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Music Cognition and Perceptual Facilitation: A Connectionist Framework

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The mind internalizes persistent structural regularities in music and recruits these internalized representations to facilitate subsequent perception. Facilitation underlies the generation of musical expectations and implications and the influence of a musical context on consonance and memory. Facilitation is demonstrated in experiments showing priming of chords: chords that are harmonically closely related to a preceding context are processed more quickly than chords that are harmonically distant from the context. A tonal context enhances intonational sensitivity for related chords and heightens their consonance. Facilitation occurs even when related chords don't share component tones with the context, and even when overlapping harmonics are eliminated. These results point to the indirect activation of representational units at a cognitive level. In a parallel study conducted in India, tones considered to play an important role in a rāg but absent from the experimental rendition of that rāg were facilitated in the same way. In a connectionist framework, facilitation is a consequence of activation spreading through a network of representational units whose pattern of connectivity encodes musical relationships. In a proposed connectionist model of harmony, each event in a musical sequence activates tone units, and activation spreads via connecting links to parent chord units and then to parent key units. Activation reverberates bidirectionally until the network settles into a state of equilibrium. The initial stages of the activation process constitute the bottom-up influence of the sounded tones, while the later, reverberatory stages constitute the top-down influence of learned, schematic structures internalized at the cognitive level. Computer simulations of the model show the same pattern of data as human subjects in experiments on relatedness judgments of chords and memory for chord sequences.

Introduction

Music cognition is a study of general principles of cognition as much as it is a study of music. In few domains of perception and cognition is structure as highly constrained and as well understood as it is in music. Through the

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formal work of music theorists and the empirical investigations of psychologists, we have a remarkable understanding of some aspects of musical structure (a notable example being harmony) and of the average listener's ability to recognize it. Music involves a myriad of context-dependent phenomena, some of which are specific to music (e.g., consonance) and some of which are not (e.g., expectations and implications, intuitions of coherence and anomaly, and memory). Yet the characteristics of each of these phenomena, as they apply to music, seem to be inextricably tied to constraints on musical structure. Despite our understanding of structure, however, a gnawing psychological question remains: What are the psychological processes that underlie these structural constraints and give rise to these associated phenomena?

A general principle that has emerged as fundamental to cognition is that the brain abstracts recurrent commonalities from the environment and encodes them in the form of schematic representations as a basis for future categorization and comprehension (Rosch, 1978; Rumelhart, 1977; Schank & Abelson, 1977). This principle, coupled with a highly structured musical environment, leads to the formation of schematic musical representations that, when activated by an appropriate musical context, facilitate the perception of some tones relative to others.

Cast in this perspective, music is (at least in part) a consequence of a general-purpose structure-abstracting process exposed to a highly structured acoustic environment. This is partially at odds with a strong modularity view that posits cognitive mechanisms specialized for different domains such as music and language (see Chomsky, 1980; Fodor, 1983; Gardner, 1983). However, domain-specific representations that are acquired on the basis of domain-general principles may function in a modular fashion. They may, for example, be automatic and informationally encapsulated, as suggested by our inability to completely suppress schematic expectancies even in a familiar piece of music. They may also, as Gardner (1983) claims, be anatomically distinct. Thus generality of processing principles does not preclude a compartmentalization of representations learned for different domains.

The activation of schematic representations underlies the expectation of events to follow, the implication of abstract organizational units (such as keys in music or meaning in language) and the concomitant sense of coherence. The mapping of tones onto abstract representational units as a criterion for coherence or well-formedness has been formalized in the hierarchical theories of Deutsch and Feroe (1981) and Lerdahl and Jackendoff (1983), and is analogous to hierarchical criteria for coherence in other domains (Bharucha, Olney, & Schnurr, 1985; Bharucha & Pryor, 1986).

The activation of schematic representations also determines the context's influence on memory. Events that are absent from, but consistent with, a coherent context may be erroneously judged to have occurred, whereas events that are inconsistent with this context are correctly judged to have been absent. These memory effects have been found for a range of domains, including melodies (Bharucha, 1984a; Cuddy, Cohen, & Miller, 1979; Dowling, 1978), chord sequences (Bharucha & Krumhansl, 1983; Krumhansl, Bharucha, & Castellano, 1982), rhythmic sequences (Bharucha & Pryor, 1986), and language (Bharucha et al., 1985; Bower, Black, & Turner, 1979). In music, these memory phenomena are central to the recognition of variations and motifs.

The same activation processes that underlie the above domain-general phenomena have domain-specific manifestations, one of which is the context's effect on consonance or stability. A tonal context enhances the subjective ratings of tones from the context key (Krumhansl, 1979; Krumhansl & Kessler, 1982) and of chords from the context key (Bharucha & Krumhansl, 1983; Krumhansl, Bharucha, & Castellano, 1982). Rating judgments of tones are highly correlated with how frequently or for how long tones occur in the context (Castellano, Bharucha, & Krumhansl, 1984; Krumhansl & Kessler, 1982; Krumhansl & Schmuckler, 1986). However, in ratings of tones following renditions of Indian rāgs, the judgments of Indian subjects were influenced by tacit knowledge of the schematic structure of a rāg, over and above the distribution of tones in the immediate prior context (Castellano et al., 1984). It thus appears that the typical distribution of tones over the course of one's long-term exposure stamps in schematic representations, but the immediate prior context can enhance the consonance of important tones even if they are absent from the context.

Events are thus expected, implied, erroneously judged to have occurred, and rendered more consonant, to the extent that their mental representations have been activated in anticipation of their occurrence. In order to unify these phenomena under the umbrella of the activation of schematic processes, we first need a methodology for testing the activation hypothesis. We then need a theoretical framework, based on general principles, that permits the development of precise models of activation processes in music.

Schematic Expectation and Implication

The concept of expectation is woven into the writings of music theorists and is a salient aspect of music's temporal dynamism (Jones, 1981, 1982; Meyer, 1956; Schoenberg, 1954/1969). A dominant chord, for example, "indicate[s] that the tonic is yet to come" (Schenker, 1906/1954, p. 219). A musical context sets up a graded array of expectations, providing the basis for ambiguity and varying degrees of resolution. As described by Meyer (1956), expectations may or may not be conscious. The generation and subtle violation of expectations is crucial to musical aesthetics (Meyer, 1956) and to the psychology of emotion in general (Mandler, 1984).

These expectations are generated automatically by the activation of learned, schematic representations that have abstracted typical relationships from the music to which one has had extensive exposure. When activated by an appropriate context, they prepare the perceptual system for events that are likely to occur. The potency of expectancy violation even when listening to a familiar piece (see Dowling & Harwood, 1985) attests to the existence and automaticity of a mechanism that generates schematic expectancies.

Schematic expectancies can be distinguished from veridical expectancies (Bharucha, 1987), which are generated either by the activation of memory traces for specific pieces or by explicit prior knowledge of what is to come. The possibility of conflict between schematic and veridical expectancies permits an enduring interest in a piece of music with which one is familiar. The deceptive cadence (V–vi) is thus a schematic expectancy phenomenon. Following the dominant, the tonic is irrepressibly expected at some level of representation, even though the listener may know that the submediant will follow.

We know what the patterns of expectation in tonal music are, and there are powerful accounts that explain them in terms of chord and key relationships. But *how* are these expectancies generated? What psychological processes underlie them? Consider the strong expectation for a C major chord generated by an F major chord followed by a G major chord. The usual structural explanation for this expectation is that the F and G major chords contain, between them, six of the diatonic tones in the C major scale, including two tones from the C major chord. This explanation tacitly assumes an underlying psychological process capable of computing relationships between tones, chords, and keys. The structural explanation is thus not an explanation of the underlying process. However, it places important constraints on the development of one.

