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Perceiving musical tension in long chord sequences

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Abstract We attempted to predict perceived musical tension in longer chord sequences by hierarchic and sequential models based on Lerdahl and Jackendoff's and Lerdahl's cognitive theories and on Parncutt's sensory-psychoacoustical theory. Musicians and nonmusicians were asked to rate the perceived tension of chords which were drawn either from a piece composed for the study (Exp. 1) or from a Chopin Prelude (Exps. 2–4). In Exps. 3 and 4, several experimental manipulations were made to emphasize either the global or the local structure of the piece and to verify how these manipultions would affect the respective contribution of the models in the ratings. In all experiments, musical tension was only weakly influenced by global harmonic structure. Instead, it mainly seemed to be determined locally, by harmonic cadences. The hierarchic model of Lerdahl and Jackendoff provided the best fit to tension ratings, not because it accounted for global hierarchic effects, but because it captured the local effect of cadences. By reacting to these local structures, tension ratings fit quite well with a hierarchic model, even though the participants were relatively insensitive to the global structure of the pieces. As a main outcome, it is argued that musical events were perceived through a short perceptual window sliding from cadence to cadence along a sequence.

Introduction

According to music theorists, the impression that music progresses dynamically through time stems primarily from the temporal alternation of stable and unstable chords (Schenker, 1935, 1979; Meyer, 1956, 1973; Lerdahl & Jackendoff, 1983): a musical fragment ending on an unstable chord evokes the feeling that there will be a continuation of the sequence. In contrast, a musical fragment ending on a very stable chord indicates that the musical process has reached some point of arrival. Musical tension may be explained by several variables: the tonal function of the chords inside a musical context (Riemann, 1893, 1896; Koechlin, 1930; Schenker, 1935, 1979; Costère, 1954), their acoustic or sensory consonance (Rameau, 1722, 1971; Helmholtz, 1877, 1885), and by the kind of melodic organization (referred to henceforth as "horizontal motion") that exists between the contrapuntal voices (Ansermet, 1961). Psychological approaches to musical tension vary in the variables they emphasize. Cognitive approaches emphasize the importance of tonal function (Lerdahl & Jackendoff, 1983; Lerdahl, 1988; Bharucha, 1984; Krumhansl, 1990), and more perceptual theories tend to focus on psychoacoustical features of chords (Helmholtz, 1877, 1885; Roberts & Shaw, 1984; Mathews, Pierce, & Roberts, 1987; Parncutt, 1989). There are only a few accounts of the effect of horizontal motion in chord progressions in psychological theory, despite the important role played by melodic contour in music perception (Dowling & Harwood, 1986; Eberlein, 1994, for a review).

The effects of musical function, sensory consonance, and horizontal motion on perceived musical tension were recently investigated with short chord sequences (Bigand, Parncutt, & Lerdahl, 1996). As a main result, it appeared that perceived tension was influenced by the tonal hierarchy (i.e., the more important the chord in the hierarchy, the weaker the tension), chordal consonance (minor more tense than major, seventh more tense than triad), and by horizontal motion (the greater the melodic distance traversed by voices, the higher the tension). Tensing values predicted by Lerdahl's (1988) cognitive theory, Parncutt's (1989) sensory-psychoacoustical theories, and a model of horizontal motion defined for the purpose of the experiment provided a good fit to tension

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ratings, suggesting that musical tension can be understood in view of current psychoacoustic and cognitive theories of music.

The purpose of the present study was to extend these findings to longer chord sequences. One of the main problems raised by long sequences is the relative importance of local and global structures. The musical tension of a given chord may be governed by its functional and/or acoustic relations to the immediately surrounding chords or by its harmonic relations with chords more distant in time. Therefore, the main goal of the study was to test cognitive and sensory-psychoacoustic models that quantify the effects of global and local structures on perceived musical tension. Let us first consider each model in detail.

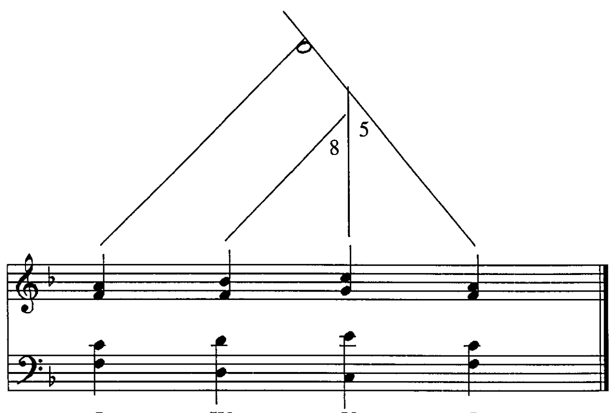
A cognitive model to predicting musical tension

According to the cognitive approach to musical tension, the sounding of a western musical piece activates in listeners an implicit knowledge of tonal hierarchies, from which the tonal function of the musical events are inferred (Bharucha, 1987). For example, in a C-major key context, the C-major chord (refered to as the tonic chord) is the most important chord of the tonal hierarchy, followed by the G-major and the F-major chords (refered to as the dominant and the subdominant chords, respectively). Cognitive representation of tonal hierarchies may be conceived of as a multidimensional space in which events of hierarchical importance (tonic, dominant, and subdominant chords, for example) are located close together (Longuet-Higgins, 1978; Shepard, 1982; Krumhansl & Kessler, 1982). In such spatial representation, the musical tension created by a given chord is assumed to be related to its distance from the instanciated tonic. Lerdahl's (1988) tonal pitch space theory follows these approaches by including a formula for computing tonal distances between musical objects. In this model, perceived musical tensions, governed at a cognitive level, may be predicted by the following relation: the smaller the tonal distance between two events in the pitch space is, the smaller is the tension perceived on the second event. An exhaustive account of the formula used for computing tonal distances is beyond the scope of this paper (see Lerdahl, 1988, 1991, 1996; Bigand et al., 1996), but let us consider some examples: In a C-major key context, the tonal distance between the hierarchically important tonic and dominant chords (C-major and G-major chords) is smaller (it has the calculated value of 5 in the present example) than the distance between a C-major chord and a hierarchically less important D-minor chord (it has the calculated value of 8). The tonal distance between a C-major chord and a non-diatonic F#-major chord is even greater (18). Accordingly, we may assume that in a C-major key context, the perceived musical tension will be smaller for the G-major chord than for the D-minor chord, and smaller for the D-minor than for the F#-major chord. With short chord sequences, tonal pitch space distances were significanlty correlated with perceived musical tension (Bigand et al., 1996).

The present study attempted to extend these findings to longer sequences. With long chord sequences, the perceived tension of a given chord is predicted to be partly determined by its tonal pitch space distance from the immediately preceding chord and partly by its global relation with all the other chords of the sequence. In order to express these local and global influences, three models of predicting perceived musical tension were defined for the purpose of the present study.

The hierarchic model relies on both the generative theory of tonal music (GTTM: Lerdahl & Jackendoff, 1983) and the tonal pitch space theory (Lerdahl, 1988). Let us consider the chord progression displayed in Fig. 1. According to the GTTM analysis ("Prolongational reduction"), the last chord is assumed to be perceived in relation to the first tonic chord. The third chord (a dominant chord) is supposed to be perceived in relation to the last chord. The second chord (i.e., a subdominant chord) is supposed to be perceived as subordinate to the dominant chord.

