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Local versus global processing of harmonic cadences in the solution of musical puzzles

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Abstract The structure of Western musical pieces is delineated by several kinds of cadence. Half cadences in the main key indicate temporary endings; authentic cadences in the main key indicate definitive endings. Authentic cadences in the dominant key are of cognitive interest, since they mark a definitive ending at a local level but a temporary ending at a global level. This study investigated the local versus global processing of these cadences. Participants were presented with sections of 16-bar minuets displayed on a computer screen in the form of a musical jigsaw puzzle. The sections consisted of either the first or the second half of the minuet (8 bars each). The first section ended with either a half cadence in the main key (all experiments), an authentic cadence in the dominant key (all experiments), or an authentic cadence in the main key (Exp. 4). The second section always ended in an authentic cadence in the main key. Participants were asked either to join the two sections of each minuet in the most coherent order (Exps. 1, 2, 4) or to rate the perceived completion of each section (Exps. 3, 4). Numerous inversion errors were observed when the first section of the minuets ended with an authentic cadence in the dominant key. Completion judgments indicated that these cadences were perceived as marking a definitive ending. Both facts suggest that local processing of harmonic cadences prevails over global processing. This finding concurs with recent studies showing that listeners had great difficulties in perceiving the higher-order organization of musical form.

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Introduction

The perception of a musical piece presupposes the understanding of structural relationships between events which are sometimes very distant from one another in time. To account for the processing of such distant relationships, it is generally assumed that local information is combined at higher, global levels to form hierarchical structures (Deutsch & Feroe, 1981; Dowling & Harwood, 1986; Lerdahl & Jackendoff, 1983; Meyer, 1956, 1973; Schenker, 1979).

Hierarchical representations of musical pieces are based on Western tonal hierarchies (see Bigand, 1993, for a review). Once the key of a musical context is recognized, the tones and the chords are perceived in a hierarchy of stability (Francès, 1984; Krumhansl, 1990). In major key contexts, the tonic tone (first degree of the scale) is perceived as more stable than the dominant tone (fifth degree of the scale), which in turn is perceived as more stable than the mediant tone (third degree of the scale). Tones of the other scale degrees are perceived as less stable, but more stable than tones out of the key. Similarly, the tonic chord (i.e., the triad built on the first degree of the scale) is perceived as a structurally more important event than the dominant chord (i.e., the triad built on the fifth degree of the scale), which is perceived as more important than chords build on the other degrees of the scale. Stable events (tones or chords) in a given musical context act as cognitive reference points to which the other events are anchored (Bharucha, 1984; Krumhansl, 1990; Laden, 1994). In Western tonal music, harmonic cadences form the most important cognitive reference points. A cadence is defined by a sequence of two chords. The authentic cadence is formed by the succession of the dominant (V) and tonic (I) chords. The half cadence is formed by the succession of a relatively unstable chord (usually the subdominant chord) and the dominant chord. Authentic and half cadences are the most important cadences in the Western musical tonal system. The authentic cadence functions as a sign of a

definitive ending, and the half cadence acts as a sign of a temporary ending that implies the appearance of an authentic cadence later on (Meyer, 1956, 1973; Narmour, 1983; Rosner & Narmour, 1992). According to several theories (Schenker, 1979; Lerdahl & Jackendoff, 1983), all the other events of the piece are more or less directly anchored to one or other of the cadences.

The way these cadences occur in time defines the overall structure of a musical piece (Lerdahl & Jackendoff, 1983). In relatively short pieces (such as those used in the present study) it is usual for the half cadence to occur at the end of the first section, and the authentic cadence at the end of the minuet (see Fig. 1a). An inversion of the sections violates the basic rule of Western harmony, since the sign of a definitive ending occurs in the middle of the piece, while the current piece finishes on a harmonic sign of temporary ending.

Western musical pieces do not necessarily remain in the same key. Even with short minuets, changes in key frequently occur in the middle of a piece, creating a temporary modulation. Western musical pieces usually modulate towards harmonically related keys, such as the dominant key or the relative major (or minor) key. Keys are said to be related when they share a great number of pitches and chords. The chromatic cycle of fifths represents these intra-key distances (Fig. 2). When a modulation occurs, listeners are supposed to remember the key with which the piece began and to continue to perceive musical events in relation to it (Schenker, 1979; Krumhansl & Kessler, 1982). A temporary modulation creates the expectation of a return to the main key. As Meyer (1956) says, "a feeling of harmonic completeness arises when the music returns to the harmonic bases from which it began" (p. 150). As a consequence, the harmonic cadences should be perceived in relation to the main key of the piece. Accordingly, an authentic cadence occurring in the key of the dominant will indicate a temporary ending that implies a return to the main key later on. In other words, an authentic cadence in the dominant key functions at a global level like a half cadence.

During the last 20 years, hierarchical representation has been accorded a great deal of attention in the field of music cognition (Bharucha, 1984; Krumhansl, 1990; Lerdahl, 1988; Lerdahl & Jackendoff, 1983; Bigand, 1993). From a cognitive point of view, the hypothesis of a hierarchical encoding of harmonic relationships is compelling for several reasons. First, it has been shown that Western listeners possess sophisticated knowledge of the tonal hierarchy, which potentially enables them to represent tonal musical pieces in a complex hierarchical event structure (Bharucha, 1984; Bharucha & Krumhansl, 1983; Krumhansl, 1990; Krumhansl & Kessler, 1982). For example, they are able to differentiate between the syntactic functions of different forms of cadences (Boltz, 1989; Francès, 1984; Imberty, 1969; Rosner & Narmour, 1992; Schwarzer, Siegismund, & Wilkening, 1993), to evaluate the strength of a modulation as a function of the distance separating the keys in the circle of fifths (Bharucha & Krumhansl, 1983; Cuddy & Thompson, 1992; Francès, 1984; Imberty 1969; Krumhansl, 1990; Krumhansl & Kessler, 1982; Thompson & Cuddy, 1989; Platt & Racine, 1994), and to perceive changes in chord functions when chords occur in different tonal contexts (Krumhansl, 1990; Krumhansl, Bharucha, & Castellano, 1982; Krumhansl, Bharucha, & Kessler, 1982; Bigand & Pineau, 1997).

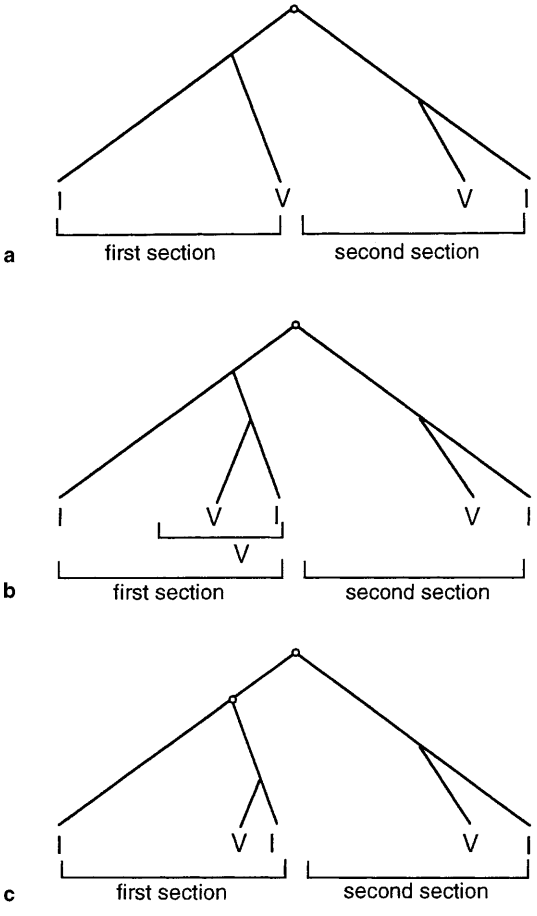


Fig. 1 Harmonic structures of the three groups of minuets: **a** half cadence minuets (Exps. 1–4), **b** dominant key minuets (Exps. 1–4), **c** main key minuets (Exp. 4)

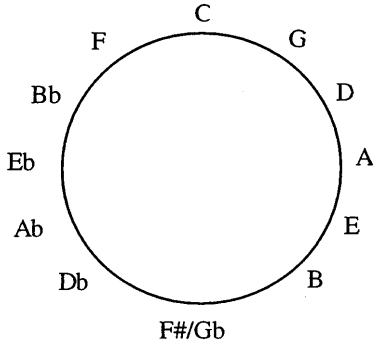


Fig. 2 Cycle of fifths representing the hierarchies that exist between keys

Second, a hierarchical representation of the musical structure creates processing advantages for perception and memorization which are consistent with a number of results obtained in different fields of cognition (Deutsch, 1982; Deutsch & Feroe, 1981; Greeno & Simon, 1974; Restle, 1970; Simon, 1972). Hierarchical structure permits a more economic encoding of information than sequential structures (Deutsch, 1982). Since hierarchical representation is highly economical, and since listeners possess knowledge of the tonal system, they may ideally establish an abstract hierarchical representation of the whole musical piece (Lerdahl & Jackendoff, 1983).

Third, various empirical studies have provided some support for the hypothesis of a hierarchical representation of musical structures. Studies involving short and simple musical sequences have revealed the psychological reality of hierarchical structures in memorization tasks (Bigand, 1990, Exp. 3; Deutsch & Feroe, 1981), in phrase completion judgments (Bigand, 1994; Boltz, 1989; Palmer & Krumhansl, 1987a,b), and in similarity judgments concerning musical sequences (Dibben, 1994; Serafine, Glassman, & Overbeeke, 1989). In relatively short musical phrases, listeners also develop expectations about subsequent events that arise from hierarchical structures (Bharucha & Stoeckig, 1986, 1987; Boltz, 1993; Schmuckler, 1989, 1990; Schmuckler & Boltz, 1994; Bigand & Pineau, 1997).

However, the hierarchical encoding assumption has recently been challenged in experimental psychology by a set of provocative results obtained with longer and more complex musical sequences. Cook (1987) systematically changed the final key of pieces so that they ended in a key other than the principal one. The direct influence of large-scale tonal closure on listeners' judgments of completion and coherence was relatively weak and was restricted to fairly short time spans (under 1 min). Cook's findings provided evidence that large-scale tonal structures are not easily audible to listeners.

Studies of the perception of musical forms have also revealed the difficulty of perceiving global relationships. In segmentation tasks, although listeners indicate different sub-groups of pieces, the selected segmentation marks do not reflect a hierarchy which is compatible with the piece's formal or harmonic construction (Kreutz, 1995) and instead tend to be based on salient characteristics (Clarke & Krumhansl, 1990). Permuting sections of a musical piece imposes significant changes on global musical structures. However, these changes do not influence listeners' judgments of coherence, completion, or expressiveness (Gotlieb & Konecni, 1985; Karno & Konecni, 1992; Konecni, 1984).