More constraining to a process theory are patterns of expectation or implication that cannot be accounted for solely on the basis of the set of tones in the context. First, a sequence that contains the component tones of two different chords may imply one chord more strongly than the other. For example, B–C–D♯–E–F♯–G implies C major more strongly than B major (Bharucha, 1984a, b; Deutsch, 1984; Deutsch & Feroe, 1981). Second, a musical context may generate expectations for tones that are *absent* from the context. (Empirical evidence for this is presented below). The simple activation of detectors in the auditory system tuned to specific frequencies cannot account for these examples. They point to a cognitive system that utilizes knowledge of typical relationships encountered in the past. This system anticipates events that, based on past exposure, are likely to occur.

Empirical and Computational Support for a Connectionist Framework

The research reported in this article had two primary goals. The first goal was to develop an empirical methodology to study the activation of schematic representations. The second goal was to develop a theoretical framework in which the activation of musical representations, and the phenomena deriving from this activation, can be understood as the result of general principles of cognition operating on a highly structured auditory environment. This goal was pursued by developing a preliminary model of harmony that is empirically and music-theoretically supported and computationally specific.

The anticipatory activation hypothesis can be tested by measuring the processing time of expected versus unexpected events. If anticipatory activation is to have general perceptual and cognitive utility, it must manifest itself as an enhanced processing capability for events that are likely to occur. Perceptual facilitation can be the result of either perceptual bias, a heightened sensitivity, or both. (In semantic facilitation the effect is thought to be a bias—M. Seidenberg, personal communication, 1987). A demonstration of the perceptual facilitation of expected events would constitute a robust measure of musical expectation.

The hypothesis that anticipatory activation is mediated at the cognitive level by the representation of musical relationships can only be seriously entertained if facilitation can be demonstrated in the absence of obvious psychoacoustic cues, such as overlapping frequency spectra between the context and the expected event. The empirical component of this article is a presentation of experiments designed to measure facilitation of expected tones (in Western harmony and in Indian rāgs) and to test the hypothesis that facilitation is mediated at a cognitive level rather than by overlapping frequency spectra.

A theoretical framework that lends itself to the domain-general understanding of context-dependent processes resulting from the activation of learned schematic structures is suggested by the neural architecture of the brain. A network of neuron-like units can give rise to intelligent behavior as a result of its pattern of connectivity. By incrementally strengthening some connections and weakening others, networks can internalize environmental structure (see McClelland & Rumelhart, 1986). Although neural network models have existed for a while, even for music (see Deutsch, 1969), it is now possible, because of faster computers, to simulate networks of greater complexity. Although little is known about the specific structure of neural networks for cognition, abstract computational models (sometimes called connectionist models) can be developed with similar principles. The computational specificity of such models enables them to make predictions that can then be tested so as to estimate parameters and decide between alternatives.

A connectionist model consists of a network of simple processing units that activate each other via links of varying strengths (Feldman & Ballard, 1982; Rumelhart & McClelland, 1986). Units can be in varying states of activation and transmit activation via connecting links in proportion to the strengths (weights) of the links. Perceptual learning can occur in some classes of networks by incrementally altering the weights of links, over the course of one's exposure, so as to minimize the disparity between external and internal structure (Rumelhart & McClelland, 1986).

Connectionist networks have properties that make them compelling for musical phenomena. They support interactions between bottom-up (acoustically driven) and top-down (cognitively driven) processes. They can satisfy multiple musical constraints and search multiple musical memories in parallel and by content. They can learn without specific tutoring. They interface with sensory systems and with extra-musical memories without problems associated with cross-model translation. Finally, they obviate the explicit representation of grammatical rules.

Schematic representations should be thought of as a component of a larger, interconnected system that includes sequential memory traces of specific pieces of music. Schematic representations generate schematic expectancies and sequential memory traces generate veridical expectancies. Schematic representations can activate, and be activated by, sequential memory traces. The hierarchical analysis assigned to musical sequences (Deutsch & Feroe, 1981; Lerdahl & Jackendoff, 1983) attests to a close relationship between veridical representations of specific sequences and the schematic representations that organize them.

Figure 1 gives an overview of the relationship between schematic and sequential representations, and the role of schematic representations in generating expectations and implications, and in influencing consonance and memory. The sequential memory traces may not necessarily be musical, since nonmusical associations can be a powerful determinant of musical interpretation and memory.

The research presented in this article will be restricted to schematic processes, as delimited by the dashed box in Figure 1. The model of harmony presented below consists of a network of representational units representing tones, chords, and keys. The choice of units and the pattern of connectivity between them reflects context-neutral harmonic structure, in particular, daughter–parent relationships between tones and chords, and between chords and keys. Context-dependent phenomena in harmony *emerge* from

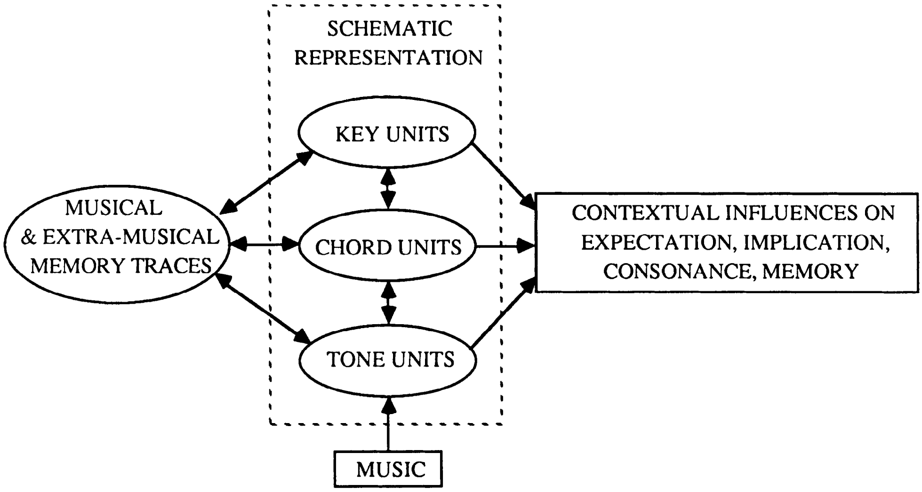

Fig. 1. An overview of the relationship between schematic representations and veridical memory traces (musical and extra-musical), which activate each other. The state of the schematic representations at any given time represents our musical expectations and implications, and governs a musical context's influence on consonance and memory.

the network's pattern of connectivity. The pattern of activation of the network following a musical context represents the array of expectations for chords to follow and the array of key implications. Representational units activated by the context transmit activation through the network via the connecting links, thereby activating keys to varying degrees. (For the psychological reality of multiple keys, see Krumhansl & Schmuckler, 1987). These keys in turn activate related chords, including some that may not have been explicitly sounded. The activation of a chord unit influences the consonance of that chord and influences the likelihood of that chord being judged to have occurred.

Perceptual Facilitation in Harmony

Facilitation was studied by developing a priming task for chords (Bharucha & Stoeckig, 1986, 1987, in prep.), which made it possible to measure the difference in processing time for chords as a function of their relationship to the preceding context. This task is adapted from the psycholinguistic study of semantic facilitation (see Swinney, 1979). In the typical psycholinguistic experiment, subjects are presented with a word (called the prime) followed by a string of letters that either forms a word in English or does not. Subjects are instructed to judge, as fast as possible, by pressing one of two keys, whether or not the letter string is a word. When the letter string is a word, it is semantically related to the prime on some trials (e.g., "nurse" following a prime of "doctor") and unrelated (e.g., "purse" following a prime of "doctor") on others. The typical result is that the related words are processed more quickly and with fewer errors than the unrelated words.

If similar principles of cognitive processing underlie musical harmony, chords that are harmonically closely related (henceforth called related) to a musical prime should be processed more quickly and with fewer errors than chords that are distantly related (henceforth called unrelated). In the musical priming task (Bharucha & Stoeckig, 1986), subjects made a true/false decision about a target chord that followed a prime chord. The prime and target were either related or unrelated, as determined by the circle of fifths.