To define the tension value of these chords, a hierarchical model was defined. This model may be divided into two stages. To define the tension value of an event x, the first stage consists of computing the tonal pitch space distance between x and an event y to which x is subordinated in the GTTM prolongational tree. We will refer to these distances as the *hierarchic distances*. In the previous example (Fig. 1), the tension value of the last chord is determined by its pitch space distance to the first chord. Since the chords are identical, the tension value is null. The dominant chord (third chord) is supposed to be perceived in relation to the last chord. As



	I	IV	V	I
Hierarchic Values	0	8 + 5	5	0
Sequential Distances	0	5	8	5
Local stability	1	3	0	1

Fig. 1 Tension values computed by the hierarchic model, the sequential model, and the local stability model (see text for details)

mentioned above, the pitch space distance between the dominant and the tonic chord is 5. Its tension value is thus 5. The second stage of the model consists of adding the tension value of *y*. In other words, the event *x* inherits the tension value of the event *y* to which it is subordinated. We will refer to these values as the *inherited values*. For example, the subdominant chord of Fig. 1 (i.e., the second chord) is supposed to be perceived as subordinate to the dominant chord (i.e., the third chord). According to Lerdahl's (1988) theory, the pitch space distance between the dominant and the subdominant chords is 8. Since the subdominant is subordinated to the dominant chord, it inherits its tension value of 5, and the total tension value becomes 13 (i.e., $8+5$). Inherited values are thus more global by comparison to the hierarchic distances. This two-stage computation is summarized by formula 1:

$$\mathrm{T}(x) = \mathrm{T}(x,y) + \mathrm{T}(y) \quad (1)$$

where T(*x*) represents the hierarchic value of tension of the event *x*, T(*y*) the tension value inherited from the event *y*, and T(*x,y*) the hierarchic distance in pitch space computed between the events *x* and *y*.

In summary, this hierarchic quantification expresses that the degree of musical tension associated with a given chord correlates to the tonal pitch space distance the chord has to the main tonic of the piece. The first experimental sequence was defined to address this assumption (see Fig. 2). The sequence contained three sections, the first two being the related keys of C and F, the last one in the far key of B. The hierarchic distance and the inherited value computed for each chord are displayed in Table 1. According to Lerdahl's (1988) theory, the tonal distance between the F tonic chord of the second section (chord number 13) and the first C tonic chord of the first is 7. Since the others chords of the second section (from chords 13–21) are subordinated to the F chord, they all inherit a minimum tension value of 7. Similarly, the tension value of the B tonic chord of the third section (chord number 23) was defined by its distance in pitch space to the F chord of the second section (chord number 13). According to Lerdahl (1988), this distance is 30. The B chord also inherits the tension values of the F chord, so that its total tension value is 37.

Table 1 Hierarchic distances through pitch space computed for each chord of the sequence used in Exp. 1

Chords	d(X–Y)	D (*x*,*y*) Hierarchic distances	T(*y*) Inherited values	Hierarchic values
1		0	*0*	0
2	d(2–1) =	7	*0*	7
3	d(3–2) =	8	*7*	15
4	d(4–5) =	5	*7*	12
5	d(5–2) =	0	*7*	7
6	d(6–7) =	5	*7*	12
7	d(7–1) =	7	*0*	7
8	d(8–7) =	8	*7*	15
9	d(9–10) =	5	*5*	10
10	d(10–11) =	5	*0*	5
11	d(11–1) =	0	*0*	0
12	d(12–13) =	5	*7*	12
13	d(13–1) =	7	*0*	7
14	d(14–15) =	5	*7*	12
15	d(15–13) =	0	*7*	7
16	d(16–17) =	8	*12*	20
17	d(17–13) =	5	*7*	12
18	d(18–19) =	5	*20*	25
19	d(19–20) =	8	*12*	20
20	d(20–21) =	5	*7*	12
21	d(21–13) =	0	*7*	7
22	d(22–23) =	5	*37*	42
23	d(23–13) =	30	*7*	37
24	d(24–25) =	5	*37*	42
25	d(25–23) =	0	*37*	37
26	d(26–27) =	8	*42*	50
27	d(27–23) =	5	*37*	42
28	d(28–27) =	8	*42*	50
29	d(29–30) =	5	*42*	47
30	d(30–31) =	5	*37*	42
31	d(31–23) =	0	*37*	37

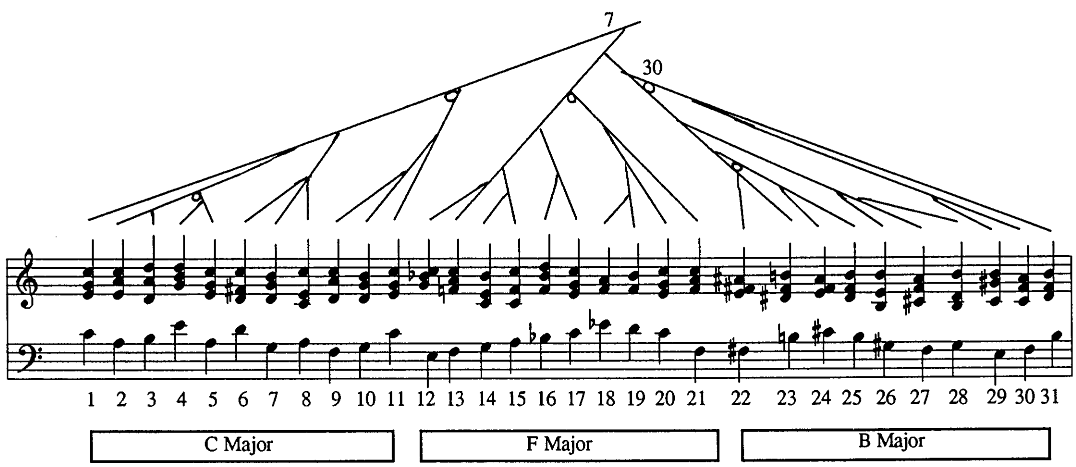


Fig. 2 Constructed chord sequence used in Exp. 1. the prolongational structure is displayed in the above tree: *white circles* represent strong prolongation. All other connections represent harmonic progression. Music notation convention: accidental (sharps, flats, naturals) remain in force until the end of the figure, unless replaced by another accidental

Consequently, all of the chords subordinated to the B chord in this third section inherit a minimum tension value of 37. This computation assumes that the third section would be perceived in relation to the C-major key, via the intermediate F-major key.

Two alternative models to quantify the tension values can be contrasted with the hierarchic model. First of all, intuitions about harmonic tension and relaxation may be due to sequential harmonic relations between adjacent chords. To express such local influences, a sequential model was defined. The tension value of an event x corresponded to the tonal pitch space distance between the event x and the event x–1 that immediately precedes it, i.e., $T(x) = D(x, x-1)$. Let us consider the chord progression displayed in Fig. 1. According to the *sequential harmonic model*, the tension value of the subdominant chord (second chord of the sequence) equals 5, since its tonal pitch space distance to the tonic chord that precedes it is 5 (see above). According to Lerdahl's (1988) theory, the tonal distance between a subdominant and a dominant chord is 8. Thus, the tension value of the dominant chord (third chord of the sequence) is 8. The tension value of the last tonic chord chord is 5, since it is supposed to be perceived in relation to the preceding dominant chord. The sequential harmonic distances computed according for the chord sequence of Exp. 1 are displayed in Table 2.