In a similar vein, Tillmann and Bigand (1996) segmented musical pieces by Bach, Mozart, and Schönberg into short chunks (locally coherent) of an average length of 6 s each. In one experimental situation, the chunks were linked in a normal, forward order. In the other experimental situation, these chunks were linked in a backward order. Such backward linking completely destroyed the global structure while preserving the local structures. The destruction of the global form achieved by the backward linking of the chunks did not alter listeners' judgments of expressiveness and coherence registered on 29 semantic scales. Moreover, after an explanation of the modifications to the pieces, participants were incapable of determining whether the pieces they had listened to were the original versions or those linked in backward order. Other findings indicating that listeners had enormous difficulty perceiving higher-level relationships have been reported by Deliège, Melen, Stammers, and Cross (1994, 1996), who used a different experimental paradigm. In their study, a musical piece was segmented into eight chunks like a jigsaw puzzle. Participants were required to create as coherent as possible a piece of music using the eight chunks. Nonmusicians did not demonstrate the ability to confer a well-formed structure on the piece; no chunk was placed in its correct position. The musicians were "generally sensitive to tonal function, though this sensitivity is far from infallible" (1994, p. 272).

In summary, several studies using short musical sequences, often specifically defined for the experiments, support the assumption of the hierarchical encoding of musical structures. Several other studies, generally performed with longer and more complex real musical pieces, suggest that the musical elements which should theoretically coordinate different parts of a piece as a coherent large-scale structure (i.e., modulation, return to the main key, half and authentic cadences) were not understood by listeners, who seemed to be more sensitive to local structures. In the present study, the importance of global versus local processing was investigated by considering relatively short and simple minuets. The main objective was to determine in greater detail the kind of difficulty participants encounter when attempting to perceive global musical structure. In particular, we attempted to determine whether or not listeners have a sense of tonal units, and whether harmonic cadences are processed locally rather than globally (i.e., with reference to the overall harmonic structure of the minuet).

In three of the following experiments, participants were asked to solve a musical jigsaw puzzle presented on a computer screen. The musical puzzle contained the two halves of minuets transposed in several more or less related keys. Participants were asked to construct a coherent piece. Correct responses consisted of choosing two sections of a minuet in the same key and linking them in the correct cadential order (i.e., the section ending on the authentic cadence should follow the section ending on the half cadence). We considered the composer's version as the "correct response" since it corresponds to the sole possible hierarchical structure that respects the basic standard harmonic rules described above.

In order to analyze the local versus global processing of cadential structures, two kinds of minuets were chosen (see Material for more details). In some of them (referred to below as "half cadence minuets"), the first

section ended on a half cadence (representing a temporary ending), and the second section on an authentic cadence in the main key (representing a definitive ending Fig. 1a). Subjects were unlikely to place the second section before the first for the "half cadence minuets," since the half cadence clearly marked a temporary ending. In the other group of minuets (referred to below as "dominant key minuets"), the second section also ends on an authentic cadence in the main key, but the first section ends on an authentic cadence in the dominant key (Fig. 1b). The critical point is that this cadence can have opposite functions depending on the way it is processed (i.e., locally or globally). Locally, it marks a definitive ending in exactly the same way as the authentic cadence in the main key. Globally, it works like a half cadence that implies a second section ending on an authentic cadence in the main key. If the cadences are perceived with reference to the overall harmonic structure, subjects are unlikely to place the second section before the first for these "dominant key minuets." On the contrary, inversion errors will be numerous if local processing of the harmonic cadences prevails over global processing.

Experiment 1

Method

Participants. Twenty students from the University of Dijon participated in this experiment. They had an average of 1.9 years of practice on an instrument and had an average of 1.1 years of formal musical training. None reported recognizing the pieces, even though they felt familiar with the style.

Material. Four minuets of a length of 16 bars were chosen (see Appendix). In two of them (Bach minuets, H-C1, H-C2), the first 8 bars ended on a half cadence in the main key (referred to below as "half cadence minuets"). In the others (Haydn minuets, D-K1, D-K2), the first 8 bars ended on an authentic cadence in the dominant key (referred to below as "dominant key minuets"). In all of the minuets, the second section ended on an authentic cadence in the main key. In order to neutralize the influence of melodic contour (Imberty, 1969 Rosner & Narmour, 1992) and of rhythm on the comprehension of cadences (Francès, 1984), the rhythm and melodic contour of the cadential structures of each section were rendered comparable (i.e., a descending bass line).

Each minuet was transposed in two keys (Table 1), so that two and five clockwise steps, respectively, were made in the chromatic cycle of fifths. These transpositions avoided any strangeness or incongruence in timbre and tessitura due to register changes.

Table 1 Original and transposed keys of the four minuets

	Keys		
	Original	Near (2 steps)	Far (5 steps)
Half cadence minuets			
H-C1	G	A	F#
H-C2	G	A	F#
Dominant key minuets			
D-K1	C	D	B
D-K2	G	A	F#

The four minutes were played with a sampled piano sound produced by a Yamaha EMT 10 Sound Expander. The sampler was controlled through the MIDI interface and by a Macintosh computer running Performer software. In order to make the musical pieces more expressive, the dynamics and velocity of several tones were modified, but no rubato was performed. The tempo of the minuets was adjusted to produce a standard length of 20 s. All the minuets were divided into two sections of eight bars each, resulting in six sections for every piece (i.e., two sections for each of the three keys). The six sections were then captured by Sound Designer-II software, and the six corresponding sections were represented on a computer screen in the form of small boxes. Clicking on one box made the software play the corresponding musical section. The boxes were presented in two blocks separating the first section and second section of the minuet and were labeled with the names of fruits or planets, respectively. The names associated with the boxes and the location of the boxes on the screen were randomized across participants and across pieces. In order to solve the puzzle, participants had to drag and link the two boxes that produced the most coherent piece. Once linked, clicking on the first box caused the software to play the two sections without interruption.

Procedure. Participants were required to link the two boxes from the two different groups (i.e., one fruit and one planet) that formed the most coherent piece. That is to say, they had to choose two sections that fitted together well and chain them in an order that provided a smooth transition and a strong feeling of completion. They were encouraged to construct a musical piece which conformed as nearly as possible to what is usually heard in serious music, instead of constructing a creative or inventive piece. Two musical examples with the same tonal structure as the experimental minuets provided training on how to use the Sound Designer software. The time taken to solve the puzzle was recorded, but the participants were allowed to listen to the musical sections as many times as they wished and to try as many pairs as they liked before giving a definitive response. All the participants worked with the four minuets separately. The order of presentation of the minuets was randomized.

Results and discussion

Participants' responses were coded in the following way: Responses concerning the correct choice of tonality (below referred to as "tonality responses") were considered correct when two sections were chosen in the same key, regardless of their order. Responses concerning the correct chaining order of the two sections (below referred to as "chaining order responses") were considered as correct when the first section ended on a half cadence (for the half cadence minuets) or on an authentic cadence in the dominant key (for the dominant key minuets), and the second section ended on an authentic cadence (for the two groups of minuets). The chaining order responses were scored independently of the tonality responses. Finally, total correct responses (correct tonality *and* correct order) were also analyzed.

As Table 2 shows, choosing two sections in the same tonality was not a simple task, though performances were above random response level. Finding the correct order of the two sections was also difficult; correct chaining order was above random response level for all

Table 2 Percentages of Correct Responses for Tonality and order of Each Minuet in Experiment 1 (Random response level for tonality responses: 33.33%, and for order respones: 50%)

	Responses	
	Tonality	Order
Half cadence minuets		
Bach 1	85%	85%
	$\chi^2(1) = 24$**	$\chi^2(1) = 9.8$**
Bach 2	90%	90%
	$\chi^2(1) = 28.8$**	$\chi^2(1) = 12.8$**
Dominant key minuets		
Haydn 1	60%	60%
	$\chi^2(1) = 6.4$*	n.s.
Haydn 2	70%	75%
	$\chi^2(1) = 12.1$**	$\chi^2(1) = 5$*

*$p < .05$; **$p < .01$

half cadence minuets, but for only one of the dominant key minuets.

To test the effect of minuet structure, two ANOVAs were performed, with the four minuets as the within-subject variable, and the correct tonality responses and chaining order responses as dependent variables. Planned comparisons were run to contrast the two types of minuets. Correct tonality responses and correct chaining order responses were more frequent for the half cadence minuets than for the dominant key minuets, $F(1,19) = 4.06$, $p = .06$, and $F(1,19) = 8.9$, $p < .01$, respectively. The analysis of the totally correct responses confirmed this effect of minuet structure, $F(1,19) = 8.8$, $p < .01$. A further ANOVA was performed on response times. Response times were significantly longer for the dominant key minuets (353.6 s on average) than for the half cadence minuets (233.3 s on average), $F(1,19) = 15.6$, $p < .001$.

Experiment 1 showed that participants made more errors and took longer to solve the musical puzzle with dominant key minuets than with half cadence minuets. It may be argued that the difference in harmonic structure was not necessarily the sole factor responsible for this drop in performance. The minuets in the two groups differ, in particular, in one specific feature: the two sections start with the same motifs in the half cadence minuets, but not in the dominant key minuets. The way this motif repetition might have influenced the participants remains unclear, but it was preferable to rerun the experiment without such a confound. In Exp. 2, none of the minuets contain a motif repetition at the beginning of the second section (see Appendix). Furthermore, different composers were chosen within the two groups of minuets, and the last bars of each section were made identical.

The second purpose of Exp. 2 was to change the presentation of the musical jigsaw puzzles in order to increase the number of correct responses, which was generally lower than expected. In a similar vein, all the minuets were played in the same key in order to enhance the feeling of the main key.

Experiment 2

Method

Participants. Twenty students from the University of Dijon participated in the experiment. None had participated in Exp. 1. They had an average of 1.4 years of practice on an instrument, and had an average 0.9 years of formal musical training. None reported recognizing the pieces, even though they felt familiar with the style.

Material. Short piano minuets of 16 bars (see Appendix) were selected in such a way that they contained a half cadence – "half cadence minuets": H-C3 (Haydn), H-C4 (Mozart), H-C5 (Pleyel) – or an authentic cadence in the dominant key at the end of the first section – "dominant key minuets": D-K3, D-K4 (Mozart), D-K5 (J. Ch. Bach). They were comparable to the minuets of Exp. 1 with regard to structure, style, and length, but none exhibited motivic repetition. All the minuets were played in C major, the overall reference key for the experiment. In the last bar of each section, the upper voice is constructed in the same way (number of notes and their duration), and the bass line is a descending arpeggiation of the tonic triad. The notes in the last bars were played with the same velocity in each section.

The material was constructed as described in Exp. 1, but the presentation of the puzzle on the computer screen was simplified. For each piece, four boxes were presented instead of six. One box, labeled with a planet name, represented a section of eight bars in the piece played in C major. The other three boxes, labeled with fruit names, represented the other section of the piece played in the keys of C major, D major, and B major. The presentation of the section in one key or in three keys was counterbalanced across pieces and participants. Different fruit and planet labels were used to represent the boxes for each minuet.

Procedure. The procedure was identical to that of Exp. 1. Participants where required to link two boxes with different labels (i.e., one fruit and one planet) to form the most coherent piece. With the simplified presentation, only one correct pair starting with a fruit or a planet was possible. For all six pieces, the correct response for tonality in the puzzle consisted of constructing a pair in C major. Each participant worked on all six pieces. The order of presentation was randomized.

