probable transition. In Experiment 3, all of the trials were previewed so that a veridical expectation would be created, but not all of these expectations were fulfilled. In all cases, effects of schematic priming were observed even when more predictive veridical information was available. When instance-based veridical knowledge of a particular transition is present, the effects of culture-based schematic expectations are not eliminated; schematically probable events are still processed more efficiently than schematically improbable events.

On Rehearing Music (Meyer, 1967b)

Meyer (1967b) was one of the first to discuss the issue of rehearing music in terms of the kinetic-syntactic position of musical aesthetics. From this perspective, music causes the listener to expect (unconsciously) a set of possible subsequent events, each with a different probability. A musical event is considered informative or significant whenever it is one not highly predicted by the listener. Meyer pointed out the inherent problem with the kinetic-syntactic position and rehearing music:

> A theory of communication in which the unexpected, the ambiguous, and the less probable are of crucial importance for the understanding of, and response to, music is apparently in direct conflict with the belief that good music can be reheard and re-enjoyed countless times. For if a work has been heard already, we will *know* what is going to happen and, in later hearings, the improbable will become probable, the unexpected will be expected, and all predictions will be confirmed. According to the kinetic-syntactic view, later hearings of a work should, therefore, yield less information—and consequently less enjoyment—than earlier ones. (p. 46)

Meyer (1967b) then considered five possible explanations as to why repeated hearings of a work retain aesthetic appeal. In terms of contemporary cognitive psychology, these explanations can be summarized as follows. First, the listener may not immediately appreciate all of the implications of the work. A rich piece of music contains patterns and structure on many different levels, and the implications of the higher level structure may not be fully comprehended until the work's organization at lower levels is first understood. This may provide a mechanism for the increasing enjoyment of a work, at least for the first few hearings.

Second, the memory of the musical event may be imperfect (Meyer, 1967b). Not only may culturally unusual patterns be difficult to encode, but also the organizational principles of memory may regularize patterns according to our schematic musical knowledge. In this way, the veridical expectation formed may be somewhat inaccurate, allowing for continuing ambiguity and significance to the musical event.

Third, with each hearing of a piece of music, the listener's internal probability system, equivalent to what we have been calling the harmonic schema, may change (Meyer, 1967b). The schematic knowledge listeners use to generate expectation is presumably subject to constant subtle modification. Otherwise, their mental representations would not be able to respond to changing environmental conditions. With such plasticity, the internal probability system used to generate expectations the first time a listener hears a particular work will have altered by the next time the listener hears it. This is based on the incorporation of initial experience of the given piece, along with all of the other pieces heard in the intervening period, into the schema, and results in a unique experience on each hearing of the same piece. However, from our viewpoint, there is no need to require such a high degree of schematic plasticity to ensure the enduring aesthetic value of a work; the existence of the schema alone provides a mechanism for this.

Fourth, each performance of the piece may be a unique event (Meyer, 1967b). The specific articulatory and temporal nuances of each performer will create slightly different experiences for the listener, with sufficient differences in the arrival of the events to create renewed informativity (see also Palmer, 1997; Raffman, 1993). In the age of recorded sound, however, this explanation provides little solution to the problem of rehearing music.

Fifth, an "aesthetic illusion" may be entered in which the listener pretends to process the piece for the first time. Meyer (1967b) provided an analogy to a dramatic work: When people attend a play in which the story line is already familiar, their enjoyment may be enhanced if they pretend that they are ignorant of what is to come, enjoying the unfolding of each new event as if experiencing the knowledge for the first time. The current explanation is also similar to this point. The use of schematic, probability-based expectations when listening to music does, in some way, allow the listener to enter into a kind of aesthetic illusion in which the music is being heard for the first time.

Is Harmonic Expectation Modular?

Jackendoff (1992), in his discussion of Meyer's (1967b) work in relation to *A Generative Theory of Tonal Music* (Lerdahl & Jackendoff, 1983), makes a similar point. If the mind has the necessary structure to parse a piece of music that it has not heard before, why should it turn off these mechanisms for familiar pieces? Furthermore, how would the mind be able to verify that the piece being heard was the same as that stored in long-term memory if it were not using the same processing mechanisms as before? The musical parser appears to be ignorant of the veridical knowledge that the listener has about the piece and always processes it for the first time. Jackendoff also suggested the connection between modularity and the problem of rehearing music:

> More generally, the idea is that the music processor, like the language and visual processors, is a *module* in the sense of Fodor 1983. As such, it is "informationally encapsulated" from long-term memory of pieces: it has only the rules of musical grammar at its disposal to develop an analysis. Moreover, its operation is obligatory: in response to any plausibly musical signal, it tries its best to develop a musical structure. (p. 148)

Schematic knowledge thus serves not only as a source of expectation when the sequence of events is ambiguous, it can play a role even when other knowledge provides a more precise prediction. Musical expectation seems to be automatic, unconscious, fast, and informationally encapsulated, many of the qualities that Fodor (1983) has attributed to modular input systems. We do not suggest, however, that these mechanisms of schematic expectation are necessarily domain specific, nor do we suggest that any such mechanism evolved for musical purposes (for a discussion of these issues, see Justus & Hutsler, 2000, 2001). Modularity in this sense implies neither domain specificity nor adaptationism; both are separate issues (see Fodor, 2000).

With the modularity of schematic expectation in mind, we now have a tentative solution to the problem of why culturally unusual transitions retain an element of surprise upon repeated exposure. In this case, the expectations generated by schematic knowledge of the musical transitions most characteristic of the culture prime the listener for these events rather than those predicted by specific long-term memories. In this way, unusual harmonic progressions can continue to violate expectations even when the listener knows exactly what to expect.

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