Table 2 Sequential harmonic distances through pitch space and local stability computed for each chord of the sequence used in Exp. 1

Chords		Sequential harmonic distances	Local stability
1	I	0	0
2	vi	7	1
3	vii7	8	4
4	iii7	5	4
5	vi7	5	4
6	V7/V	6	4
7	V/I	5	1
8	ii/V	8	1
9	ii/I	5	7
10	V	5	1
11	I	5	0
12	V7/IV	5	7
13	I	5	1
14	V	5	7
15	I	5	4
16	IV	5	1
17	V	8	0
18	V7/IV	8	7
19	IV	5	4
20	V	8	0
21	I	5	1
22	V7/#IV	36	4
23	I	5	0
24	V	5	7
25	I	5	0
26	IV	5	4
27	V	8	1
28	vi	8	1
29	ii	5	7
30	V	5	1
31	I	5	0

Secondly, musical tensions or relaxations may simply be due to the local harmonic stability of the chords. For example, chords in first inversion should be perceived as harmonically less stable than chords in root position. To account for this last aspect, a third quantification model (referred to henceforth as the *local stability model*), was defined. Quite arbitrarily, this local stability model confers a tension value of 3 to chords in inversion (i.e., the bass is not the root). A further 1 point is added if the soprano is not the root, and a further 3 points for every non-triadic tone in the chord (see Fig. 1).

Each of these three models expresses the potential influences of three different features on musical tension: the hierarchic model expresses the influence of the global harmonic structure, the sequential harmonic model expresses the influence of the local harmonic structure, and the local stability model expresses the influence of the chordal voicing and quality. One of the purposes of the present study was to compare how much variance in perceived musical tension was accounted for by each of these models.

Sensory models of musical tension

In contrast to cognitive approaches to tension, psychoacoustic theories predict the strength of harmonic pitch relationships between successive chords without considering the listener's implicit knowledge of tonality. In the mainstream theory of tonal-harmonic music, successive chords are considered to stand in a strong harmonic relationship with each other if they satisfy one or more of the following conditions: (1) They have one or more tones in common, (2) their roots are close to each other on the cycle of fifths, and/or (3) their notes all belong to the same major or minor scale.

Of these three, only the first (the notes-in-common condition), can be unequivocally defined and applied to any chord sequence. A problem with the cycle of fifths condition is that the roots of chords are generally somewhat ambiguous (Terhardt, 1974a; Parncutt, 1988), so that the distance on the cycle of fifths is not always clearly defined. For example, in an appropriate context, an A-minor triad can function as a C chord. A problem with the scale-belongingness condition is that it is not always clear which pitches belong to the prevailing scale and which do not – for example, if there is a modulation taking place, or if the ambiguous sixth and seventh degrees of the minor scale are involved. Moreover, some major-minor scale degrees are clearly more perceptually important than others (Krumhansl & Kessler, 1982).

The sensory model of Parncutt (1989) predicts the strength of harmonic pitch relationships between successive chords without invoking music-theoretic constructs, such as the cycle of fifths and the harmonic/melodic minor scales. The model does not directly account for the listener's implicit or explicit knowledge of tonality. Instead, predictions are based entirely on the degree to which the chords have perceived pitches in common (see Bigand et al., 1996). In the present study, pitch-commonality was defined as the percentage of perceived pitches a given chord has in common with the previous ones, taking into account variations in the salience of perceived pitches. High pitch-commonality is due either to chord repetition, high note-commonality (i.e., holding three tones constant and changing the fourth), or high chroma-commonality (i.e., repeating the same chord in a different inversion). Low pitch-commonality is due either to large distances traversed on the cycle of fifths, or to the absence of a chroma in common between two chords. From this qualitative overview, it is clear that pitch-commonality encapsulates several of the criteria involved in the perception of harmonic tension. Table 3 displays the pitch-commonality values of each chord with the previous one, labelled P.C. ($n-1$), the second-previous chord, P.C. ($n-2$), and the third-previous chord, P.C. ($n-3$).

Horizontal motion

The cognitive and sensory approaches described above emphasize the effect of the vertical arrangement of the tones on musical tension. The effect of the melodic arrangement between the tones of successive chords is neglected by these models. In music theory, good horizontal organization of harmonic sequences is produced by adhering to a number of more or less strict rules, referred to as "counterpoint rules" in pedagogical treatises. It has been shown that horizontal motion has a strong influence on perceived musical tension and that the sizes of the intervals covered by each voice when passing from one chord to the next affect tension ratings, notably for nonmusicians (Bigand et al., 1996). In the present study, a similar model of melodic motion was applied to the voices of the chord sequence. The values in Appendix 1 are pitch distances between successive tones in semitones (half steps) computed for the composed chord sequence used in Exp. 1.

In summary, we have seen that several variables can affect the tension perceived in chord progressions. The variables differ in the extent to which they are cognitive or sensory, local or global. We hypothesized that a linear combination of these models would explain a large portion of variance in tension ratings of chords in longer progressions.

Table 3 Pitch-commonality values, P.C., in percent computed with the previous chord, P.C. ($n-1$), with the second previous chord, P.C. ($n-2$), and the third previous chord, P.C. ($n-3$), for each chord of the sequence tested in Exp. 1

Chords	P.C. ($n-1$)	P.C. ($n-2$)	P.C. ($n-3$)
1	–	–	–
2	–	–	–
3	–	–	–
4	77	60	74
5	75	58	91
6	64	58	79
7	65	67	90
8	54	71	94
9	75	59	78
10	59	54	100
11	66	67	91
12	87	60	60
13	60	65	48
14	50	90	84
15	65	93	72
16	62	68	65
17	51	80	84
18	57	69	80
19	75	52	96
20	52	54	100
21	65	72	87
22	33	50	50
23	66	28	30
24	66	94	32
25	66	100	66
26	80	65	80
27	51	65	93
28	54	88	91
29	75	59	91
30	59	54	100
31	65	67	91

Experiment 1: Composed chord sequence

Method

Participants. Twenty students from the music conservatory of Boulogne, France (referred to hereafter as "musicians") volunteered to participate in the experiment. All had received at least 10 years of intensive training in music (i.e., music theory, ear training, and instrumental performance). Twenty college-age students (referred to henceforth as "nonmusicians") also took part in the experiment. They had never played nor studied music. All were students in psychology and participated in the experiment on a volunteer basis.

Materials. The chord sequence used in this experiment is displayed in Fig. 2. According to Lerdahl (personal communication), two prolongational structures may be defined for this sequence: one oriented toward the C-major key, the other toward the B-major key. The former structure, however, provided a better analysis of the sequence: it seemed more likely to correspond to perceiving musical events in reference to a key that has been already heard than the reverse. The tree structure of Fig. 2 represents the prolongational structure oriented toward the C-major key. Following Lerdahl and Jackendoff's (1983) convention, *white circles* designate weak prolongation, and the *lack of circles* indicates a progression. The number 7 at the first node of the tree represents the distance in pitch space between the keys of C and F major, and the number 30 represents the distance in pitch space between the keys of F and B major.

Following Palmer and Krumhansl (1987a, b; Bigand, 1997), the chord sequence was segmented into several fragments. Each segment started at the beginning of the sequence and stopped on a different chord. The first fragment stopped on chord 2, the second on chord 3, and so on. The 30 fragments were played with sampled piano sounds produced by the EMT10 Yamaha Sound Expander at a tempo of 80 quarter notes per minute. The Yamaha sampler was controlled through a MIDI interface by a Macintosh computer running Performer software. *Velocity*, a MIDI parameter related to the force with which a key is struck, was held constant for all pitches. Participants were allowed to adjust the output of the amplifier to a comfortable level. There was no silence between the offset of a tone and the onset of the succeeding tone, nor was there any overlap.