We first employed a major/minor decision, and then, for reasons described below, settled on an intonation decision. It was important that the task involve a true/false judgment. A true/false judgment minimizes task demands and experimenter bias, and circumvents (in the case of musically trained subjects) a possible influence of the subject's explicit theoretical knowledge of harmony. During a training session, subjects were given feedback to enable them to acquire objective criteria for making the decision. With feedback, even subjects who initially claimed to be unsure of the decision had an opportunity to learn it. The task was therefore free of subjectivity, and provided a robust measure of the processes underlying harmonic expectation.

Major/Minor Discrimination

For the major/minor decision task, the target chord was either major or minor, following either a major or minor prime. The prime and target were harmonically related on half the trials and unrelated on the other half, for each combination of prime target modes. Relative chord relationships were as follows. If the prime was C major, the related target was either F major or A minor and the unrelated target was either F♯ major or D♯ minor. If the prime was A minor, the related target was either C major or D minor and the unrelated target was either F♯ major or D♯ minor. Each relationship was presented on 12 different trials over the course of the experiment, with each of the 12 chromatic tones serving as the root of the prime once. Trials were presented in random order.

Chords were constructed by sampling the components of the triad from five octaves, with loudness tapering off to threshold at the low and high ends of the frequency range (Shepard, 1964). This was done to minimize the melodic prominence of the top voice and to minimize differences based on inversion (Krumhansl, Bharucha, & Kessler, 1982).

Overall, the major/minor discrimination was made more quickly and with fewer errors when the target chord was related than when it was unrelated. However, a significant interaction reveals that the reverse was true for minor targets (see Figure 2, top), although not significantly so.

The crossing of the major and minor functions implies that the prime has a biasing effect on the target, since related targets were more likely to be judged major and unrelated targets were more likely to be judged minor. This would be expected if subjects were relying, at least in part, on the intrinsic difference between the stability or consonance of major and minor chords in order to discriminate between them, since major chords are intrinsically more consonant than minor chords (Roberts, 1983). The prime thus enhances the consonance of related chords, increasing the probability of judging them to be major, and diminishes the consonance of unrelated chords, increasing the probability of judging them to be minor.

The Effect of Context on Consonance

In order to test the hypothesis that the reversal of the predicted facilitation for minor chords was the result of the prime's biasing effect on the target's consonance, an intonation decision task was developed to test facilitation of major and minor chords separately. Subjects were to discriminate between target chords and mistuned foils. Foils were created by flattening the fifth degree of the triad by a factor of $2^{1/48}$ (an eighth-tone). Relative chord relationships were as follows. If the prime was C major, the related target was either G major or A minor and the unrelated target was either F♯ major of G♯ minor.

Each trial was preceded by a rapid sequence of 16 tones (each lasting 125 msec) whose frequencies were selected at random from the frequency continuum—a different random sequence for each trial. The purpose of this sequence was to mask the effect of the previous trial.

Both major and minor targets were processed more quickly and with fewer errors when related than when unrelated (see Figure 2, bottom). This priming effect demonstrates that a musical context facilitates the processing of related chords.

Responses to the foils (not shown here) indicated that this effect reflects two aspects of the prime's influence, as revealed by signal detection theory. First, the prime has a biasing effect on consonance. Targets and foils were both less likely to be judged mistuned when related than when unrelated. Second, the prime influences intonational sensitivity. Targets and foils were discriminated from each other more accurately when related than when unrelated.

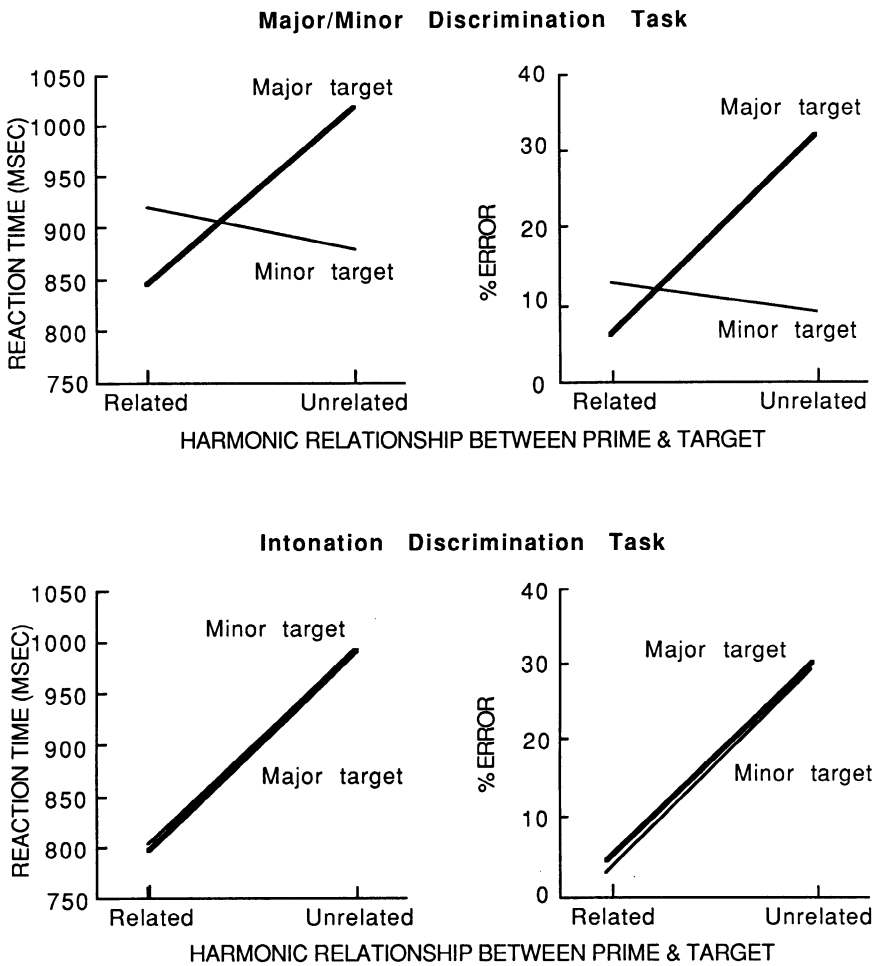

Fig. 2. (Top) Subjects made a speeded major/minor decision about a target chord following a prime chord. The prime and target were either closely related ("related") or distantly related ("unrelated") harmonically. Overall, the major/minor discrimination was made more quickly, and with fewer errors, when the prime and target were related than when they were unrelated. The reversal of this trend for minor targets indicates that related targets were more likely to be judged major and unrelated targets minor, reflecting the prime's biasing effect on the target's consonance or stability. (Bottom) Subjects made a speeded intonation judgment, discriminating target chords form mistuned foils. Both major and minor chords were processed more quickly and with fewer errors when related than when unrelated, demonstrating perceptual facilitation. The prime enhances the consonance of related targets and heightens intonational sensitivity to them. (Data summarized from Bharucha & Stoeckig, 1986).

Musical Training

The size of the priming effect (the difference in reaction time between related and unrelated targets) was not correlated with years of musical training. Although trained musicians were much faster overall, and often made no errors, they showed the same priming effect as untrained subjects. Both trained and untrained subjects thus seem to be engaging similar processes with similar structural constraints.

Shared Harmonics Don't Explain Harmonic Facilitation

Before we can conclude that schematic representations activated by the prime were responsible for the observed priming effect, we must rule out an obvious psychoacoustic explanation. The related targets in the above experiments shared a component tone with the prime, whereas the unrelated targets did not, since related prime–target pairs were adjacent on the circle of fifths whereas unrelated pairs were diametrically opposed. The first hypothesis to consider, therefore, is that facilitation is solely a consequence of the repetition of tones shared by the prime and target. If this hypothesis is confirmed, there would be no grounds for invoking the activation of representations at a cognitive level.