Results

The percentages of correct tonality and order responses for the two groups of minuets are presented in Table 3. As already observed in Exp. 1, associating two parts in the same tonality remained a difficult task. The fact that all the minuets were played in the same key throughout the entire experimental session did not facilitate the task. Tonality errors indicated more associations with near keys (i.e., 72% of time) than with distant keys. The number of correct order responses was somewhat low, and only above random response level for two of the half cadence minuets (Table 3).

ANOVAs were performed separately with correct tonality responses, correct order responses, totally correct responses, and response times as the dependent variables. In each analysis, the minuets defined the within-subject factor. Participants more often linked two sections of the puzzle in the same tonality for half cadence minuets than for dominant key minuets,

Table 3 Percentages of Correct Responses for tonality and order of Each Minuet in Experiment 2 (Random response level for tonality responses: 33.33%, and for order responses: 50%)

Pieces	Responses	
	Tonality	Order
Half cadence minuets		
Haydn	95%	85%
	$\chi^2(1) = 34.2$**	$\chi^2(1) = 9.8$**
Mozart	70%	85%
	$\chi^2(1) = 12.1$**	$\chi^2(1) = 9.8$**
Pleyel	95%	65%
	$\chi^2(1) = 34.2$**	n.s.
Dominant key minuets		
Mozart 1	50%	55%
	n.s.	n.s.
Mozart 2	70%	70%
	$\chi^2(1) = 12.1$**	n.s.
J. Ch. Bach	55%	35%
	$\chi^2(1) = 4.2$*	n.s.

*$p < .05$; **$p < .01$

$F(1,19) = 16.5$, $p < .001$. Correct chaining order was chosen significantly more often for half cadence minuets than for dominant key minuets, $F(1,19) = 7.2$, $p < .01$. The analysis of the totally correct responses confirmed this effect of minuet structure, $F(1,19) = 11.1$, $p < .01$. Finally, the response times necessary for the solution of the musical puzzle were significantly longer for dominant key minuets (247 s on average) than for half cadence minuets (208.8 s on average), $F(1,19) = 5.7$, $p < .05$.

The present results confirmed the conclusion of Exp. 1 using a new set of minuets: choosing two sections in the same key and linking them in the correct cadential order was easier and faster for the half cadence minuets than for the dominant key minuets. Simplifying the presentation of the puzzle and playing all the minuets in the same key did not improve the number of correct responses, even when it shortened response times. This observation suggests that the new presentation facilitated the puzzle by reducing the number of possible solution, but it did not remove the main perceptual difficulty encountered in dominant key minuets.

Discussion of Experiments 1 and 2

Experiments 1 and 2 revealed that solving a two-element musical puzzle was not an easy task, even with simple piano minuets. Several participants chose sections of the minuet from different keys and had a great deal of difficulty linking the two sections of the minuets in the correct order. These findings are consistent with those reported by Deliège et al. (1994, 1996) with a more complex puzzle, and also with other findings obtained with different experimental paradigms (Karno & Konecni, 1992; Tillmann & Bigand, 1996).

The critical finding of the present experiment is that participants encountered more difficulties with dominant key minuets than with half cadence minuets. Firstly, they more often associated sections of different keys when the minuet contained a modulation to the dominant key. On the one hand, this finding provides evidence that they perceived the temporary modulation which provoked a shift in the reference tonic on the chromatic fifth cycle. Because of this shift, the feeling of the main key vanished, and this probably encouraged several participants to link sections from different keys. On the other hand, this finding also suggests that participants failed to understand this modulation with reference to the overall structure of the minuet and to perceive its tonal unity.

Secondly, participants made more inversion errors when the first section of the minuet ended with an authentic cadence in the dominant key. This suggests that this cadence was interpreted as a definitive ending rather than as a temporary ending. If both sections seemed to provide a coherent ending for the pieces, there was no longer any harmonic reason to place one section in the first or second position. The purpose of the next experiment was to further explore this interpretation using another experimental task. Participants were asked to evaluate the completion of each musical section presented separately. According to music theory, half cadences should evoke weak completion; authentic cadences, strong completion. Authentic cadences in the dominant key would cause weak completion judgments if they are integrated into the global structure, but strong completion judgments if they are perceived locally. In addition, comparative result profiles for the phrase completion judgments and for the puzzle task would confirm that order responses in the puzzle were actually determined by cadential structures and not by more superficial features.

Experiment 3

Method

Participants. Eleven students from the University of Dijon participated in this experiment. They had only little instrumental and formal musical training (1.2 years on average). None had participated in Exps. 1 and 2.

Material and procedure. Two "half cadence minuets" (H-C3, H-C4) and two "dominant key minuets" (D-K3, D-K5) from Exp. 2 were used. These pieces were played in C major, and the order of presentation of the eight sections was randomized. The participants task was to rate the completion of every musical excerpt on a 7-point scale, ranging from 1 (weak completion) to 7 (strong completion).

Results and discussion

The mean ratings of completion are presented in Fig. 3. As expected, all the second sections with an authentic cadence in the main key generated a high rating of

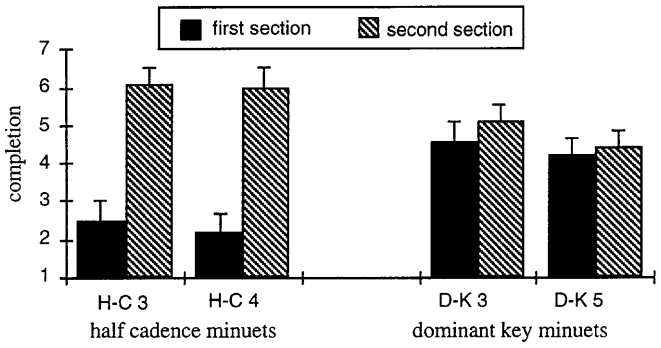


Fig. 3 Average ratings for completion judgments for the 2 sections of the 4 minuets

Table 4 Means of Completion Differences (second section minus first section) and Percentages of Correct Order Responses (observed in Experiment 2) for the Four Minuets

Piece	Completion differences	Correct Order responses
Half cadence minuets		
Haydn	3.6	85%
Mozart	3.8	85%
Dominant key minuets		
Mozart 1	0.54	55%
J. Ch. Bach	0.18	35%

completion in listeners, while the first sections of the half cadence minuets were judged as weakly complete. Moreover, the completion ratings for the first and second sections of these minuets were very different (3.75 points on average), which confirmed that the syntactic function of both kinds of cadence was clearly understood. In contrast, in dominant key minuets, authentic cadences in the dominant key were judged to be complete at the same, somewhat high, level as authentic cadences in the main key (difference of .35 points on average).

An ANOVA was performed with the four minuets and the two sections as the within-subject variables, and with the completion ratings as the dependent variables. Planned comparisons revealed that the effect of minuet structure was stronger for the first section, $F(1,10) = 21.3$, $p < .001$. Completion judgments of first sections were stronger for dominant key minuets than for half cadence minuets, $F(1,10) = 12.88$, $p < .01$. This contrast explained most of the interactive effect ($R^2 = .74$). There was no significant difference in completion judgments between the first and second section in the dominant key minuets, although this was observed for half cadence minuets, $F(1,10) = 58.4$, $p < .0001$. This provides some evidence that the authentic cadence was interpreted as a definitive ending whenever it occurred in the dominant or in the main key.

The present experiment confirmed that participants distinguished between the syntactic functions of half and authentic cadences, even though these cadences exhibited similar superficial features (i.e., melodic contour, rhythm, loudness); half cadences provoked a weak feeling of completion compared to that evoked by the authentic cadences. The crucial point concerns the degree of completion perceived when the authentic cadence occurs in the dominant key. In this case, the degree of completion increased significantly and did not differ from that experienced with the authentic cadence in the main key. This suggests that the authentic cadences in the dominant key were perceived locally rather than globally. The data from the phrase completion judgments was therefore highly consistent with that of the responses in the puzzle task. As shown in Table 4, the greater the difference in completion judgments, the higher the level of correct order responses in the puzzle task. It is likely that the harmonic structure was an important cue for linking the sections of the minuets in the puzzle task: participants found the correct chaining order when the cadences at the end of the sections generated distinct feelings of completion. When the cadences generated the same degree of completion, linking the two sections in one order or the other did not affect the coherence of the whole, because the minuet always sounded correctly completed.

In the three previous experiments, minuet structure had a significant effect on tonality responses, order responses, the time needed to solve the puzzle, and the degree of completion perceived at the end of each section. All these suggest that the authentic cadence in the dominant key did not function as a temporary ending but as a definitive ending, exactly like an authentic cadence in the main key. In order to further this interpretation, a third group of minuets was used in Exp. 4. These pieces (referred to below as "main key minuets") contained two authentic cadences in the main key (Fig. 1c and Appendix). Finding the correct order should be difficult for them, since authentic cadences in the main key generate strong feelings of completion. The crucial point was to compare the inversion error rate observed for the three groups of minuets. If the authentic cadence in the dominant key is interpreted locally like an authentic cadence in the main key, inversion error rates should be similar for the dominant key minuets and the main key minuets. In contrast, if the global harmonic structure governs subjects responses – at least weakly –, inversion error rates should be smaller for the dominant key minuets that for the main key minuets. Finally, the inversion error rate should be the lowest in the half cadence minuets, as already observed in the previous experiments. Consistent effects of these three minuet structures should also be obtained in the phrase completion task.

The second purpose of Exp. 4 was to further investigate the effect of the minuets' structure on the time necessary to solve the puzzle. In previous experiments, longer response times were observed for dominant key minuets. In order to investigate this increase in response time, an observation grid tracking the subjects' problem-solving behavior was used.

The final aim of Exp. 4 was to evaluate the effect of musical expertise. Indeed, it may be argued that the predominance of local processing may result from the listeners' lack of musical expertise. The importance of participants' musical background was underlined by Batt (1987) and by Karno and Konecni (1992). Participants' knowledge has also been identified as a crucial factor that influences both performance and strategy in problem-solving experiments. For example, chess experts recognize complex patterns, memorize information better, and resolve problem situations more easily than novices (Chase & Simon, 1973). In Exps. 1–3, the extent of musical expertise was not manipulated: on average, participants had a low level of musical education. This low level of musical expertise might partly explain the difficulty of solving the musical puzzle, in particular for the dominant key minuets. Musicians were expected to perform better in puzzle tasks, to give different phrase completion judgments, and to develop different problem-solving strategies than amateur musicians and nonmusicians.

Experiment 4

Method

Participants. Fifty-seven students from the University of Dijon participated in this experiment, including 19 musically untrained students of psychology, none of whom had received either instrumental or formal training (referred to below as "nonmusicians"); 19 students from different departments with an average of 2.5 years of practice on a musical instrument and 3.8 years of formal musical training (referred to below as "amateur musicians"), and 19 students in the third year of musicology studies with an average of 11.5 years of practice on an instrument and 9.7 years of formal musical training (referred to below as "musicians"). None of them had participated in Exps. 1, 2 or 3, and none reported recognizing the pieces, even though they felt familiar with the style.