Task. The participants' task was to evaluate the musical tension at the final chord of each fragment using a rating scale ranging from 0 (no tension) to 10 (very high tension). In a preliminary session, participants listened to musical examples exhibiting different degrees of musical tension. They were told that strong musical tension at the end of a fragment evokes the feeling that there must be a continuation of the sequence. Low musical tension evokes the feeling that the sequence could naturally stop at this point. As musical tension may be varied in subtle ways in music, the participants were encouraged to use all the degrees of the rating scale.

Design and procedure. Before running the experiment, participants were trained on the evaluation of musical tension with 10 fragments. No feedback was provided unless participants used the scale in the reverse order. The experiment started with the first fragment of the experimental sequence, and participants had 8 s to give their tension rating. After that, the fragment terminating on chord 2 was played, followed by the fragment ending on chord 3, and so on. The rationale for such a chronological presentation is set out in Bigand (1993).

Results

The average ratings for musical tension are displayed in Fig. 3. Nonmusicians' ratings tended on average to be higher than the musicians', but correlation between the mean ratings of each group was very high (r = .94; df = 28, $p < .001$).

Multiple regressions were performed that predicted mean values for musical tension from the cognitive model, the sensory-psychoacoustic models, and the horizontal motion model (Table 4). On the whole, each model provided a significant but moderate fit to musical tension. In the cognitive model, the inherited values (i.e., the more global aspect of the model) failed to significantly contribute. The main discrepancy arose on the last 10 stop chords of the sequence: musical tension experienced on these chords was not stronger than those for the first two sections of the sequence (see Fig. 3). A further analysis revealed that the inherited values only marginally contributed to musical tension when the last 10 chords were excluded from the regression analysis (t = 1.85, p < .07). This suggested that the chords in the B-major key were not perceived in relation to the previous keys of C and F major, but more probably in reference to the new tonic chord of B major. The most interesting finding in this regard concerned the differences in tension ratings observed for the B chords that immediately followed the modulation to the B-major key (chords 23 and 25) and the last B chord. Tension was much higher on chords 23 and 25 than on the last B chord, $t(39) = 12.58$, $p < .001$, and $t(39) = 8.47$, $p < .001$, respectively. This indicates that the B tonic chords that immediately followed the modulation were perceived in relation to the previous F tonic region, but that the feeling of the F-major key later vanished. A similar pattern of data was also observed at the modulation from C to F major. Perceived tension was higher for chord 13 than chord 21, $t(39) = 6.26$, $p < .001$. Both results suggest that the influence of a previous key remained at a local level. The sensory-psychoacoustic model provided a moderate but significant fit to average ratings of musical tension: the greater the percentage of common perceived pitches between two chords, the less the perceived tension. Melodic arrangement between successive chords also provided a significant but moderate fit to tension ratings, with the intervals traversed by the bass voice as the most important contributor.

Since the cognitive model, the sensory-psychoacoustic model, and the model for horizontal motion all significantly contribute to tension value, a stepwise regression predicting the average ratings from a linear

Fig. 3 Mean and standard deviation of tension ratings of musicians and nonmusicians for chords 2 to 31 in Exp. 1

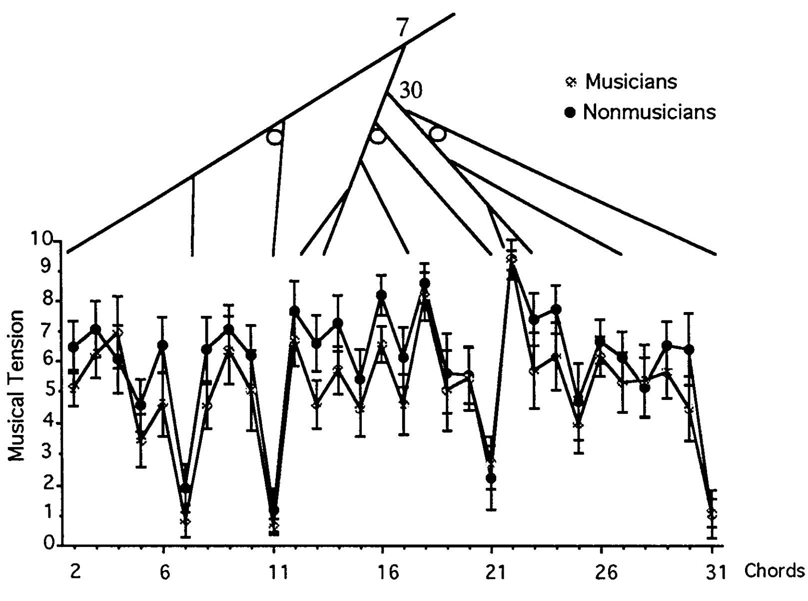


Table 4 Summary of multiple regression analysis predicting the average ratings obtained in Exp. 1 by a combination of several models and the extent of musical expertise

Cognitive models	$R^2 = .56$	$F(5, 54) = 13.63$	$p < .001$
Hierarchic distances	$sr = .37$	$t = 4.10$	$p < .001$
Inherited values	$sr = .04$	$t < 1$	
Sequential harmonic dist.	$sr = .43$	$t = 4.72$	$p < .001$
Local stability	$sr = .48$	$t = 5.27$	$p < .001$
Musical expertise	$sr = .24$	$t = 2.68$	$p < .01$
Pitch-commonality	$R^2 = .29$	$F(4, 51) = 5.38$	$p < .01$
$(n - 1)$	$sr = .21$	$t = 1.83$	$p = .07$
$(n - 2)$	$sr = .19$	$t = 1.57$	$p > .10$
$(n - 3)$	$sr = .42$	$t = 3.59$	$p < .001$
Musical expertise	$sr = .23$	$t = 1.99$	$p = .05$
Horizontal motion	$R^2 = .37$	$F(5, 54) = 6.42$	$p < .001$
Soprano	$sr = .00$	$t < 1$	
Alto	$sr = .26$	$t = 2.42$	$p < .05$
Tenor	$sr = .09$	$t < 1$	
Bass	$sr = .40$	$t = 3.71$	$p < .001$
Musical expertise	$sr = .24$	$t = 2.25$	$p < .05$

combination of these models was performed. As shown in Table 5, a linear combination of four variables accounted for 63% of the variance. All of these variables express the influence of local features on musical tension. A second stepwise regression was also performed that predicted perceived tensions for the C and F regions only (i.e., from chords 2 to 21). This time, the hierarchic values entered at the first step in the model and explained 56% of the variance. This result confirmed that the main weakness of the hierarchic model was to confer very high inherited values to the chords in the key of B. A further analysis was run to support this interpretation. Since chords 25 to the end of the sequence seemed to be perceived in reference to the new tonic chord of B major (instead of the C tonic chord), new inherited values were defined. Inherited values were lowered by a value of 37 for these chords. A stepwise regression was rerun with these new hierarchic values. As shown in Table 5, the hierarchic model was now the most important contributor to tension ratings for the entire sequence.