We therefore tested prime–target pairs that do not share component tones (Bharucha & Stoeckig, 1987). The C and B♭ major chords, separated by an intervening chord along the circle of fifths, are more closely related to each other than are the C and F♯ major chords, yet neither pair shares any tones. Using these pairs as prime and target, related targets were once again facilitated relative to unrelated targets (see Figure 3).

Despite their lack of shared component tones, however, the related targets shared harmonics. The component tones used to construct the chords contained the first four harmonics. If the prime was a C major chord, for example, the third harmonic of the component tone G was D. D was a component tone of the related target, B♭ major. The next hypothesis to consider, therefore, is that facilitation is solely a consequence of the repetition of harmonics shared by prime and target.

This hypothesis was tested by stripping the component tones of their non-octave harmonics (Bharucha & Stoeckig, 1987). The removal of harmonics slowed down the judgments but did not reduce the magnitude of the priming effect. The difference in reaction time between related and unrelated targets was about 90 msec with and without the shared harmonics (see Figure 3).

Upper harmonics are known to play a role in sensory consonance (Helmholtz, 1863/1954; Terhardt, 1984; Levelt, van de Geer, & Plomp, 1966), and in this experiment the lack of upper harmonics seems to render the intonation judgment more difficult. However, the psychoacoustic mechanisms that utilize spectral information in intonation judgments do not seem to interact with the higher cognitive mechanisms that are responsible for generating expectations, even though within the cognitive system there may be considerable interaction.

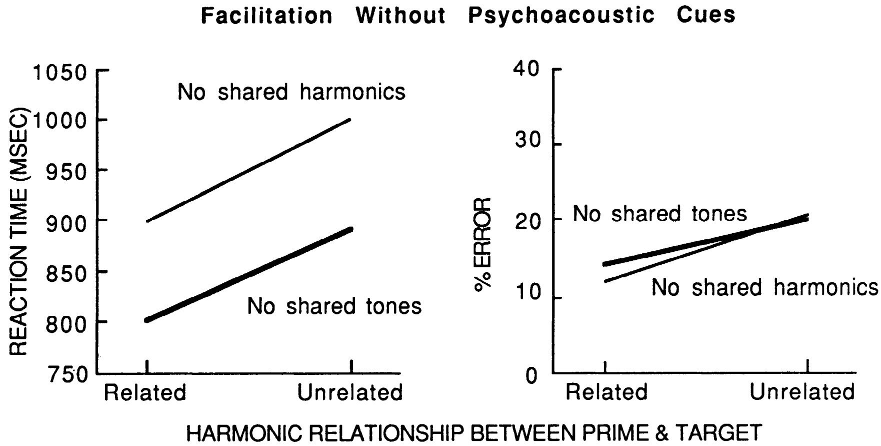

Fig. 3. In order to distinguish between psychoacoustic and cognitive explanations of perceptual facilitation, prime–target pairs with no component tones in common were selected. Related chords were processed more quickly and with fewer errors than unrelated chords. When harmonics shared by prime and target were eliminated, the difference between related and unrelated was just as strong, although the reaction times slowed down. This is evidence that cognitive mechanisms play a role in the perceptual facilitation of related chords. (Data summarized from Bharucha & Stoeckig, 1987.)

The results of the above experiments establish that shared harmonics cannot explain the perceptual facilitation of related chords. This is strong evidence for a cognitive process that, when activated by the context, facilitates the processing of related chords, even though the frequency components of the related chords were not explicitly sounded in the context.

Changing the Probabilities of Related and Unrelated Chords

In order to see if the pattern of facilitation would reverse if unrelated chords became commonplace during the experiment, unrelated targets were presented on 80% of the trials and related chords on only 20% of the trials (Stoeckig & Bharucha, 1987). Over the course of a 240-trial experiment, the priming effect was markedly reduced, but was not reversed. Schematic processes thus exhibit a weak short term malleability.

Graded Patterns of Activation

If the representational system that activates related chords internalizes relationships in music, and if the circle of fifths is an accurate formal description of these relationships, then the facilitation of related chords should decrease with greater harmonic distance. A priming experiment was carried out with intermediate degrees of harmonic relatedness to test for intermediate degrees of facilitation (Bharucha & Stoeckig, in prep.). For a C major prime, for example, the target was either G, A, F♯, E♭, or F major. Foils were mistuned variants of the targets.

Reaction times and error rates increased with the target's harmonic distance from the prime (see Figure 4).

Perceptual Facilitation in Indian Rāgs

Expectations play a dramatic role in Indian classical music. The performer begins a rendition of a rāg by straightforwardly outlining its features, including its member tones and characteristic figures. Once the rāg is well established, the performer occasionally teases the audience by setting up strong expectations and failing to resolve them. An eventual resolution brings dramatic vocal acknowledgment from the audience.

In a series of experiments I conducted in India, facilitation in Indian music was examined by a priming task adapted to the nonharmonic character of Indian music. The hypothesis was that a tone that is considered important in a particular rāg would be facilitated even if it doesn't occur in the experimental context. This would suggest that the presence of other tones, used in characteristic ways, activates the mental representation of the rāg, which in turn activates the representations of all important tones in that rāg, including those that may not have been sounded.

Subjects were presented with a context that established rāg Bhairav, a rāg common in both North and South Indian music. The experimental context is shown in Figure 5. Bhairav contains the notes Sa, Re-, Ga, Ma, Pa,

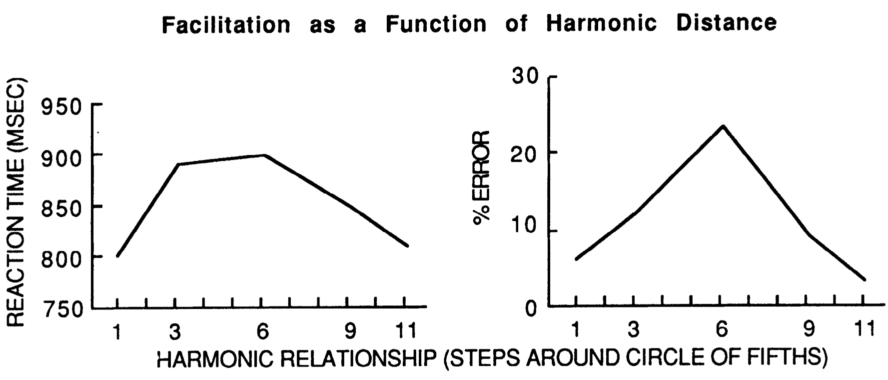

Fig. 4. The harmonic relationship between the prime and target was varied around the circle of fifths. Target chords were processed more quickly and with fewer errors the closer their relationship was to the prime. (Data summarized from Bharucha & Stoeckig, in prep.).

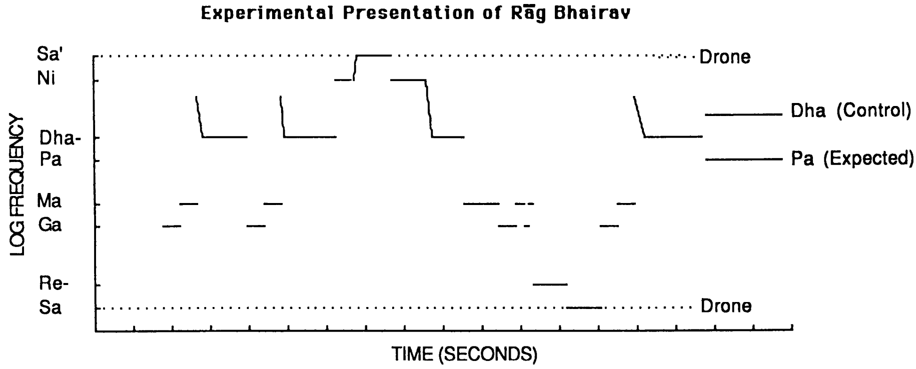

Fig. 5. Indian subjects were presented with this rendition of rāg Bhairav, followed by one of two target tones, Pa or Dha, which were to be discriminated from mistuned foils. Pa, an important note in the rāg, was absent from the context, yet is strongly expected given the context.