Material. The "half cadence minuets" and "dominant key minuets" of Exp. 3 were used. A third group of pieces was added (see Appendix, M-K1, M-K2), including two Haydn dances in which each section ended on an authentic cadence in the main key. These new pieces were similar to the others in terms of length, tempo, and style. For convenience, this group is referred to as "main key minuets." The stimuli were constructed as explained in Exp. 2, and the puzzle was presented in the same way as in Exp. 2.

Procedure. The experiment took place in two stages, with the first stage relating to the puzzle paradigm. Participants had to construct a coherent piece (see Exp. 2 for more details). Each participants worked on all six minuets. The order of presentation was randomized. During the puzzle-solving process, an observation grid tracking three types of information about participants' actions was filled out. The experimentator noted (1) how many times sections were listened to separately, (2) how many pairs were constructed prior to the final pair, and (3) how many times the chaining order of the two sections was changed. In the second stage of the experiment, the 12 sections were presented separately in a randomized order. All were played in the C major key. The participant's task was to rate the completion of each section on a 7-point scale, ranging from 1 (weak completion) to 7 (strong completion).

Results

Tonality and order responses

The percentages of correct tonality responses registered for the three groups of minuets and the three levels of musical expertise are presented in Table 5. Generally, the two sections were matched in the same tonality, except by nonmusicians for one of the dominant key minuets. Overall in tonality errors, the near keys were associated more often (i.e. 75% of the time) than the distant keys. Nonmusicians chose the far key 31% of the time, amateur musicians 25%, while musicians never chose far keys. The percentages of correct order responses are presented in Table 6. The correct order was determined at above random response level for the half cadence minuets, but not systematically for the other minuets.

Table 5 Percentages of correct responses for tonality of each minuet and for each participant group in Exp. 4 (random response level: 33.33%).

Pieces	Musical expertise		
	Nonmusicians	Amateur musicians	Musicians
Half cadence minuets			
H-C3	63%	84%	90%
	$\chi^2(1) = 7.6$**	$\chi^2(1) = 22.2$**	$\chi^2(1) = 27$**
H-C4	79%	74%	100%
	$\chi^2(1) = 17.8$**	$\chi^2(1) = 13.9$**	
Dominant key minuets			
D-K3	37%	79%	90%
	n.s.	$\chi^2(1) = 17.8$**	$\chi^2(1) = 27$**
D-K5	84%	84%	90%
	$\chi^2(1) = 22.2$**	$\chi^2(1) = 22.2$**	$\chi^2(1) = 27$**
Main key minuets			
M-K1	69%	79%	95%
	$\chi^2(1) = 10.5\%$	$\chi^2(1) = 17.8$**	$\chi^2(1) = 32.3\%$
M-K2	84%	84%	100%
	$\chi^2(1) = 22.2$**	$\chi^2(1) = 22.2$**	

Note: *$p < .05$; **$p < .01$

Table 6 Percentages of Correct Responses for Order of Each Minuet and for Each Participant Group in Experiment 4 (Random response level: 50%)

Pieces	Musical expertise		
	Nonmusicians	Music lovers	Musicians
Half cadence minuets			
Haydn	79%	95%	100%
	$\chi^2(1) = 6.4$*	$\chi^2(1) = 15.2$**	
Mozart	90%	95%	95%
	$\chi^2(1) = 12$**	$\chi^2(1) = 15.2$**	$\chi^2(1) = 15.2$**
Dominant key minuets			
Mozart 1	42%	68%	74%
	n.s.	n.s.	$\chi^2(1) = 4.3$*
J.Ch.Bach	37%	53%	63%
	n.s.	n.s.	n.s.
Main key minuets			
Haydn 1	74%	74%	84%
	$\chi^2(1) = 4.3$*	$\chi^2(1) = 4.3$*	$\chi^2(1) = 8.9$**
Haydn 2	47%	63%	68%
	n.s.	n.s.	n.s.

*$p < .05$; **$p < .01$

Three separate ANOVAs were performed on tonality responses, order responses, and totally correct responses (correct tonality and correct order); musical expertise was the between-subject factor, and minuets the within-subject factor. There was a main effect of musical expertise for tonality responses, $F(2, 54) = 9.7$, $p < .001$, and for order responses, $F(2, 54) = 4.9$, $p < .01$. Planned comparisons revealed a significant linear tendency; performances improved proportionally to the level of musical expertise for tonality responses, $F(1, 54) = 19.4$, $p < .001$, and for order responses, $F(1, 54) = 9.4$, $p < .01$, while the quadratic trends were not significant. For tonality responses, there was no main effect of the minuets, nor any significant interaction with musical expertise. As observed in previous experiments, nonmusicians produced slightly more correct responses for half cadence minuets (27) than for dominant key minuets (23), but this difference failed to reach a significant level here.

For correct order responses, there was a main effect of the minuets, $F(5, 270) = 10.7$, $p < .001$. Planned comparisons indicated that the correct order responses were more numerous for half cadence minuets than for the main key minuets, $F(1, 54) = 24.6$, $p < .001$. Finding the correct order seemed to be more difficult when each section terminated with an apparently definitive ending. The correct order responses were also more numerous for the half cadence minuets than for the dominant key minuets, $F(1, 54) = 60.1$, $p < .001$, suggesting that the authentic cadence in the main key was not understood as a temporary ending. Finally, the number of correct order responses observed for the dominant key minuets and main key minuets did not significantly differ for musicians and amateur musicians. The finding that these response patterns were even roughly comparable further suggests that the authentic cadence in the dominant key was perceived locally as a definitive ending. For nonmusicians, the number of correct order responses for dominant key minuets and main key minuets differed significantly, $F(1, 54) = 5.4$, $p < .05$. However, the inversion errors were more numerous in the dominant key minuets, further indicating that the authentic cadence in the dominant key was not perceived globally. In addition, there was no significant interaction of the two factors for order responses, indicating that the effect of the minuet structure did not depend on the extent of musical expertise (see Fig. 4).

The third analysis performed on totally correct responses confirmed the effects of minuet structure and musical expertise observed with correct order responses.

Phrase completion judgments

The mean completion ratings for each section are displayed in Fig. 5. Weak completion judgments were generated by half cadences, and strong ones by authentic cadences in the main and in the dominant key. Of greatest interest are the differences in completeness judgments between the two sections of each minuet. Only in the case of half cadence minuets were considerable differences observed. For dominant key minuets, the authentic cadences in the dominant key were judged to be complete at the same, somewhat high level as were authentic cadences in the main key. Thus, the two sections generated the same high degree of completion in listeners as for the main key minuets.

To analyze the effect of minuet structure on phrase completion judgments, the difference in ratings between the first and second sections of each minuet were computed for each participant. An ANOVA was performed on these differences, with musical expertise as the between-subject factor, and minuets as the within-subject factor. There was a significant minuet factor effect, $F(5, 270) = 28.3$, $p < .001$, but no effect of musical expertise and no interaction.

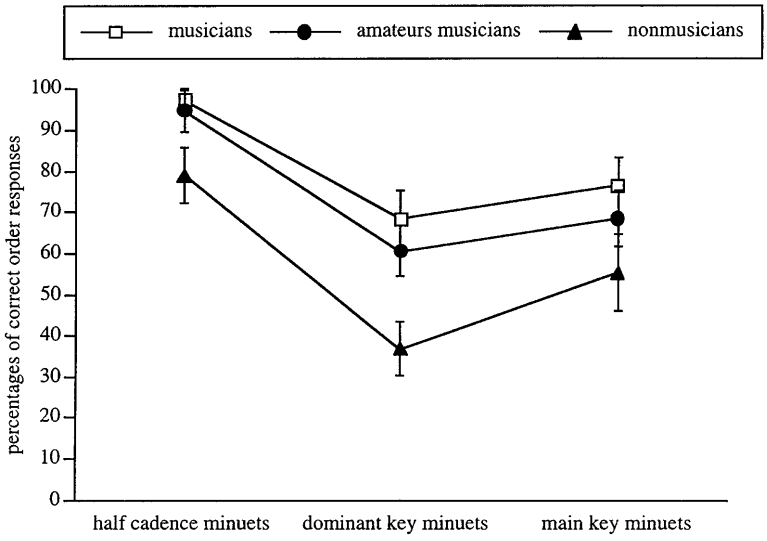


Fig. 4 Percentages of correct order responses for the 3 groups of minuets and the 3 levels of musical expertise

Planned comparisons were run in order to compare the groups of minuets two by two. The completion differences for half cadence minuets were greater than for dominant key minuets, $F(1,54) = 97.8$, $p < .001$, or main key minuets, $F(1,54) = 99.99$, $p < .001$. This confirms that participants understood the completion provided by half cadences and authentic cadences in the main key, but failed to understand the authentic cadences in the dominant key as a temporary ending. In addition, the difference in judgment for the dominant key minuets tended to be slightly greater than for the main key minuets, $F(1,54) = 4$, $p = .05$. However, this difference did not reach a significant level when each group of participants was considered separately.

Finally, the present finding confirmed the link between phrase completion judgments and performance on the puzzle task already reported in Exp. 3: the greater the difference between phrase completion judgments, the higher the number of correctly ordered puzzle segments. Correlations based on the values of the six minuets make it possible to illustrate the link between the two measures: $r = .85$ for musicians and amateur musicians, $r = .75$ for nonmusicians.

Response times and problem-solving behavior

An ANOVA on response times also revealed a significant effect of the minuets, $F(5, 270) = 3.5$, $p < .01$, and of musical expertise, $F(2, 54) = 10$, $p < .001$, but no significant interaction. Musicians had shorter response times than nonmusicians and amateur musicians, the latter having the longest response times. Planned comparisons on the minuet factor revealed that the response

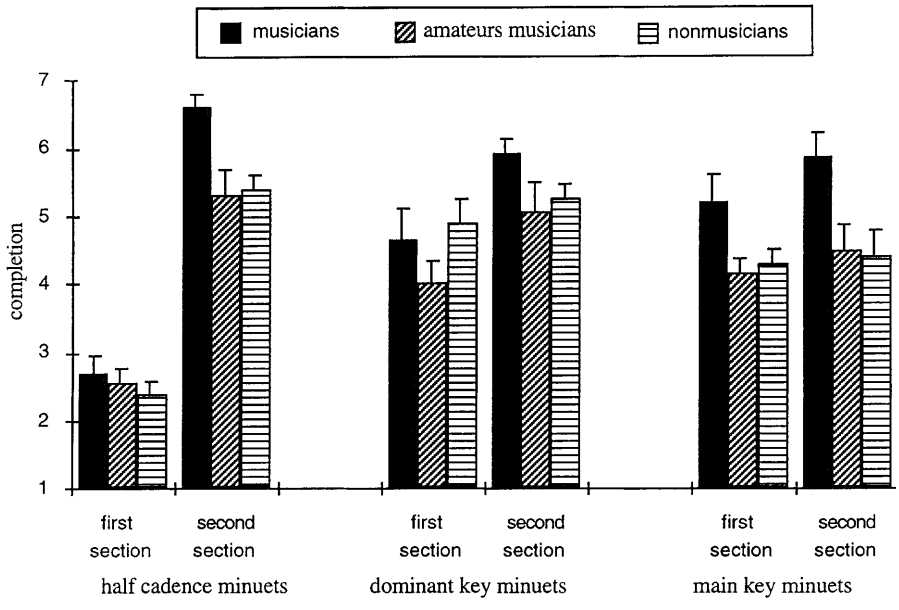


Fig. 5 Average ratings for completion judgments for the 2 sections of the 3 groups of minuets and for the 3 levels of musical expertise

time for dominant key minuets was significantly longer than for half cadence minuets, $F(1, 54) = 9.5$, $p < .01$. Response times did not differ either between half cadence minuets and main key minuets, or between dominant key minuets and main key minuets (Fig. 6).