Table 5 Summary of a stepwise regression analysis predicting the average ratings of Exp. 1 by a combination of all the models

	Step	R^2
All chords		
Sequential d.	1	.31
Bass voice	2	.41
Local stability	3	.55
P.C. $(n - 3)$	4	.63
C and F regions		
Hierarchic values	1	.56
Alto voice	2	.62
Bass voice	3	.67
P.C. $(n - 1)$	4	.72
Hierarchic revised		
Hierarchic revised	1	.39
Local stability	2	.56
Bass motion	3	.68

Discussion

The present findings indicate that part of the tension perceived in a long chord sequence may be predicted by quantifying the influence of local features (i.e., pitch-commonality, local stability, or the melodic distance traversed by voices of successive chords) and the influence of the global harmonic structure. In the present study, local models tended to predominate over global ones, mainly because the tension values defined by the hierarchic model for the chords in the B region were too strong. Post-hoc analysis suggested that chords in the B region were not perceived in a strictly hierarchic way – that is, in reference to the previous tonal center of F and C major. The influence of a previous key actually occurred over a short time span, since the first tonic chords following a modulation received quite high tension-values, but this influence did not continue over all the sequence. Table 5 (*bottom*) shows that a less hierarchic model would provide the most important contribution to musical tension for the entire sequence.

On the one hand, a strictly hierarchic model failed to significantly contribute to tension ratings, which suggests that local features could be more important for listeners than global ones, a finding consistent with several recent studies (Cook, 1987; Karno & Konecni, 1992; Tillmann & Bigand, 1996, Tillmann, Bigand, & Madurell, 1998a). On the other hand, the failure of the hierarchic model may be explained because of the unusual harmonic structure of the experimental sequence. The sequence was chosen because it exhibits a large variety of distances through pitch space. However, the modulations it contains are sudden, making the main key somewhat arbitrary. This could have encouraged listeners to perceive each section independently, notably the last one which was in a very far key. The purpose of Exp. 2 was to remedy this problem by using a chord sequence which progressed more gradually through regions in pitch space.

Experiment 2: Chopin Prelude in E major

A harmonic reduction of the first two phrases of the Chopin Prelude in E major was used in Exp. 2 (Fig. 4). As expressed by the prolongational tree, the first phrase, (i.e., the first four measures) turns around the dominant chord and remains in the E-major region. The second phrase modulates progressively toward the G-major, C-major, F-major, and F-minor region and reaches the distant A-flat region (measure 8). The A-flat chord (local tonic chord) is then followed by a return to the main key of E major (chord 32) (see Lerdahl, 1991, for a complete analysis). The musical tensions created by this chord sequence were quantified according to the hierarchic and sequential models explained above. As shown in Table 6, tension values computed by the hierarchic model become stronger as long as the second phrase progresses toward distant regions, with a climax in musical tension in measure 7. The tensions accumulated through the second phrase would then be resolved by the return to the main key of E major, which occurs on chord 32. At this point in the sequence, however, the tension value predicted by the sequential model is very high (17), since there is a great pitch space distance between the A-flat chord (chord 31) and the B7 chord (chord 32) that follows. Therefore, if musical tension is governed by the local harmonic relations, the tension experienced on this B7 chord will be strong, whereas if musical tension is governed by the function of the chord in the overall structure of the piece, the tension experienced will be very low, or at least lower than the tension perceived on the A-flat chord. As before, tension values that derive from the disposition of individual chords (local stability model), and those defined by the sensory-psychoacoustic model and the model for horizontal motion were also computed. In relation to Exp. 1, it was assumed that the hierarchic model would strongly contribute to tension ratings, with all of the other factors being included in the regression analysis.

Method

Participants. Twenty-five students from the French music conservatory (referred to hereafter as "musicians") volunteered to participate in the experiment. All had received at least 10 years of intensive training in music (i.e., music theory, ear training, and instrumental performance). At the end of the experiment, none of the musicians reported knowing the Chopin Prelude used in the study. Twenty-five college-age students (referred to henceforth as "nonmusicians") also took part in the experiment. They had never played or studied music. All participated in the experiment on a volunteer basis.

Materials, task, and procedure. The harmonic reduction of the Chopin Prelude was segmented into 33 fragments. Each started at the beginning of the sequence and stopped on a different chord. The first fragment ended on the third chord, the second fragment on the fourth, and so on. The 33 fragments were played in order of increasing length at a tempo of 55 quarter notes per minute, using the same equipment as in Exp. 1. The participants' task and the procedure were the same as in Exp. 1.

Results

The average ratings for musical tension are displayed in Fig. 5. Most of the inter-subject correlations (i.e., 95%) were significant for musicians. There was less agreement between nonmusicians. The correlation between the mean ratings of the two groups of participants was rather high ($r = .82$; $df = 31$, $p < .01$).

Multiple regression analysis was performed to assess the portion of variance accounted by each model separately. As displayed in Table 7, the contribution of each model depended on musical expertise. The cognitive model provided a better fit to musicians' ratings than to nonmusicians'. The inherited values significantly contributed to the regression model. Moreover, these were among the two most important factors for both groups of participants. The sensory-psychoacoustic models provided a moderate but significant fit to musical tension, and each variable contributed in a different way,

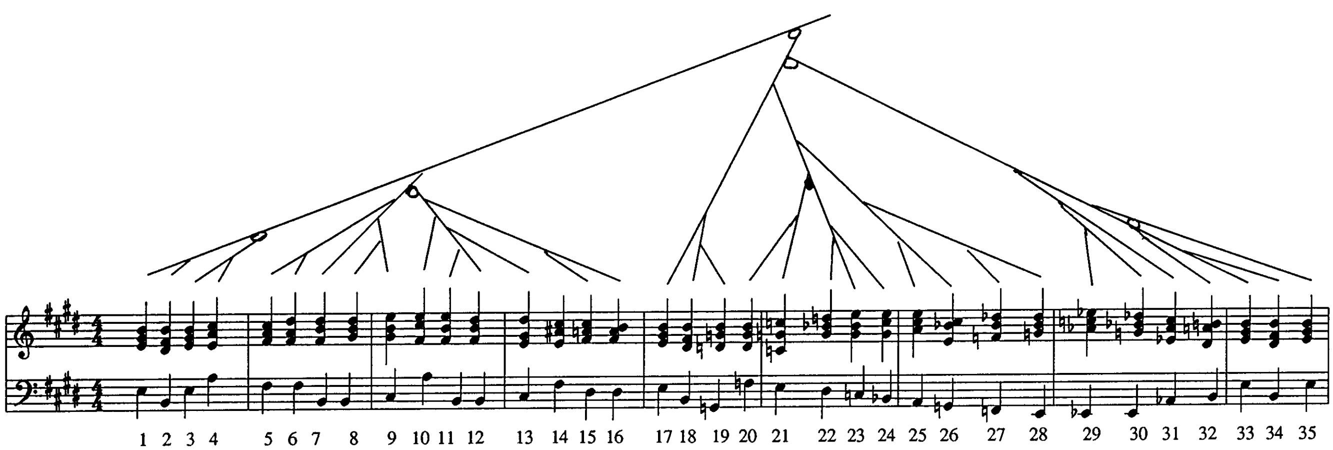


Fig. 4 Harmonic reduction of the Chopin Prelude in E major used in Exps. 2 and 4. The prolongational structure is represented by the tree: *white circles* represent strong prolongation, *black circles* represent weak prolongation, and other connections represent harmonic progression