Dha-, Ni, Sa′ (C, D♭, E, F, G, A♭, B, C′). It also has a characteristic figure, the glide down to Dha-. This figure typically resolves to Pa. In the experimental context, Pa was omitted altogether.

Following the context, a target tone was presented that was either Pa (the expected tone) or a control tone, Dha. Both the expected tone and the control tone were equidistant from the last tone in the context, Dha-. The subject's task was to distinguish, as fast as possible, between a target (either Pa or Dha) and a mistuned foil. The foil for Pa was slightly flat and the foil for Dha was slightly sharp in order to maintain the same distance between the two foils and the last tone in the context. The subject pressed a designated key with the right hand to indicate the presence of a target, and pressed another designated key with the left hand to indicate the presence of a foil. Subjects were given training, with feedback, prior to the experiment, in order to learn which key to press in response to which tone.

The crucial comparison was between the reaction time to recognize the expected target and the control target, both of which involved the same hand. The expected tone was discriminated from its foil more quickly and more accurately than the control tone was discriminated from its foil (see Figure 6). The foils (not shown here) indicate that the facilitation takes the form of a substantially heightened intonational sensitivity, and a slight enhancement of consonance, for the related target.

In the first experiment, the context was accompanied by a drone played on Sa. The drone, which is a mainstay of Indian music, was used to make the synthesized rāg sound more natural and therefore more likely to engage

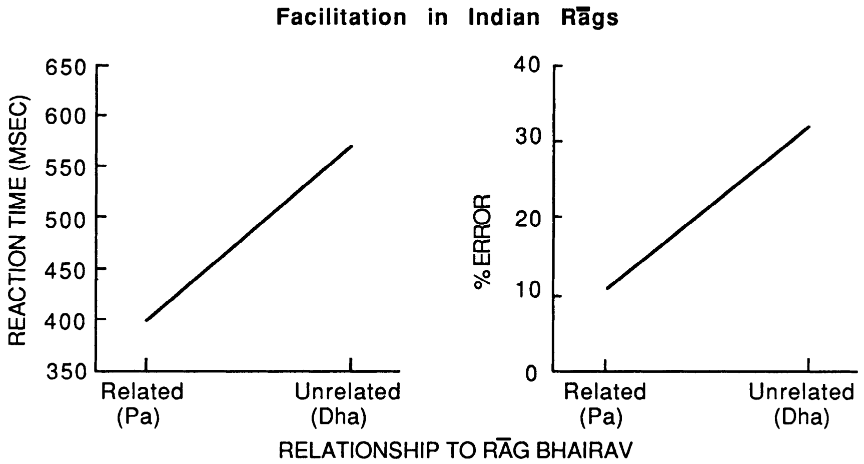

Fig. 6. Pa was discriminated from its foils more quickly and with fewer errors than was Dha. The context enhances the consonance of Pa and heightens intonational sensitivity to it.

the requisite cognitive mechanism. However, the overlap between the harmonic spectra of the drone and Pa could explain the facilitation of Pa on the basis of a repetition of harmonics.

The drone was eliminated in a second experiment. Pa still enjoyed considerable facilitation. Shared harmonics therefore cannot explain the observed facilitation. As a further test, Sa was eliminated from the context altogether; its one occurrence was replaced by silence. Once again, Pa was facilitated relative to Dha.

The rāg studies lend support to the view that a musical context activates mental representations of musical regularities. Tones that are absent from the context but typically follow are facilitated by top-down activation from these representations. Facilitation takes the form of an enhanced consonance and occasionally a heightened intonational sensitivity.

A Connectionist Model of Harmony

The experiments on perceptual facilitation of chords demonstrate that activation spreads via a representational system to representations of related but nonpresented chords at a cognitive level. This spread of activation can be modeled by a network that embodies harmonic relationships.

Figure 7 shows a network of units representing tones, major and minor chords, and major keys (future versions of the model may incorporate minor keys as well). Tone units are linked to their parent chord units, which are linked to their parent key units. The network wraps around so that the

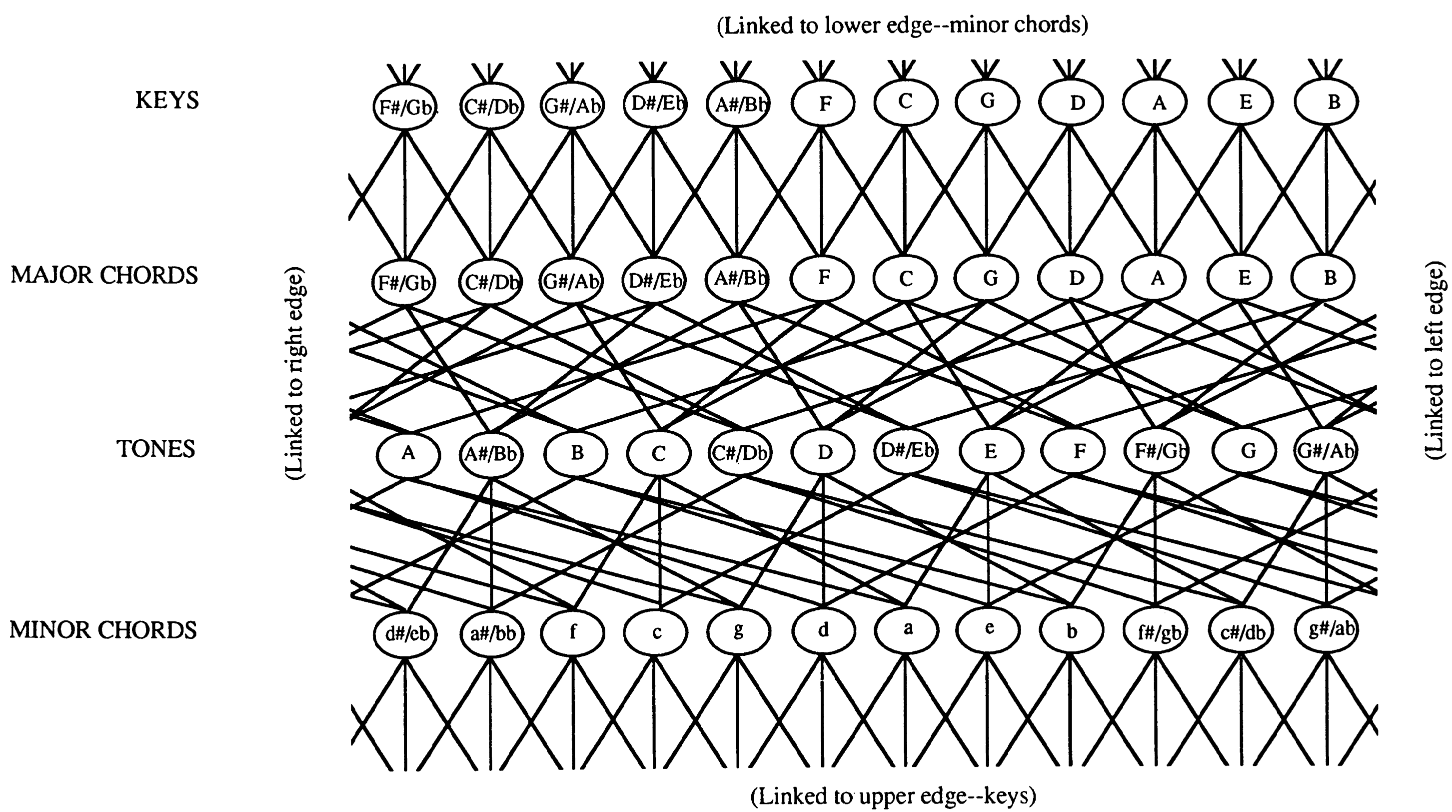

Fig. 7. A network representing relationships between tones, chords, and keys. Links between units reflect the membership of tones in chords and the membership of chords in keys. A musical context activates tone units, and activation spreads through the network, reverberating until it settles into a state of equilibrium. The pattern of activation at equilibrium represents the array of chordal expectations and key implications and influences the consonance and recognition of events that follow. (From Bharucha, 1987. Copyright by the Cognitive Science Society.)

bottom and top edges are identical and the left and right edges are identical. The links shown in the figure are the nonzero links in a general multileveled network that might have had other links strengthened if exposed to a different environment.