In order to further investigate these response time differences, participants' puzzle-solving behavior was tracked by three measures: (1) number of times participants listened to the sections, (2) number of pairs constructed before the final answer, and (3) number of orders changed (Fig. 7). Three separate ANOVAs performed on these dependent variables revealed a main effect of musical expertise, of minuet structure, but no interaction. The strategies developed to solve the puzzle varied with the extent of subjects' musical expertise: As the extent of musical expertise increased, the number of times participants listened to the sections increased, $F(1, 54) = 5.6$, $p < .05$, but the number of constructed pairs, $F(1, 54) = 12.8$, $p < .001$, and the number of changed orders decreased, $F(1,54) = 9.4$, $p < .01$. The participants seemed to find the puzzle problem easier to solve for the half cadence minuets. More pairs were constructed for dominant key minuets than for half cadence minuets, $F(1,54) = 7.7$, $p < .01$. The chaining order was changed more often for dominant key minuets, $F(1,54) = 12.6$, $p < .001$, and for main key minuets, $F(1,54) = 12.6$, $p < .001$, than for the half cadence minuets.

Discussion

The purpose of Exp. 4 was to further investigate the local versus global processing of harmonic cadences by considering three groups of minuets. The hypothesis that cadences are processed locally was supported by the following findings: (1) the number of correct order responses registered for the dominant key minuets was lower than for the half cadence minuets; (2) they were roughly the same as for the main key minuets; (3) the differences in degrees of completion experienced between each section of the dominant key minuets were very small and weaker than those observed for the half cadence minuets; (4) the differences in degrees of completion observed for the dominant key minuets did not differ greatly from those recorded for the main key minuets. All of these results indicated that the pattern of data observed for the dominant key minuets was more similar to that of the main key minuets than of the half cadence minuets. This suggests that participants perceived the same kind of harmonic structure in the dominant key minuets and the main key minuets, and that they failed to interpret the authentic cadence by considering the overall tonal structure of the minuet. It is interesting to note that musicians, despite a higher absolute performance level, produced the same pattern of errors for the three groups of minuets as did amateur musicians and nonmusicians.

In addition, the data of the phrase completion judgments were highly consistent with those of the puzzle task. This indicates that finding the correct chaining order was easier when the cadences at the end of each section generated distinct feelings of completion. A section ending on an unstable event (i.e., half cadence) probably generated a clear expectation that a section ending on a more stable event (i.e., authentic cadence) should follow. When each part of the minuet generated the same degree of completion, more inversion errors were made. In this case, linking the parts in one order or another did not affect the coherence of the whole. Regardless of order, the minuet sounded correctly completed.

The effect of the minuet structure was also reflected in response times and problem-solving behavior. For all three levels of musical expertise, response times were longer for dominant key minuets and main key minuets. For these minuets, participants constructed more pairs and frequently changed the chaining order, indicating that they found the puzzle problem more difficult. They therefore attempted to solve the puzzle by a trial and error strategy, probably because the cognitive structures

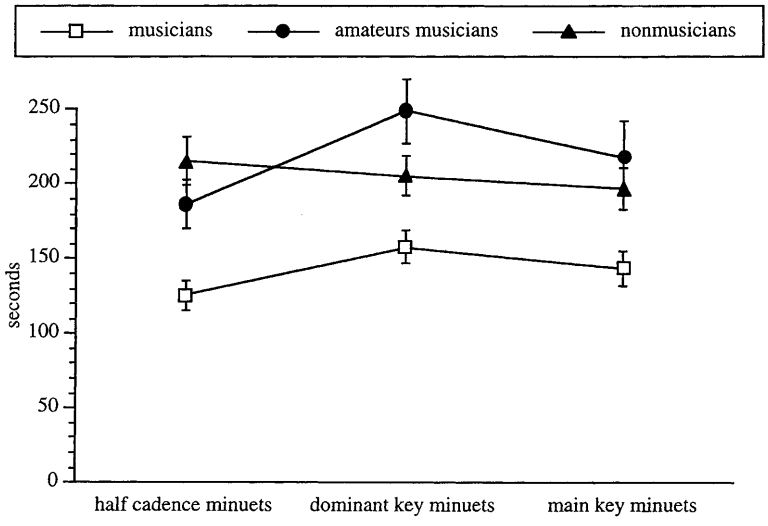


Fig. 6 Average response times for the 3 groups of minuets and the 3 levels of musical expertise

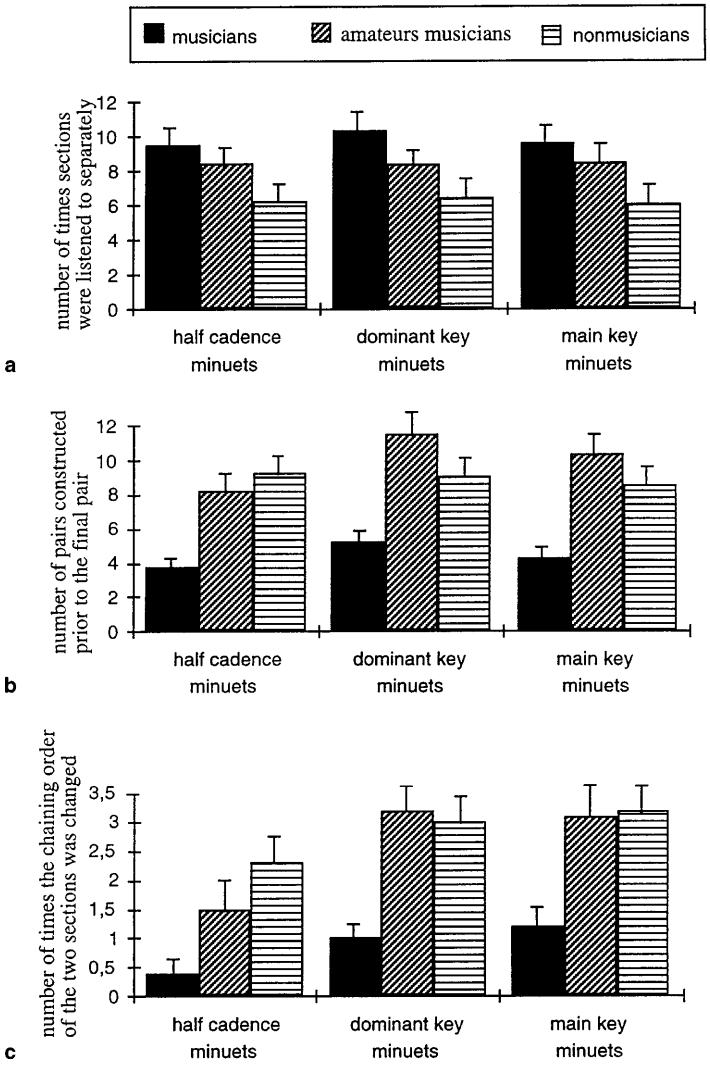


Fig. 7 Means of: **a** number of times sections were listened to separately, **b** number of pairs constructed prior to the final pair, and **c** number of times the chaining order of the 2 sections was changed for the 3 groups of minuets and for the 3 levels of musical expertise

which aid in integrating local information into global structures were lacking.

The third outcome concerns the influence of musical expertise. The significant effect of this factor was observed in tonality and chaining order responses, in totally correct responses, as well as in response times and problem-solving behavior. Musicians responded more quickly, made fewer errors, listened more often to sections separately, and compared fewer pairs than did amateur musicians and nonmusicians. Explicit knowledge might allow different strategies to be used in problem-solving behavior and information to be more efficiently encoded. However, beyond this main effect of musical expertise, it is noteworthy that no significant interaction between the minuet structure and musical expertise was observed in either experimental task. This suggests that all groups of participants experienced the same kind of perceptual difficulties, but that this was reduced for subjects with greater musical expertise. These findings are consistent with several others reported by Cohen (1994), by Bigand et al. (1996), and by Croonen and Houtsma (1994). All these studies suggest that less sophisticated listeners may use the same perceptual principles as experienced listeners, but in a less efficiently way.

General discussion

During the last 20 years, the importance of global structure on music perception has been emphasized in music theory (Lerdahl & Jackendoff, 1983) and in cognitive theory (Deutsch & Feroe, 1981). The hypothesis of hierarchical encoding of musical structures was supported by several studies using short musical sequences, often specifically defined for the experiments. It has recently been challenged by empirical studies showing that manipulating the global structure of real musical pieces does not affect the perception of overall coherence and expressiveness (Karno & Konecni, 1992; Tillmann & Bigand, 1996). The purpose of the present study was to further investigate the role played by local and global structures using simple real musical pieces.

The main finding was that solving a two-element puzzle was not as easy as we had imagined. Often the number of correct tonality and order responses remained at random response level, sometimes even for participants with a considerable musical expertise (see Exp. 4). This finding is consistent with those of Deliège et al.'s study (1994, 1996) using a more complex puzzle. It goes one step further by indicating that even with a very simple puzzle, listeners have difficulty perceiving the musical structures which turn the musical piece into a unified whole. In itself, this finding calls into question music theory models that emphasize the importance of the global structure and higher-order organization of musical form.

The present study, however, attempted to go beyond this observation in specifying the nature of the difficulties encountered during the processing of global musical structure. The main goal was to investigate the processing of harmonic markers (modulation, half and authentic cadences) that – in theory – should coordinate musical sections over time. Three critical findings concerning this issue were observed. First, the effect of minuet structure (half cadence minuets versus dominant key minuets) on tonality responses provided evidence that participants were sensitive to temporary modulations. Second, the great number of correct order responses observed for the half cadence minuets confirmed that participants correctly perceived the syntactic functions of half and authentic cadences, a fact also revealed by the completion judgments. Both findings confirmed a well established conclusion: Participants correctly perceived the basic structural markers of tonal musical pieces (i.e., temporary modulation, half and authentic cadences). Such findings are consistent with others already reported (Francès, 1984; Imberty, 1969; Rosner & Narmour, 1992), and confirm the internalization of the harmonic hierarchy by musically untrained listeners (Bigand et al., 1996; Bigand, 1994; Bigand & Pineau, 1997).