Table 6 Tension values predicted for the Chopin Prelude. H.D. represents hierarchic distances. I.V., the inherited values. S.H.D.. the sequential harmonic distances. L.S.. the local stability. and P.C.. the pitch-commonality values with the previous chords (n − 1) and the second previous chord (n − 2). C.M. represents the values of a cadential model used in Exp. 4

Chords		H.D.	I.V.	S.H.D	L.S.	C.M.	P.C. ($n-1$)	P.C. ($n-2$)
1	I	0	0	0	1	0	–	–
2	V	5	0	5	0	1	–	–
3	I	0	0	5	1	0	62	100
4	IV	5	0	5	1	2	65	51
5	ii	5	5	7	1	2	80	50
6	vii	0	10	7	3	2	90	68
7	V	5	0	5	1	1	81	67
8	iii6	5	13	7	4	2	90	65
9	vii7	8	5	5	4	2	75	64
10	ii$^6_5$	5	5	5	7	2	63	43
11	V^4	5	0	5	4	2	80	76
12	V	5	0	5	1	1	86	60
13	vi	8	5	8	4	2	65	52
14	V7/V	7	5	5	4	2	58	58
15	V	0	11	11	10	2	74	43
16	V$^6_5$	5	0	5	6	1	88	61
17	I	0	0	5	1	0	61	46
18	V	5	0	5	0	1	62	86
19	III	14	5	14	1	2	51	53
20	V$^4_2$/^{b}VI	5	16	0	7	2	94	52
21	I^6/^{b}VI	0	16	5	3	2	63	60
22	V$_4^{b6}$/^{b}VI	5	16	5	7	2	63	75
23	I/^{b}VI	16	0	5	4	2	62	95
24	V/bII	7	16	0	7	2	91	66
25	V/bII	0	29	11	1	2	49	50
26	vii^{07}/bII	0	23	0	6	2	68	51
27	vii^{07}/bII	0	29	7	4	2	70	44
28	vii$^4_2$/bII	0	23	7	7	2	69	86
29	V/#II	0	21	5	4	2	49	53
30	V^7/#III	5	16	5	4	1	62	84
31	1/#II	16	0	5	1	0	51	91
32	V^7	5	0	17	3	2	49	42
33	I	0	0	5	1	0	60	48
34	V	5	0	5	0	1	62	89
35	I	0	0	5	1	0	62	100

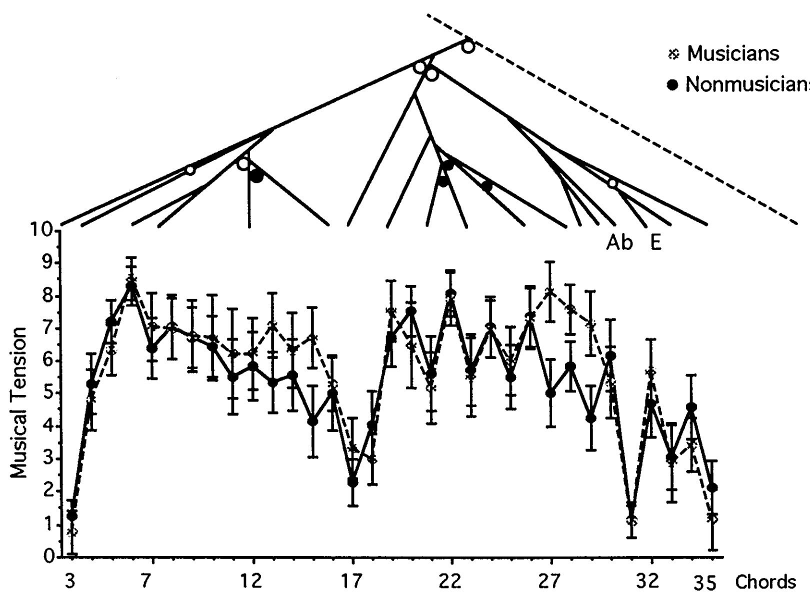


Fig. 5 Average tension perceived by musicians and nonmusicians for chords 3 to 35 of the harmonic reduction of the Chopin Prelude

Table 7 Summary of multiple regression analysis predicting the average ratings by a combination of several models for the Chopin Prelude (Exp. 2)

	Musicians	Nonmusicians
Cognitive models	$R^2 = .56$	$R^2 = .28$
	$F(4, 28) = 9.0, p < .001$	$F(4, 28) = 2.73, p < .05$
Hierarchic distances	$t = 1.69, p > .10$	$t = 1.72, p < .10$
Inherited values	$t = 3.01, p < .001$	$t = 2.11, p < .05$
Sequential harmonic dist.	$t = 2.25, p < .01$	$t < 1$
Local stability	$t = 3.16, p < .001$	$t = 1.20, p > .10$
Pitch-commonality	$R^2 = .37$	$R^2 = 3.1$
	$F(2, 30) = 8.72, p < .01$	$F(2, 30) = 6.67, p < .015$
P.C. $(n - 1)$	$t = 2.29, p < .02$	$t = 3.28, p < .005$
P.C. $(n - 2)$	$t = 3.37, p < .01$	$t = 1.46, p > .10$
Horizontal motion	$R^2 = .07$	$R^2 = .07$
	$F(4, 28) < 1$	$F(4, 28) < 1$

Table 8 Summary of a stepwise regression analysis predicting the average ratings for musical tension in the Chopin Prelude (Exp. 2)

	Step	R^2
Musicians		
Hierarchic values	1	.35
P.C. $(n - 2)$	2	.53
P.C. $(n - 1)$	3	.64
Sequential harmonic dist.	4	.73
Alto voice	5	.79
Nonmusicians		
P.C. $(n - 1)$	1	.26
Hierarchic values	2	.51

depending on the extent of musical expertise. The model for horizontal motion failed to contribute to musical tension, even for nonmusicians. Including the direction of motion in the model (i.e., coding 7 for an ascending fifth and –7 for a descending fifth) did not improve the power of this model. Compared to the finding of Exp. 1, the failure of the horizontal motion model suggests that the contribution of melodic motion may depend on the musical style: In chromatic chord progressions where the voice leading is such that voices typically traverse small intervals (mostly semitones and tones, i.e., half steps and whole steps), the contribution of melodic motion is negligible by comparison to the contribution of harmonic effects.

Stepwise regression analyses predicting the ratings from a combination of all models were performed for musicians and nonmusicians separately. Each model contributed differently, depending on musical expertise. In each case, the amount of variance accounted for was greater for musicians than nonmusicians (Table 8). In both groups, the influence of global harmonic structure was reflected by the significant contribution of the hierarchic model (i.e., hierarchical distances + inherited values). The influence of local features was reflected by the contribution of pitch commonality and, in musicians, by the sequential distances.

The present findings suggest that a substantial proportion of the experienced tension in this piece came from its global harmonic structure. This conclusion should be moderated, however, in the light of discrepancies between the present data and the tension values predicted by the hierarchic model. First of all, the tension values at chord 17 (prolongation of the tonic chord) were higher than those at chord 31 (A-flat chord), for which the hierarchic model predicted a strong tension value, $t(24) = 3.93, p < .001$; $t(24) = 2.5, p < .05$ for musicians and nonmusicians, respectively. Secondly, the hierarchic model predicted a decrease in tension ratings between chords 31 and 32, when the Prelude returned to the main E-major key. As shown in Fig. 5, there was a strong increase in tension ratings for both groups on chord 32, suggesting that this chord was more likely perceived as a new departure from the A-flat key than as a return to the E region. Moreover, the tension values on the E tonic chord that followed (i.e., chord 33) remained higher than the tension values on the previous A-flat chord, $t(24) = 2.44, p < .05$; $t(24) = 3.15, p < .001$, for musicians and nonmusicians, respectively. Finally, for both groups of participants, the tension values during the second phrase of the Prelude were not significantly stronger than those for the first phrase.