Tone units represent pitch classes assimilated to a chromatic schema (see Shepard & Jordon, 1984). These pitch classes are defined relative to a starting reference pitch. Thus, the letter names indicated in the figure do not represent absolute pitch levels.

The musical input to the system activates tone units, and activation spreads through the network via the connecting links. The output of the network is thus an array of activation levels for chords and keys. The levels of activation of chord units underlie the expectations for those chords and are responsible for their perceptual facilitation.

Activation reverberates through the network, passing from tones to chords and vice versa, and from chords to keys and vice versa. The activation levels of units are updated cyclically. On each cycle, a unit receives activation from all the units to which it is linked, weighted by the strengths of the links. The activation is phasic, meaning that a unit responds to a neighboring unit only in proportion to the neighbor's change in activation since the last update, not to the neighbor's absolute level of activation. Phasic activation underlies the salience of onsets in music.

Phasic activation dissipates as it reverberates through the network (because the links have relatively low weights) and the network eventually converges to a state of equilibrium. Equilibrium is the point at which the phasic activation is less than the threshold for a unit to respond. When equilibrium is reached, all the constraints embodied in the network are satisfied. (The process of settling into a state of equilibrium is assumed to occur extremely quickly—as quickly as it takes to get a good perceptual sense of a chord). The resulting pattern of activation represents the array of expectancies for chords to follow and the graded levels of key implications.

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

In order to specify the activation properties of the network more precisely, let d be the rate at which activation decays following the offset of the last event, and let t be the time transpired since the last offset. Let A be the activation received directly from the musical event. Only tone units can have non-zero values of A, because only tone units are activated directly by the music. Let $w_{i,j}$ be the weight of the link between units i and j, such that

$w_{i,j}$ is between 0 and 1. The phasic activation (i.e., the change in activation), $\Delta a_{i,e,c}$, of unit i after reverberation cycle c following event e is the weighted sum of the phasic activations of the units, j, that are linked to i, and is given by:

$$\Delta a_{i,e,c} = \sum_{j=1}^{n} w_{i,j} \, \Delta a_{j,e,c\text{-}1}.$$

The total phasic activation accumulated by unit i due to event e is thus

$$\sum_{c=1}^{q} \Delta a_{i,e,c},$$

the phasic activation summed over the q reverberatory cycles needed to reach equilibrium. The total activation, $a_{i,e}$, of unit i after event e is given by:

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

Computer Simulations of the Model: Emergent Properties

The model has been simulated with a range of weight assignments. Its behavior is quite robust under weight assignments that specifically differentiate tonal functions. According to such an assignment, the links between chords and keys that correspond to tonic relationships (the vertical lines in Figure 7) are most highly weighted, followed by the dominant and subdominant links, and then by the minor links.

However, of particular interest is a weight assignment that does not explicitly differentiate between chord functions of the same mode but only between major and minor, chord types that differ in their intrinsic or context-independent stability. The pattern of connectivity alone should endow the chords with context-dependent differentiation. According to this assignment, the links between chords and keys that correspond to tonic, dominant, and subdominant are equal, and the links for minor chords are weaker but equal among themselves. Weight assignments for the simulations reported below were .244 for links between major chords and their parent keys, .22 (90% of .244) for links between minor chords and their parent keys, and .0122 (5% of .244) for links between tones and chords.

Figures 8 and 9 show the activation levels of major chord and key units after hearing the tones C, E, and G simultaneously. Figure 8 glimpses the network after activation has reached the key level but before it has had a chance to reverberate. The state of the network therefore represents the result of bottom-up processes. The only chords activated are those that con-

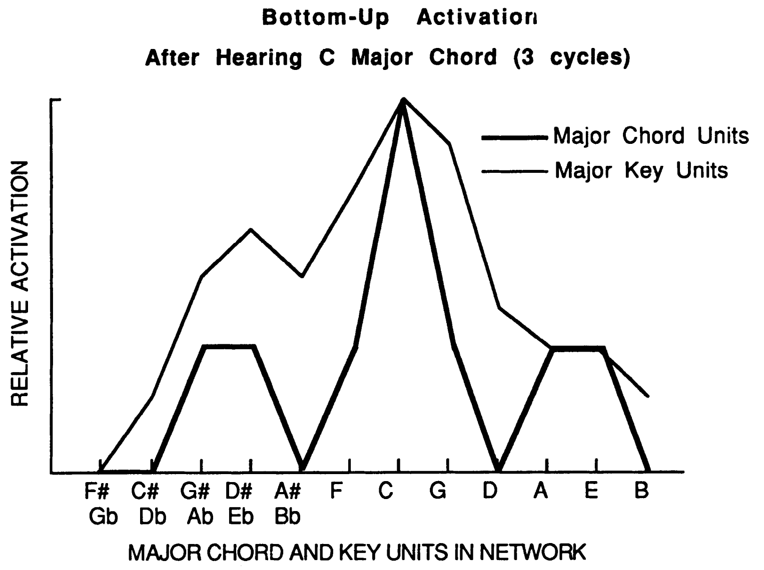

Fig. 8. The state of the network just after hearing the tones C, E, and G (a C major chord) but before activation has had a chance to reverberate back from key units to chord units. Only chord units directly activated by C, E, or G have any activation. This bottom-up process occurs in the first three cycles of network updating. In subsequent cycles, top-down influences will have a chance to assert themselves. (For Figures 8–10, activation is plotted in relative units in order to compare the *shapes* of the activation distributions. Each curve represents activation as a proportion of the highest activation value, scaled between the lowest and highest values.)

tain C, E, or G as component tones, and the only keys that are activated are those that have an activated chord as a member.

Figure 9 shows the state of the network at equilibrium, which is reached in 49 cycles with a unit threshold of .005A. Notice that, during the reverberation between cycle 4 and equilibrium, the pattern of activation has changed considerably. The learned schematic representation has had a chance to exert its top-down influence. In some cases, chords that do not contain any of the explicitly sounded tones are more highly activated than chords that do. For example, the D major chord, which receives no bottom-up activation, eventually exceeds the A major chord in activation, even though the latter receives bottom-up activation from the tone E.

The equilibrium state shows the highest activation for the C major key, with monotonically decreasing levels for keys as a function of distance from

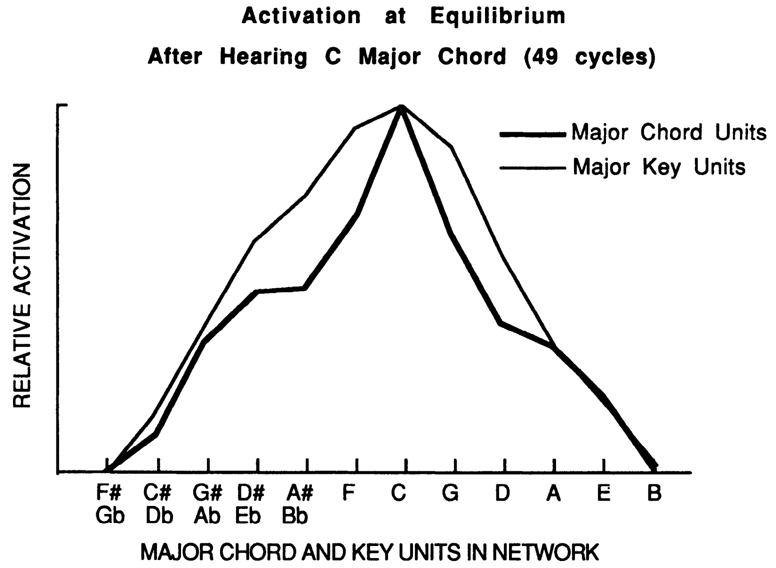

Fig. 9. The state of the network after activation has reverberated to a state of equilibrium following a C major chord. The activation of units decreases with increasing harmonic distance from C major.