The third critical finding was that solving the musical puzzle was more difficult with dominant key minuets than with half cadence minuets. The former minuet differs from the latter in the way the cadences and the modulation are combined in the global structure of the piece. The present findings therefore suggest that the main difficulties encountered by participants do not result from the understanding of the basic harmonic markers, but from their integration into the overall structure. Several items of evidence support this interpretation. Participants more often associated sections in different keys with the dominant key minuets. This indicates that they are sensitive to modulation but that they failed to perceive the temporary key in relation to the main key of the piece. Similarly, there were many inversion errors with dominant key minuets, and participants perceived the authentic cadence in the dominant key as a sign of a definitive ending. Both findings indicate that the local function of the authentic cadence prevails over its global function. Experiment 4 went one step further in showing that the data observed for the dominant key minuets was more similar to that of the main key minuets than to that of the half cadence minuets. This indicates that participants did not benefit greatly from the fact that, in the former case (i.e., dominant key minuets), the first section ended on an authentic cadence in the dominant key, but this was not so in the latter case (i.e., main key minuets). The fact that they did not take advantage of this strong difference in global harmonic structure suggests that they probably failed to differentiate between these overall structures.

Conclusion

The present results agree with others showing that the processing of local structures may take precedence over the processing of global ones (Deliège et al., 1994; Gotlieb & Konecni, 1985; Karno & Konecni, 1992; Konecni 1984; Tillmann & Bigand, 1996). However, these findings call into question current theories which assume that musical events are integrated in a strict harmonic hierarchy (Lerdahl & Jackendoff, 1983; Meyer, 1956, 1973).

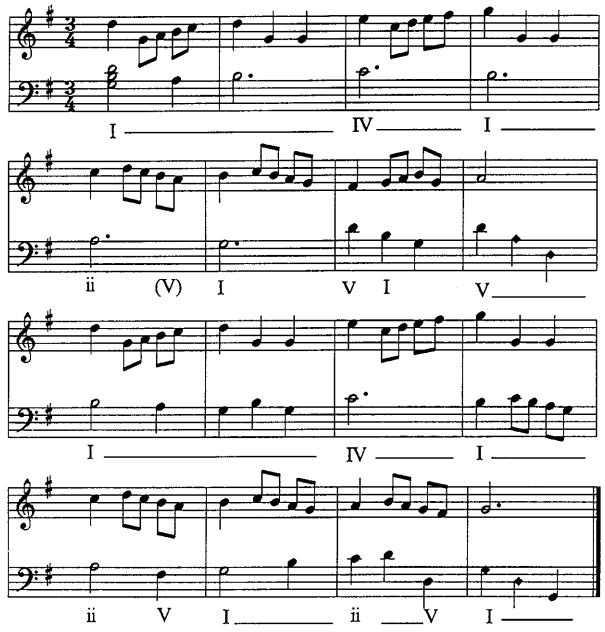
The present study revealed that one difficulty in processing global musical structure might not be due to the understanding of the basic structural features of Western tonal grammar, but to problems in integrating these features into a coherent global form. Our conclusion is similar to that arrived at by Imberty (1969) for 10-year-old children. Ten-year-old children assigned the same level of completion to an authentic cadence in the dominant key as to an authentic cadence in the main key. Tonal closure was not necessary to indicate completion. According to Imberty, this observation might be due to the fundamental characteristic of children's thought, which is that they are not able to understand distant temporal relations. Up to now, however, there is no empirical evidence that adults process music in different way from children. The present study adds new evidence that this inability does not simply represent a developmental problem, but a cognitive one as well. This conclusion is reinforced by the observation that musicians experienced the same difficulties as did musical novices, but to a lesser extent.

Appendix

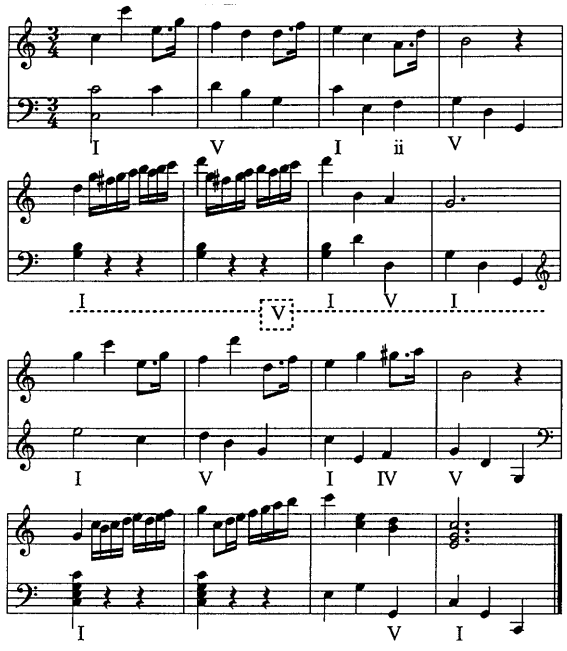
Scores of all minuets used in the present study. Diamond-shaped notes represent changes to original scores to meet experimental requirements

Half cadence minuets (Exp. 1)

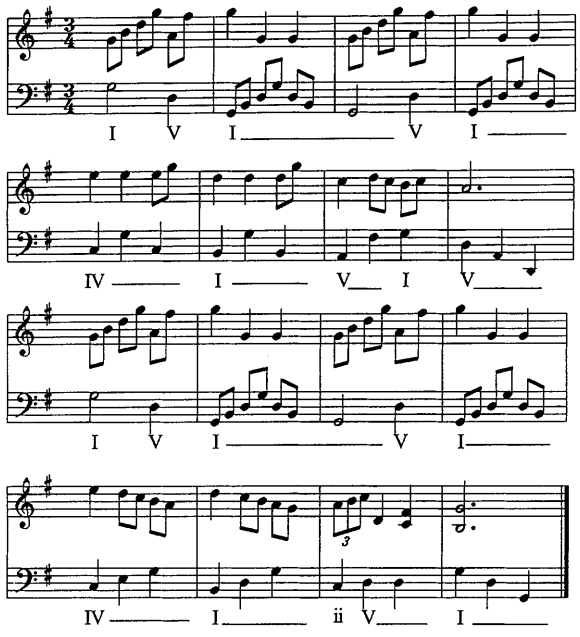
H-C1 (Bach). The first bars of this minuet exhibit a clear tonal development in G major. The progression from the tonic chord (bar 1) to the dominant chord (bar 8) ends on a half cadence. The second section starts with the same motif as bar 1 and ends on an authentic cadence in G major. Since there is a strong similarity of the motifs in both section, the correct ordering of this minuet necessarily relies on the syntactic function of the cadence.



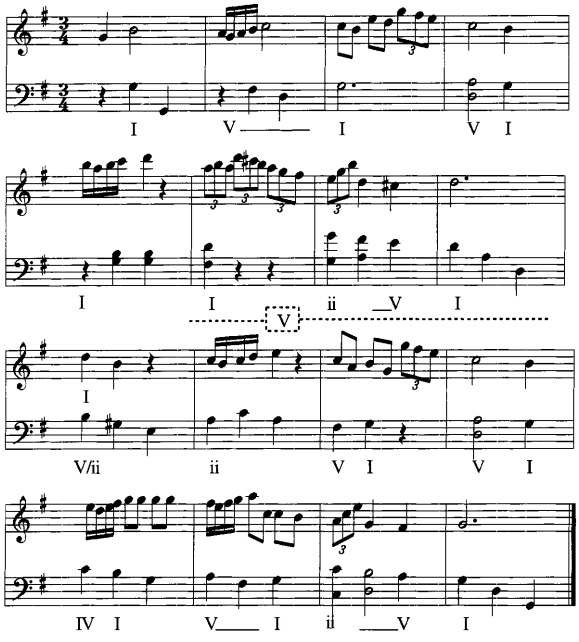
H-C1: J.S. Bach (Experiment 1)



D-K1: Haydn (Experiment 1)



H-C2: J.S. Bach (Experiment 1)

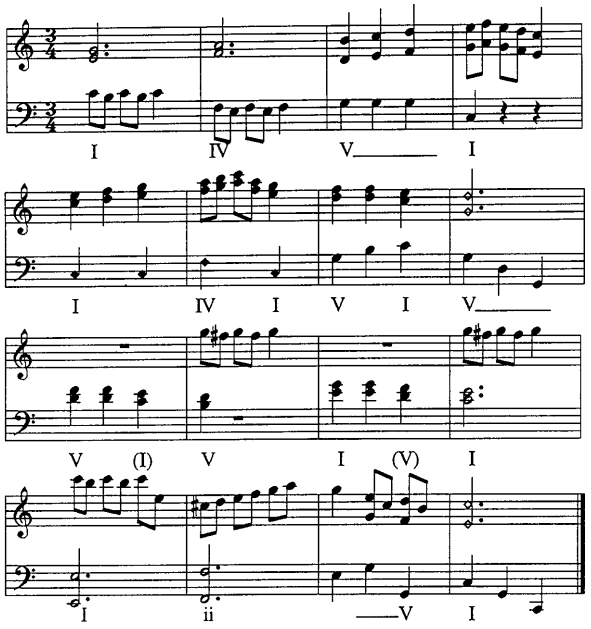


D-K2: Haydn (Experiment 1)

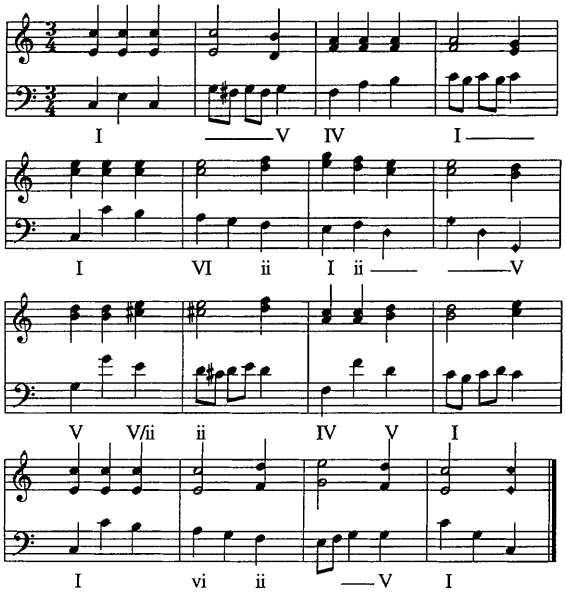
H-C2 (Bach). This minuet is constructed in a comparable way to Bach H-C1. The motif of bar 1 is repeated in bar 9. The first section ends on a half cadence, the second one on an authentic cadence in G major. Since there is a strong similarity of the motifs in both section, the correct ordering of this minuet necessarily relies on the syntactic function of the cadence.