Discussion

As expected, the hierarchic model significantly contributed to musical tension in Exp. 2. However, such findings are far from compelling, because several discrepancies occurred between the data and the predictions. First of all, the tension values during the first part of the Prelude were not weaker on average that those during the second part. Secondly, the tension values reported by participants on several of the chords were contrary to the prediction of the hierarchic model. The clearest discrepancies occurred at the time of the return to the main E-major key. The tension values at the B and E chords (chords 32 and 33) were significantly greater than at chord 31, suggesting these chords were perceived as a modulation to a new distant key and not as a return to the main key. Therefore, local harmonic structures seem to prevail over the global structure when modulation occurs, which is consistent with the findings of Exp. 1.

Since the previous experiment failed to clearly establish the influence of the global harmonic structures on musical tension, two other experiments were designed to further address this issue. In both, the presentation of the Chopin Prelude was systematically manipulated in order to emphasize either the global harmonic structure of the piece (Exp. 3) or the local structures (Exp. 4). It was assumed that these manipulations would significantly affect the participants' ratings and consequently, the contribution of each model. The manipulations were performed so that the contribution of the hierarchic model should be stronger in Exp. 3 and weak or null in Exp. 4. The reverse was expected for the other models.

Experiment 3: The influence of the reduction and the familiarity on perceived tension

Several changes were made in Exp. 3 in order to facilitate the perception of the global harmonic structure of the piece. In Exps. 1 and 2, the participants had never heard the chord sequence before the experiment. Their responses expressed the tension values experienced during the first listening. This may explain why local structures prevail over global ones when a modulation occurs. We expected that listening to the Chopin Prelude several times before the experiment would increase the chance that listeners perceive the return to the main key (E major) and would also increase the chance that listeners perceive the climax of the Prelude during the second phrase.

In Exp. 2, a harmonic reduction of the actual Prelude was used. The absence of rhythmic variation in the reduction may have weakened listeners' understanding of the global structure of the piece. Rhythm creates temporal accents that capture listeners' attention and emphasize high-order relationships among the musical events (Jones, 1987; Boltz & Jones, 1986). Playing the original version of the Prelude (i.e., with its original rhythm and melody) may clarify the symmetry of the piece (i.e., two phrases of four measures, each ending on a full cadence in the main key) and may therefore increase the tension experienced on the A-flat chord. Finally, several participants observed that testing the 33 chords of the sequence made Exp. 2 very repetitive and could have encouraged them to focus on the local structure that ends the fragments rather than on the global structure. Testing a smaller number of final chords would probably encourage participants to pay more attention to the overall structure of the fragment. The purpose of Exp. 3 was to test how all of these changes in experimental method would affect the participants' responses.

Method

Participants. Thirty-nine students from the music department of La Sorbonne (Université Paris IV) (referred to hereafter as "musicians") volunteered to participate in the experiment. All had received at least 10 years of intensive training in music (i.e., music theory, ear training, and instrumental performance). Thirty-nine college-age students (referred to henceforth as "nonmusicians") also took part in the experiment. They had never played nor studied music. All participated in the experiment on a volunteer basis.

Materials. Two versions of the Chopin Prelude were used in this experiment: the harmonic reduction displayed in Fig. 4 and the original piece. Both versions were played at a tempo of 55 quarter notes per minute with the same equipment as in Exp. 1. Both versions were segmented into 18 fragments, with each fragment starting at the beginning of the sequence and stopping on a different chord. Nine chords from the first phrase were tested (i.e., chords 3, 4, 6, 7, 8, 12, 13, 15, 17, in Fig. 4), and 9 from the second phrase (chords 20, 23, 24, 25, 26, 27, 31, 32, 33). To neutralize the influence of the duration of the final chord, the duration of the chords ending the fragments in the original version were all adjusted to a quarter note.

Task, procedure and design. The participants' task was the same as described in previous experiments. In two experimental situations the experiment started immediately after the training session, with half of the participants listening to the harmonic reduction of the Prelude and the other half listening to the original version. In the third experimental situation, the harmonic reduction of the Prelude was played three times before the running of the experiment. These three experimental situations are referred to henceforth as (1) first listening of the harmonic reduction, (2) original version, and (3) fourth listening of the harmonic reduction. Participants were randomly assigned to one of these conditions, and the data of conditions 2 and 3 were compared to those of condition 1.

Results

The average ratings of tension experienced in each condition are displayed in Fig. 6. The average rating registered in the first-listening condition significantly correlated with those registered on the chords in Exp. 2, indicating the reliability of the experimental method, $r = .84$, $df = 16$, $p < .001$ in musicians; $r = .69$, $p < .01$, in nonmusicians.

To test the effect of the listening situations, two 2×2 (Musical expertise $\times$ Listening situation) MANOVAs were performed, with the two variables as the between-subject factor and the 18 final chords as the dependent variables. The first MANOVA compared the ratings registered in conditions 1 and 2 (i.e., first listening of the harmonic reduction versus original version). There was a significant main effect of the version on the profile of tension, $F(17, 32) = 2.72$, $p < .01$: in the original version, stronger tensions were observed in the first part of the sequence (Fig. 6). This effect of the version was more pronounced in nonmusicians, $F(17, 32) = 7.71$, $p < .001$. Playing the original version, however, did not alter the tension ratings at chords 31, 32, and 33: in both cases, the ratings were very low on the A-flat chord (chord 31) and increased on the following B and E chords.

The second MANOVA compared the first listening of the harmonic reduction and the fourth listening.