C around the circle of fifths. Among the two keys adjacent to C (F and G major), F major is slightly more highly activated than G major. This means that a chord in isolation is more likely to be heard as a dominant than as a subdominant. However, it also means that, for a chord heard in isolation, the key of the subdominant is closer than the key of the dominant. This would not necessarily be inconsistent with the standard view that the key of the dominant is closer than the key of the subdominant. In a typical musical sequence, dominant chords outnumber subdominant chords, thereby activating the dominant key more than the subdominant key. In any case, the difference between the activation of the dominant and subdominant keys after hearing an isolated chord is so small as to be easily reversed by strengthening the tone-chord link that corresponds to the root of the chord, relative to the third and the fifth. Future experimentation should be able to distinguish between these alternative models.

Figure 10 shows the state of the network after hearing the F and G major chords in succession. As would be predicted by music theory, the most highly activated key is C major. Furthermore, the C major chord unit is

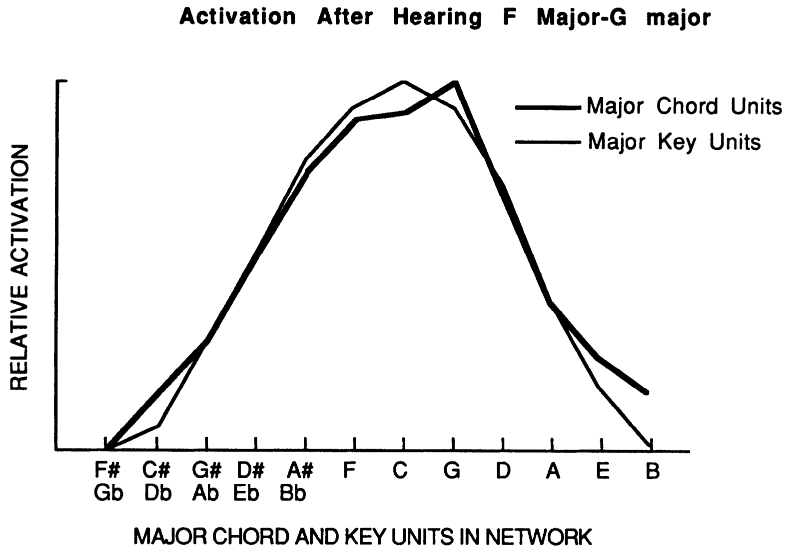

Fig. 10. The state of the network after hearing an F major chord followed by a G major chord. The most highly activated key is C major. The G major chord, having just been heard, is the most highly activated chord. However, the C major chord is more highly activated than the F major chord even though F was heard and C was not.

more highly activated than the F major chord unit, even though F was heard and C was not.

The Simulation As a Subject in Music Experiments

Simulations of the model were conducted to compare its performance with human subjects in experiments on rating judgments of, and memory for, chords (Olney, 1985). In a series of experiments demonstrating the convergence of data from rating judgments and memory confusions, subjective ratings and memory judgments of chords were obtained as a function of the harmonic context (Bharucha & Krumhansl, 1983; Krumhansl, Bharucha, & Castellano, 1982).

In the rating task, subjects heard a IV–V–I cadence followed by a pair of chords in succession. Subjects judged how closely related the last two chords sounded, in the context of the prior cadence. Chords in the pair were drawn from the set of chords that are members of maximally unrelated keys, C and F♯ major. All possible ordered pairs of chords from this set were used.

The context-dependent results can be encapsulated as follows. The closer (harmonically) the last chord was to the key of the cadence, the higher the rating. This pattern encompassed two subpatterns. First, if the two chords were members of the same key, the closer their parent key was to the cadence, the higher the rating. Second, if the two chords were members of maximally unrelated keys, ratings were higher when the chord closer (harmonically) to the cadence was last. An asymmetry analogous to this had been obtained earlier for tones (Krumhansl, 1979).

The model predicts that subject's judgments are based on the level of activation of the last chord. Thus, the computer simulation of this experiment involved a readout of the activation of the last chord. The pattern of data from the simulation was monotonically identical to the pattern of data from human subjects.

In addition to the context-dependent pattern of responses, subjects gave higher ratings when the last chord was major than when it was minor, when the data were averaged across contexts. This includes the case in which one chord of the pair was major and the other minor; subjects gave higher ratings when the minor chord was first and the major chord last than when the same two chords were reversed. The simulation exhibits this pattern of responses because major chords accrue higher levels of activation than do minor chords after reverberation, even though they receive equal amounts of bottom-up activation from their component tones.

In the memory task, subjects heard a sequence of seven chords in succession, followed by another sequence that was either identical or had one chord changed. Subjects were to judge whether the sequences were the same or different. If the sequence as a whole established a key, a change was less likely to be detected the closer the new chord was to the key of the sequence. This manifested itself in two ways. First, if both the old and new chords were about equally close to the key, a change was less likely to be detected the closer the chords were to the key. Second, if either the old or new chord was closer to the key than the other, a change was less likely to be detected when the closer of the two was the new one.

In the model, the probability with which the new chord was judged to be the same as the old one was monotonically related to the activation received by the unit representing the new chord when the old chord was heard. The key established by the sequence indirectly activates related chords. If an indirectly activated chord occurs for the first time in the second sequence, it is erroneously judged to have occurred in the first. Analogous results have been obtained for rhythmic sequences (Bharucha & Pryor, 1986) and sentence pairs (Bharucha et al., 1985), for which the analogs to key were beat and semantic theme, respectively.

Limitations of the Model's Scope

The model presented above is not intended to be a complete model of harmony, but only a demonstration of the possibility of eventually understanding the processes underlying music cognition along connectionist lines. Among the limitations of the present model are the following. It is limited to so-called vertical structure in Western harmony. Tone units serve only to channel activation to more abstract units. Future versions will have to incorporate other features of harmony, among them voice-leading, which is, at least in part, a consequence of a privileged relationship between tones proximal in pitch (see Bharucha, 1984a, b; Deutsch, 1978, 1984). The addition of tones will impose new constraints and will have to conform to the patterns of rating judgments of tones (Krumhansl & Kessler, 1982). Other melodic factors, and rhythmic factors as well, would have to play a role in any complete version. The model is also limited to schematic representations. The incorporation of sequential memory traces of specific pieces would enable recognition of familiar pieces and of variations and motifs, and will have to satisfy constraints on sequential representation, as described by Deutsch and Feroe (1981) and Lerdahl and Jackendoff (1983). In spite of these and other limitations in the model's scope, it serves as a demonstration of the naturalness with which disparate musical phenomena emerge from general principles of network activation, and therefore serves as converging evidence for connectionist processes underlying aspects of music cognition.

Connectionist Theory and Music Cognition

One of the many contributions of music theory to the psychology of music has been the identification of likely cognitive units of representation. In the absence of additional evidence, the choice of representational units for a psychological theory should be driven by our intuitions about what aspects of music are perceived to be unitary (see Anderson, 1983, for cognitive units in language). Although this criterion is atypical in connectionist modeling, the unitary quality of an abstract percept implies that there must be some level of representation onto which instances that evoke this percept map.

Typical tone clusters such as major and minor chords are heard as unitary, not just as their individual component tones. A key is a cognitive unit par excellence. It doesn't correspond to any particular acoustic property, yet is evoked by an infinite number of particular musical sequences.