Dominant key minuets (Exp. 1)

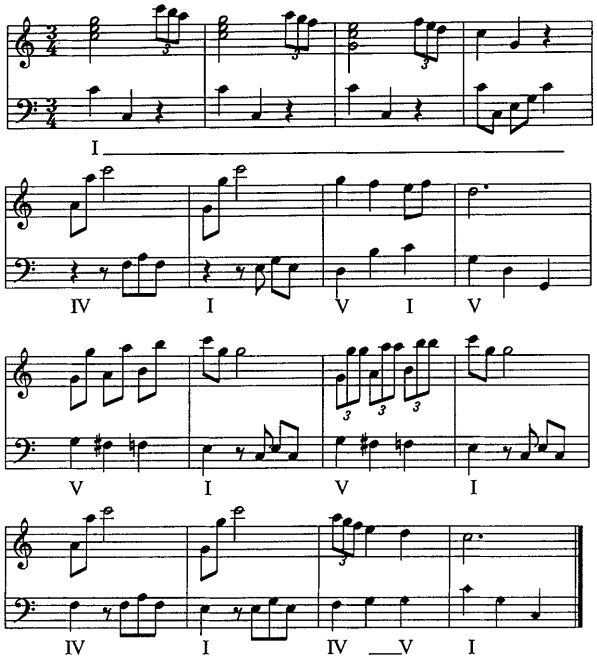
D-K1 (Haydn). This minuet contains two sections of 8 bars, each being subdivided into two parts of 4 bars. The first 4 bars end on the dominant chord (G) of C major. The f# of bar 5 affirms this G chord as the new tonic chord. The G major key is confirmed by the authentic cadence in G major (bars 7 and 8). The second section (bars 9–16) starts on a C major chord (first inversion) with a simple variation of the first motif of the minuet. Unlike in the first section, the half-cadence in C major (bar 12) is now followed by the tonic I of C major in bar 13, and the second section ends on an authentic cadence in C major. Krumhansl's key-finding algorithm indicates that C is more likely to be the main of the minuet ($r = .87$) than G($r = .85$). In addition, the correct ordering of the minuet could be facilitated by the fact that the second section starts in a higher register than the first one played by the left hand.



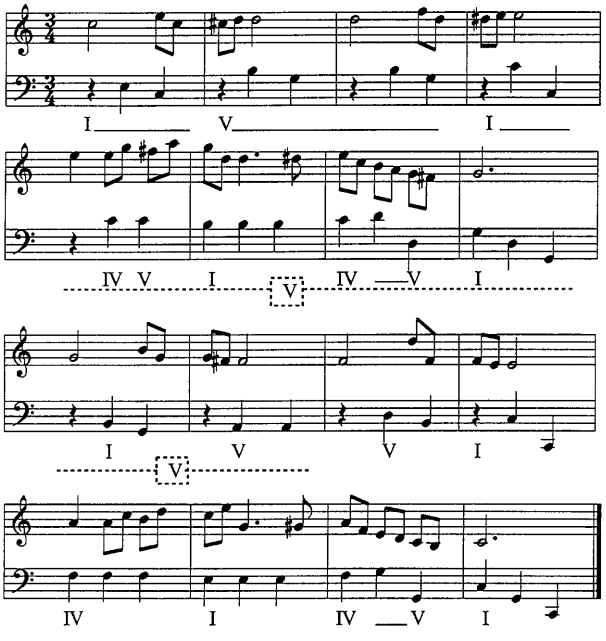
H-C3: Haydn (Experiment 2,3,4)



H-C5: Pleyel (Experiment 2)



H-C4: Mozart (Experiment 2,3,4)



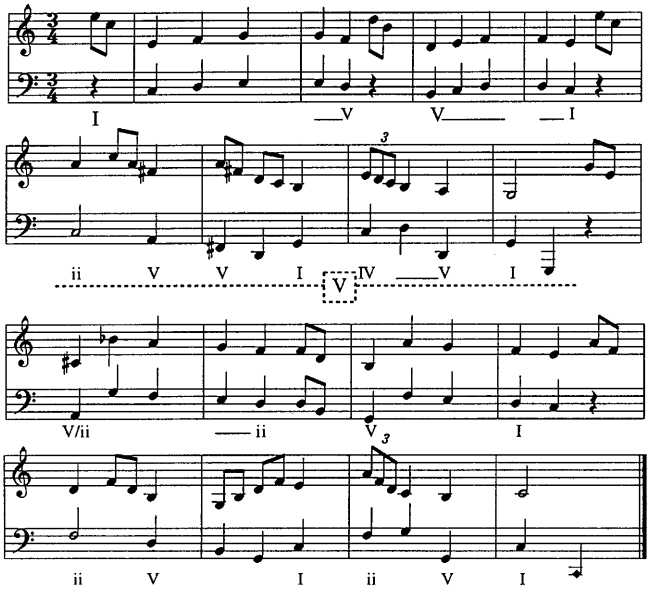
D-K3: Mozart (Experiments 2,3,4)

D-K2 (Haydn). This minuet contains two sections of 8 bars, each being subdivided into two parts of 4 bars each. The first part strongly instills the G major key with the authentic cadence in G of bar 4. The G chord of bar 5 acts as a pivot chord and turns into a subdominant chord (IV) of the following D major key. This new key is introduced by the C# of bar 6, and is definitely affirmed by the authentic cadence of bars 7 and 8. The second section (bars 9 and 10) starts with an unstable descending fifth progression returning to the G major key (bar 12). The melodic motion of the first motif of the minuet is repeated in a descending form. The return to the main G major key is reaffirmed in bar 13 by the presence of c natural, and finally by the authentic cadence in G. Krumhansl's key-finding algorithm indicates that G is more likely to be the main key ($r = .95$) than D ($r = .70$). In addition, the correct ordering of the minuet could be facilitated by the fact that the second section starts with an unstable harmonic progression.

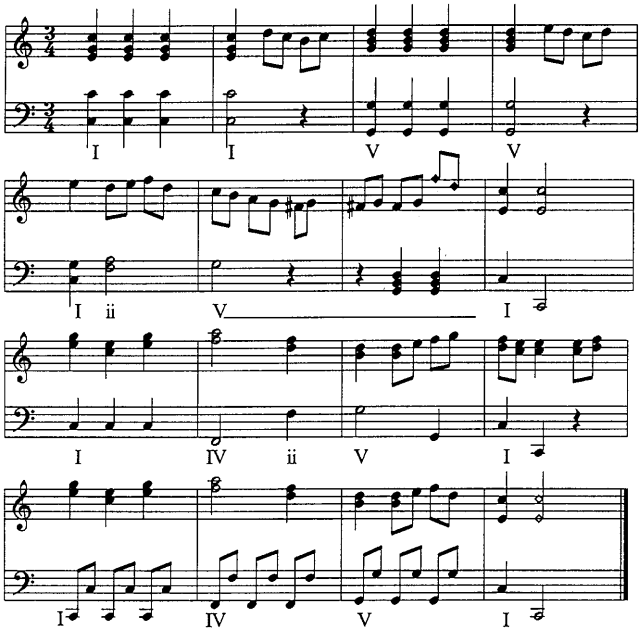
Half cadence minuets (Exps. 2,3,4)[1]

H-C3 (*Haydn, Exps. 2,3,4*). The first section (bars 1–8) starts on the tonic chord (I) of C major and ends on the dominant chord (half cadence). The second section starts on the dominant chord. The motif of bar 7 is transposed one octave below and played in a descending form by the left hand in bar 9. The embroidery of the

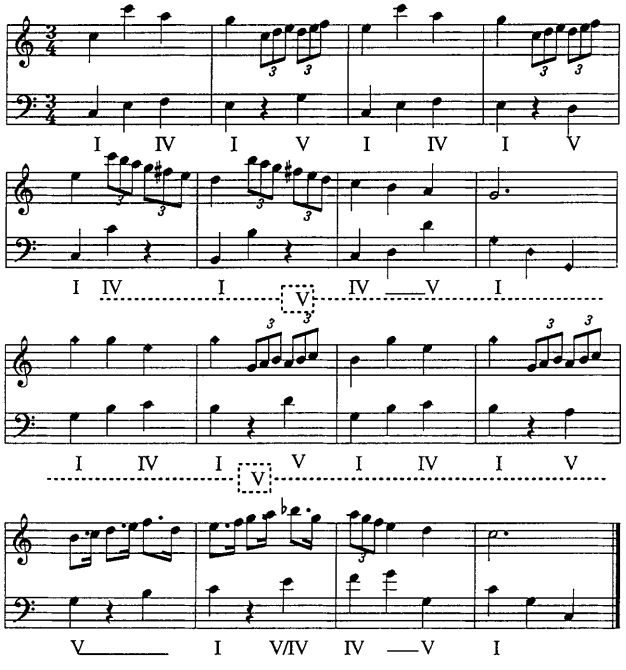
[1] In these experiments, all minuets were transposed in C major.



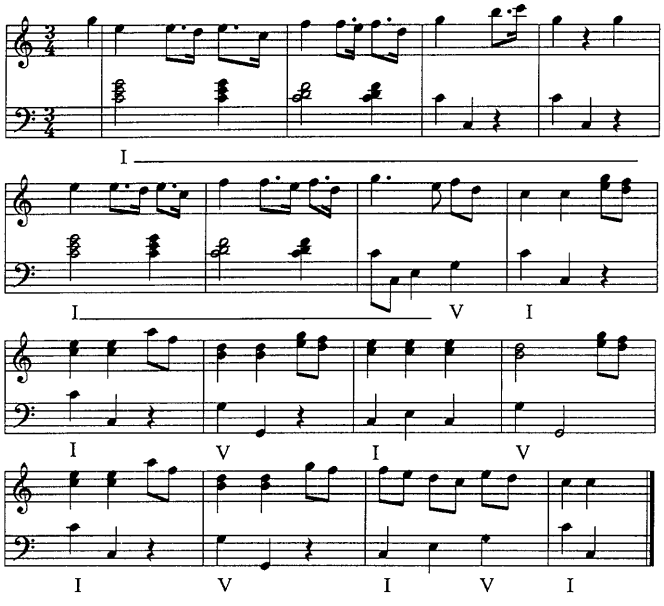
D-K4: Mozart (Experiment 2)



M-K1: Haydn (Experiment 4)



D-K5: J. Ch. Bach (Experiments 2,3,4)



M-K2: Haydn (Experiment 4)

bass movement of bar 1 is evoked by the right hand in bar 10. This second section ends with an authentic cadence in the main key.

H-C4 (*Mozart*, *Exps. 2,3,4*). This minuet has a similar harmonic structure to Haydn H-C3. After a tonic pedal of 4 bars, the first section ends on the dominant chord (half cadence). The second section starts on the dominant chord with a melodic elaboration of the motif presented in bar 5. This second section ends on an authentic cadence.

H-C5 (*Pleyel*, *Exp. 2*). This minuet contains the same harmonic structures as the two previous ones: the first section starts on the tonic chord and ends on the dominant chord. The second section starts on the dominant chord, returns through an harmonic fifth progression to the tonic chord (bar 12) and ends with an authentic cadence. The sole characteristic of this minuet is that the motif of bars 1 and 2 is repeated in bars 13 and 14 with the bass movement of bars 5 and 6.

Dominant key minuets (Exps. 2,3,4)[1]

D-K3 (*Mozart, Exp. 2,3,4*). The first section starts on the tonic chord and ends on an authentic cadence (V–I) in G major. The G major key is evoked by the f# of bar 5 and is definitely established in bars 7 and 8. The second section starts on the tonic chord of G

major and returns to C major on bar 10 (f natural). It ends with an authentic cadence in the main key. Krumhansl's key-finding algorithm indicates that C major is more likely to be the main key of the minuet ($r = .92$) than G major ($r = .78$). In addition, there is a continuous change in register through the minuet (with higher pitches at the beginning and lower pitches at the end) and a relatively unstable passage at the beginning of the second section created by the chromatism in the upper voice (G, F#, F, E; bars 9–12). Both characteristics could help to find the correct ordering.

D-K4 (*Mozart, Exp. 2*). The first section starts in C major. The G major key is evoked in bar 5 by the f# and is definitely established in bars 7–8 by the authentic cadence in G major (V–I). The context of C major is clearly established and changes to G major with II–V–I. The second section starts with a harmonically unstable passage: this is a fifth progression that leads to C major (bar 12) by borrowing from D minor (bar 9). From bars 9–12, the melodic line re-exposes a distortion of the initial motif. Krumhansl's key-finding algorithm indicates that C major is more likely to be the main key of the minuet ($r = .93$) then G major ($r = .64$). The correct ordering of this minuet could be facilitated by the harmonically unstable passage of the beginning of the second section.

D-K5 (*J. Ch. Bach, Exps. 2,3,4*). The first section starts in C major. The G major key is introduced in bar 5 by the f# and is definitely established in bars 7–8 by an authentic cadence in G major (V–I). The second section starts on the G tonic chord, returns to C major in bars 13–14 (with a short borrowing from the F major key in bar 14), and ends with an authentic cadence in C in bars 15–16. The return to the C major key is introduced by a somewhat surprising new rhythmic motif. In this minuet there are as many bars in C major (8) as in G major key. Nevertheless, Krumhansl's key-finding algorithm indicates that C major is more likely to be the main key ($r = .90$) than G major ($r = .83$).

Main key minuets (Exp. 4)[1]

M-K1 (*Haydn*). Both sections start on the C major tonic chord and end on a strong authentic cadence (V–I) in C major. There is no modulation (the f# in bars 6–7 is an embroidery of the G and does not introduce a change in key). Only a few features distinguish the two sections. In the first section, the prolongation of the tonic and dominant chords over two bars (bars 1–4) renders the harmonic rhythm broader, somewhat material. The second section ends with a very peculiar bass movement (bars 13–15) that could help to indicate the end of the piece.

M-K2 (*Haydn*). Both sections start on the C major tonic chord and end on an authentic cadence (V–I) in C major. There is no modulation. The first section is characterized by a long prolongation of the tonic chord. This section is harmonically stable, but the rhythm is agitated. The second section is divided into two groups of 4 bars, with a half cadence in bar 12. The rhythm is quieter, but the harmony constantly alternates between the tonic and the dominant chords.

References

Batt, R. (1987). Comments on "The effects of instrumentation, playing style, and structure in the Goldberg Variations by Johann Sebastian Bach." *Music Perception*, *5*, 207–213.

Bharucha, J. J. (1984). Event hierarchies, tonal hierarchies and assimilation: A reply to Deutsch and Dowling. *Journal of Experimental Psychology: General*, *133*, 421–425.

Bharucha, J. J., & Krumhansl, C. L. (1983). The representation of harmonic structure in music: Hierarchies of stability as a function of context. *Cognition*, *13*, 63–102.

Bharucha, J. J., & Stoeckig, K. (1986). Reaction time and musical expectancy. *Journal of Experimental Psychology: Human Perception and Performance*, *12*, 403–410.

Bharucha, J. J., & Stoeckig, K. (1987). Priming of chords: Spreading activation or overlapping frequency spectra? *Perception and Psychophysics*, *41*, 519–524.

Bigand, E. (1990). *Perception et compréhension des phrases musicales*. Unpublished doctoral dissertation, Université de Nanterre (Paris X), Nanterre [microfilm]. (Available from Universal microfiche ISSN: 0294–1767 n°42, 09882/90, Lille, France)

Bigand, E. (1993). Contributions of music to research on human auditory cognition. In: S. McAdams & E. Bigand (Eds.), *Thinking in sound: The cognitive psychology of human audition* (pp. 231–277). Oxford: Clarendon Press.

Bigand, E. (1994). The influence of implicit harmony, rhythm and musical training on the abstraction of "tension-relaxation schemes" in tonal musical phrases. *Contemporary Music Review*, *9*, 128–139.

Bigand, E., & Pineau, M. (1997). Global context effects on musical expectancy. *Perception and Psychophysics*, *59*, 1098–1107.

Bigand, E., Parncutt, R., & Lerdahl, F. (1996). Perception of musical tension in short chord sequences: The influence of harmonic function, sensory dissonance, horizontal motion and musical training. *Perception and Psychophysics*, *58*, 125–141.

Boltz, M. (1989). Perceiving the end: Effects of tonal relationships on melodic completion. *Journal of Experimental Psychology: Human Perception and Performance*, *15*, 749–761.

Boltz, M. (1993). The generation of temporal and melodic expectancies during musical listening. *Perception and Psychophysics*, *53*, 585–600.

Clarke, E., & Krumhansl, C. (1990). Perceiving musical time. *Music Perception*, *7*, 213–252.

Chase, W. G., & Simon, H. A. (1973). Perception in chess. *Cognitive Psychology*, *4*, 55–81.

Cohen, A. (1994). Musical training and pitch schemata: Tonal inferences in micro-tonal contexts. *Proceedings of the Third International Conference for Music Perception and Cognition*, *Liège*, 81–82.

Cook, N. (1987). The perception of large-scale tonal closure. *Music Perception*, *5*, 197–206.

Croonen, W., & Houtsma, A. (1994). Recognition of tone series: Effects of tonal structures, inference and training. *Proceedings of the Third International Conference for Music Perception and Cognition*, *Liège*, 247–248.

Cuddy, L., & Thompson, W. (1992). Asymmetry of perceived key movement in chorale sequences. *Psychological Research*, *54*, 51–59.

Deliège, I., Melen, M., Stammers, D., & Cross, I. (1994). Musical schemata in real time listening. *Proceedings of the Third International Conference for Music Perception and Cognition*, *Liège*, 271–272.

Deliège, I., Melen, M., Stammers, D., & Cross, I. (1996). Musical schemata in real time listening to a piece of music. *Music Perception*, *14*, 117–160.

Deutsch, D. (1982). The Processing of pitch combinations. In: D. Deutsch (Ed.), The psychology the music (pp. 271–316). Orlando, Fl: Academic Press.

Deutsch, D., & Feroe, J. (1981). The internal representation of pitch sequences in tonal music. *Psychological Review*, *88*, 503–522.

Dibben, N. (1994) The cognitive reality of hierarchic structure in tonal and atonal music. *Music Perception*, *12*, 3–17.

Dowling, W.J., & Harwood, D. L. (1986). *Music cognition*. Orlando, FL Academic Press.

Francès, R. (1984), *La perception de la musique* (2nd ed.) Paris: Vrin.

Gotlieb, H., & Konecni, V. J. (1985). The effects of instrumentation, playing style, and structure in the Goldberg Variation by Johann Sebastian Bach. *Music Perception*. *3*, 87–102.

Greeno, J.G., & Simon, H. A. (1974). Processes for sequence production. *Psychological Review*, *81*, 187–196.

Imberty, M. (1969). *L'acquisition des structures tonales chez l'enfant*. Klincksieck: Paris.

Karno, M., & Konecni, V. J. (1992). The effect of structural interventions in the first Movement of Mozart's symphony in G-minor, K. 550, on aesthetic preference. *Music Perception 10*, 63–72.

Konecni, V. J. (1984). Elusive effects of artists' "messages." In: W. R. Crozier & A. J. Chapman (Eds.), *Cognitive processes in the perception of art* (pp. 71–96). Amsterdam: North-Holland.

Kreutz, G. (1995) Aspekte musikalischer Formwahrnehmung. In: de la Motte-Haber & Kopiez, R. (Eds.), *Der Hörer als Interpret: Tagungsbuch* (pp. 125–148). Frankfurt: Peter Lang.

Krumhansl, C. L. (1990). *Cognitive foundations of musical pitch*, New York: Oxford University Press.

Karumhansl, C. L., & Kessler, E. (1982). Tracing the dynamic changes in perceived tonal organization in a spatial representation of musical keys. *Perception and Psychophysics*, *32*, 96–108.

Krumhansl, C. L., Bharucha, J. J., & Castellano, M. (1982). Key distance effects on perceived harmonic structure in music. *Perception and Psychophysics*, *32*, 96–108

Krumhansl, C. L., Bharucha, J J., & Kessler, E. J. (1982). Perceived harmonic structures of chords in three related keys. *Journal of Experimental Psychology: Human Perception and Performance*, *8*, 24–36.

Laden, B. (1994). Melodic anchoring and tone duration. *Music Perception*, *12*, 199–212.

Lerdahl, F. (1988). Tonal pitch space. *Music Perception*, *5*, 315–345.

Lerdahl, F, & Jackendoff, R. (1983). *A generative theory of tonal music*. MIT, Cambridge, MA.

Meyer, L. B. (1956). *Emotion and meaning in music*. Chicago: University of Chicago Press.

Meyer, L. B. (1973). *Explaining music: Essay and exploration*. Berkelely: University of California Press.

Narmour, E. (1983). Some major theoretical problems concerning the concept of hierarchy in the analysis of tonal music. *Music Perception*, *1*, 129–199.

Palmer, C., & Krumhansl, C. (1987a). Independent temporal and pitch structures in determination of musical phrases. *Journal of Experimental Psychology: Human Perception and Performance*, *12*, 116–126.

Palmer, C., & Krumhansl, C. (1987b). Pitch and temporal contributions to musical phrase perception: Effects of harmony, performance timing and familiarity. *Perception and Psychophysics*, *41*, 505–264.

Platt, J., & Racine, R. (1994). Detection of implied harmony changes in triadic melodies. *Music Perception*, *3*, 243–264

Restle, F. (1970). Theory of serial pattern learning: Structural trees. *Psychological Review*, *77*, 481–495.

Rosner, B., & Narmour, E. (1992). Harmonic closure: Music theory and perception. *Music Perception*, *9*, 383–412.

Schenker, H. (1979) *Free composition*, (E. Oster, Trans.). Longman: New York. (Original work published 1935)

Schmuckler, M. A. (1989). Expectation in music: Investigation of melodic and harmonic processes. *Music Perception*, *7*, 109–150

Schmuckler, M. A. (1990). The performance of global expectations. *Psychomusicology*, *9*, 122–147.

Schmuckler, M. A., & Boltz, M. (1994). Harmonic and rhythmic influences on musical expectancy. *Perception and Psychophysics*, *56*, 313–325.

Schwarzer, G., Siegismund, A., & Wilkening, F. (1993). Entwicklung des Tonalitätsverstehens bei der Beurteilung und Produktion von Liedschlüssen. In: K. Behne, G. Kleinen, & H. de la Motte-Haber (Eds.), *Jahrbuch der Musikpsychologie* (pp. 75–89). Wilhelmshaven: Florian Noetzel.

Serafine, M., Glassman, N., & Overbeeke, C. (1989). The cognitive reality of hierarchic structure in music. *Music Perception*, *6*, 397–430.

Simon, H. A. (1972). Complexity and the representation of patterned sequences of symbols. *Psychological Review*, *79*, 369–382.

Thompson, W. & Cuddy, L. (1989). Sensitivity to key change in chorale sequences. *Music Perception*, *7*, 151–168.

Tillmann, B., & Bigand, E. (1996). Does formal musical structure affect perception of musical expressiveness? *Psychology of Music*, *24*, 3–17.