This assertion about keys is not likely to find favor among psychologists of the ecological persuasion (see Bartlett, 1984; Gibson, 1979), who would suggest that the key is not a representational unit, but rather, a stimulus invariant specified by a musical sequence. However, assuming that there are no key detectors in the auditory system capable of directly picking up a key invariant over time, some high-level processing system must exist that extracts it from the output of low-level auditory processes. The representational unit for a key is a representation only insofar as its activation underlies our perception of that key. As such, it can be said to resonate to an environmental invariant (see Shepard, 1984), in accord with the ecological position.

It would be surprising if chord and key units existed innately. A more plausible hypothesis is that a hierarchical organization of units characterizes a general-purpose cognitive architecture that finds, over time, the mapping of low-level units onto high-level units that produces the optimal patterns of expectation. Thus the same neonatal networks exposed to the musics of different cultures will develop different unit mappings, but they will all have hierarchical structure.

A connectionist framework recommends itself to an understanding of music cognition for a number of reasons, some of which go beyond the scope of the particular model presented here. However, it is worth exploring the connectionist terrain as a basis for projecting the application of this framework to a wider range of musical phenomena.

Interaction between Bottom-Up and Top-Down Processes

Music cognition involves both bottom-up and top-down processes. Low level units in a network can activate more abstract, subsuming units and vice versa. A sequence of tones can thus imply chords, keys, rāgs, or perhaps phrases and motifs, which can in turn influence the perception of tones that follow. This mechanism enables the facilitation of events absent from the context.

Rule Governed vs. Rule Following Behavior

A dogma of cognitivism that derives from the computer metaphor is that intelligent systems explicitly represent the rules or laws that govern their behavior (see Fodor, 1975). Whereas the planets do not represent and follow (in the sense of consult) the laws of motion that govern them, it is often claimed that humans represent and explicitly follow the laws of cognition that govern them. Those representations are generally presumed to be strings of symbols, and cognition is thus thought to be symbol manipulation. In contrast, the regularities that govern the behavior of a network are not explicitly represented, but emerge from the constraints imposed by the pattern of connections. Although we are clearly capable of rule-following, particularly at the conscious level, the laws that govern automatic, nonconscious processes needn't be represented explicitly. Grammars are therefore valuable formal models but not models of psychological process.

In a connectionist system, constraints on processing are satisfied simultaneously rather than in sequence. In a system that follows explicitly represented rules, rules are executed in sequence because, with the execution of each rule, the state of the system may change. Hence matching the antecedent of a rule to the current state of the system requires the system to be transformed by only one rule at a time.

Parallel vs. Serial Processing

Given the speed with which musical intuitions are engaged, melodies are recognized and structure is extracted, and given the sluggishness of neuronal transmission, there is strong support for a theory that posits the simultaneous satisfaction of harmonic constraints. Parallel processing permits the simultaneous activation of memory traces. A serial search through long-term memory would be implausible given the rapidity with which we recognize pieces we have not heard for years.

With a parallel architecture, it would not necessarily be faster to recognize a piece that was heard more recently. Although decay would probably increase recognition time as a function of time since the last hearing, strength of encoding could more than compensate for this loss. It would therefore be possible that a piece heard frequently but a long time ago may be recognized more quickly than a piece heard less frequently but more recently. Factors influencing the activation of memory traces—not the position of the trace along a serial search path—would be the determinants of retrievability. These factors include all those long and short term factors that bear on the strength of the links between units in the network, and the short term pattern of activation generated by the immediate prior context. This context includes not just musical stimuli but any information that could activate musical representations by virtue of having been associated with them in the past. Many of these factors have been investigated for linguistic material (Anderson, 1983), and, if general cognitive principles cut across domains, should occur in the case of music as well.

Parallelism at particular stages of processing doesn't preclude seriality across stages. Indeed, the additive relationship between the psychoacoustic and cognitive processes in the priming task suggests seriality across stages in spite of parallelism within stages. The top-down influences within the network are thus contained within the cognitive level and don't permeate down to peripheral levels of processing.

Content-Addressable Musical Memories

A connectionist model permits the retrieval of musical memories by their content rather than by an index. Much of the recent work on artificial intelligence in the symbol manipulation tradition has been devoted to deciding on the appropriate labels that must be stored with a memory in order to index it during retrieval. This entails the advance knowledge of what aspects—musical or extramusical—of a musical memory are likely to be a basis for future retrieval. Will it be the harmonic structure, the rhythmic structure, or something about the melody that will, years hence, trigger a memory of the tune I am hearing now? Or will it be the singer's voice, the person I was with, or perhaps the smoke-filled room? Indexing is a problem for any theory that postulates the explicit representation of rules: aspects of stimuli that could cause them to serve as retrieval cues must be specified explicitly.

In a connectionist architecture, associative links are strengthened between representations of all contiguous aspects of the context that are categorized by perceptual and semantic processes during the experience. Depending upon the history of one's musical and extramusical exposure, particular combinations of stimuli on some future date may conspire to trigger a memory if its trace receives sufficient activation.

Perceptual Learning in Networks

A network internalizes environmental structure by incrementally altering connection strengths so as to minimize the disparity between the pattern of activation in the network and the environmental structure (see McClelland & Rumelhart, 1986). In music, this can be accomplished by incrementally altering the connection strengths so as to bring the expectations generated by the network in line with the transitional probabilities of the music to which one has been exposed. The violation of expectancies thus produces an error signal which, over a period of extended exposure, is minimized. This error signal could also trigger the emotional responses posited by theories of emotion that invoke expectancy violation (see Mandler, 1984; Meyer, 1956). The pattern of expectancies that results from this learning is adaptive because it anticipates events to a degree commensurate with their probability of occurrence.

The facilitatory function of mental schemata resulting from internalized structures underlies much of cognition, and the musical case can be thought of as a consequence, perhaps in part inadvertent, of a general purpose cognitive learning mechanism exposed to a highly structured musical environment. The development of musical structures may, in some cultures, have been biased in the direction of the acoustic relationships between tones because of a preference for the sensory consonance these relationships engender. Furthermore, the ubiquitous co-occurrence of frequencies in the harmonic series, resulting from the natural vibratory properties of objects, may cause the strengthening of connections between representations of these frequencies.

Neural Architecture and Physiological Reductionism

Neural plausibility has not, on the traditional cognitivist view, been a criterion for evaluating a theory. The traditional view (see Fodor, 1975) considers cognition on the model of computer software: understanding a program requires no knowledge of the underlying hardware, since the same program can be instantiated by radically different hardware. Although a cognitive state must be reducible to a physiological state token, it is not necessarily reducible to a physiological state type (Fodor, 1975). However, given the implausibility of tacitly acquiring explicitly represented rules, and given recent advances in research on network learning, physiological principles serve as promising hypotheses for studying the cognitive principles to which they give rise.

Caveat and Conclusion

The proposed model of harmony represents the internalized structure of an average Western listener who is exposed primarily to typical chordal relationships. No compositional prescription or value about tonal music is in any way entailed. The claim is only that if a musical context engages a schematic representation, perceptual facilitation will occur automatically in accord with the representation's structural constraints. A composer may choose to violate the ensuing expectancies, or to avoid a context that generates them in the first place. However, the existence of automatic facilitatory processes seems to suggest, although it does not necessarily imply, that music that at least minimally mirrors an internalized representation is likely to be more accessible to the average listener. The average listener may not have had the requisite exposure to alternative structures and may not expend the extra attention and effort needed to compensate for the absence of automatic facilitation.

In conclusion, a musical context facilitates the perception of some events relative to others. Facilitation cannot be explained by shared harmonics, thereby implicating a representational system at the cognitive level that has internalized musical structure through extended exposure. The facilitation of expected events via the activation of a representational system can be modeled as a connectionist network. Networks through which activation spreads provide a framework for understanding the cognitive processes that underlie the apparently disparate musical phenomena that are characterized by the same constraints on structure.[1]

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