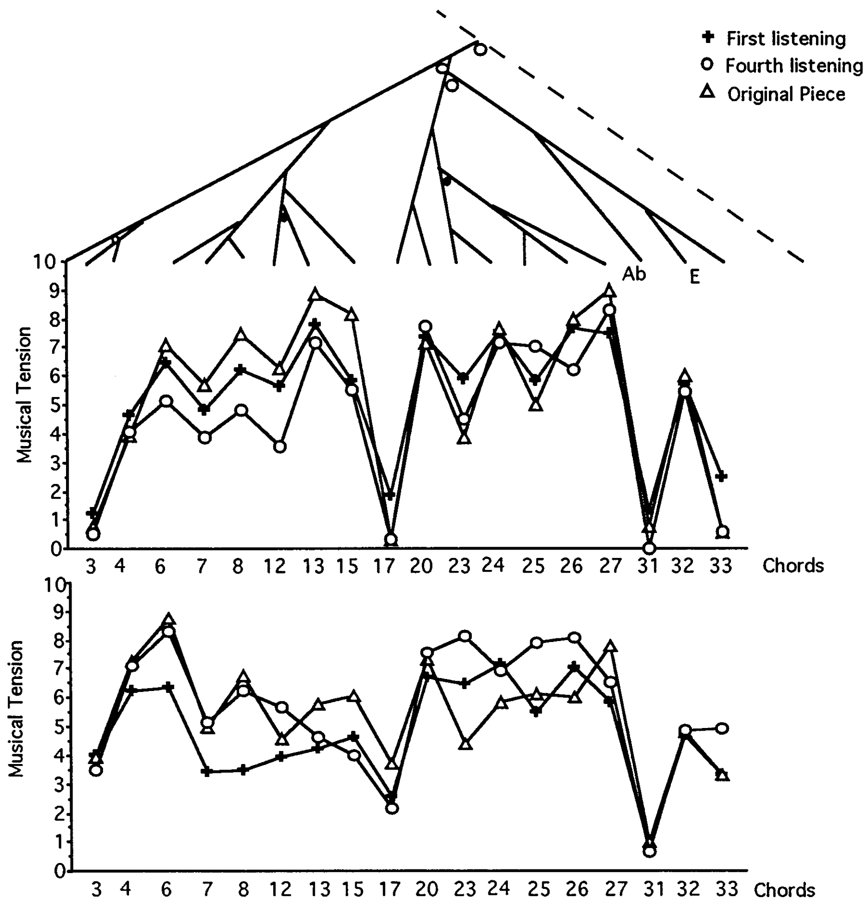


Fig. 6 Average tension perceived by musicians (*top*) and nonmusicians (*bottom*) for 18 chords of the Chopin Prelude. Participants listened either to a harmonic reduction heard for the first time (First listening) or for the fourth (Fourth listening), or they heard the original version of the Prelude (Original Piece)

Contrary to what was expected, musical tension experienced during the first listening of the piece did not differ from that experienced during the fourth listening. Moreover, the tension perceived on chords 31 and 32 was almost identical in both experimental situations: the ratings were very low on the A-flat chord and increased when the piece returned to the main key.

Stepwise regression analyses predicting the ratings from a combination of all models were performed for musicians and nonmusicians separately (Table 9). The outcome of these analyses did not strongly vary with the experimental conditions: with the musicians, the hierarchic values (i.e., hierarchic distances + inherited values) were always the most important factor, but in a

Table 9 Summary of a stepwise regression analysis predicting the average ratings for musical tension in the three conditions of Exp. 3 and for both group of subjects separately

	Musicians			Nonmusicians	
	Step	R^2		Step	R^2
Original piece					
Hierarchic values	1	.32	Local stab.	1	.36
P.C. ($n-1$)	2	.53	Tenor voice	2	.52
Sequential harmonic dist.	3	.72			
Alto voice	4	.82			
P.C. ($n-2$)	5	.88			
First listening					
Hierarchic values	1	.42	Hierarchic values	1	.36
P.C. ($n-1$)	2	.57	Tenor voice	2	.44
P.C. ($n-2$)	3	.69			
Fourth listening					
Hierarchic v.	1	.53	Hierarchic values	1	.25
P.C. ($n-2$)	2	.67	Tenor voice	2	.47
Tenor	3	.80			
Alto	4	.85			
P.C. ($n-1$)	5	.89			

lesser extent when the original version was played. The portion of the variance explained in nonmusicians was weaker, and only two models contributed significantly. These findings are consistent with those already reported in Exp. 2. They confirm that modifying the experimental paradigm altered the contribution of each model, but only slightly.

Discussion

The purpose of Exp. 3 was to manipulate the presentation of the Prelude in order to boost the influence of global structures. Playing the original piece instead of a harmonic reduction had a moderate effect on perceived tension but did not, as expected, increase the contribution of the hierarchic model. Playing the Prelude three times before the experiment did not significantly modify the profiles of musical tension. Some consistent changes were observed in musicians' profiles, and the hierarchic model tended to contribute to a larger extent to this experimental condition. However, as the discrepancy observed in Exp. 2 on chords 31 and 32 remained, it is obvious that the local harmonic structure continued to prevail over the global structure.

The purpose of the next experiment was to manipulate the presentation of the sequence in order to further investigate the role played by local structures. The harmonic reduction of the Prelude was segmented into 33 pairs of chords that were played in isolation in a chronological or a random order. In a third condition, the 33 pairs of chords were randomly transposed to a different key. Since these manipulations destroyed the global structure of the piece, we hypothesized that the profiles of perceived tensions would now strongly differ from those registered in Exp. 2. Moreover, we predicted that these presentations would boost the contribution of the local models and weaken the contribution of the hierarchic model tested in Exp. 2.

Experiment 4: The influence of global and local features on the perception of musical tension

Method

Participants. Seventy-five students (referred to hereafter as "musicians") from the French music conservatory and from the music department of La Sorbonne (Université Paris IV), volunteered to participate in the experiment. All had received at least 10 years of intensive training in music (i.e., music theory, ear training, and instrumental performance). Seventy-five college-age students (referred to henceforth as "nonmusicians") also took part in the experiment. They had never played nor studied music. All participated in the experiment on a volunteer basis. Participants were tested individually or in small groups.

Materials. The harmonic reduction of the Chopin Prelude was segmented into 33 pairs of adjacent chords: the first pair contained the second chord of the sequence and chord 3, the second pair contained chords 3 and 4, the third pair contained chords 4 and 5 chords, and so on. The 33 pairs were played at a tempo of 55 quarter notes per minute with the same equipment as described in Exp. 1.

Task, procedure and design. The participants' task was to rate the tension of the second chord relative to the first using a rating scale ranging from 0 (no tension) to 10 (very high tension). The pairs of chords were played in three different ways, thus defining three experimental conditions. In the *chronological order* condition, the 33 pairs were played in a chronological order: after the first pair, participants had 8 s of silence to give their responses, after which the second pair was played, and so on. In the *random order* condition, the 33 pairs were presented in a random order. The *random transposition* condition was identical to the chronological order condition except that each pair was randomly transposed to a different key. Participants were randomly assigned to one of these experimental situations.

Results

Average ratings for musical tension are displayed in Fig. 7. Five 2×2 (Musical expertise $\times$ Condition) MANOVAs were run to compare the data of the present experiment to the results observed in Exp. 2. The two levels of musical expertise and the two conditions defined the between-subject variables; the 33 stop chords defined the dependent variable. The profiles of tension significantly differed from those observed in Exp. 2 in all cases – when pairs of chords were played in a chronological order, $F(32, 65) = 3.6$, $p < .001$, in a random order, $F(32, 65) = 4.21$, $p < .001$, and randomly transposed, $F(32, 65) = 9.89$, $p < .001$. The effect of random transposition was more pronounced in nonmusicians, $F(32, 65) = 1.64$, $p < .05$. The profile of tension registered in the chronological order condition significantly differed from that obtained in the random transposition condition, $F(32, 65) = 4.43$, $p < .001$, but not from that obtained in the random order condition, $F(32, 65) = 1.26$, p.10. Thus, destroying the tonal unity of the whole experiment (random transposition) had a stronger effect on the subjects' ratings than shifting the order of the pairs of chords. This is evidence that the musical tensions perceived in Exp. 2 were not entirely determined by local structures. However, the effect of global structure was weaker than expected, and the average ratings observed in the present experiment correlated significantly with those observed in Exp. 2 (Table 10). This is evidence that the sensory and harmonic features that exist between adjacent chords were a main determinant of the tension experienced with the Chopin Prelude.

Stepwise regression analysis was performed separately for each experimental condition. Since the experimental manipulations preserved the local structure but not the global structure, we expected that, by comparison to Exp. 2, the contribution of the hierarchic model (i.e., hierarchical distances + inherited values) would decrease, while the contribution of the local model would increase. The present findings did not support this

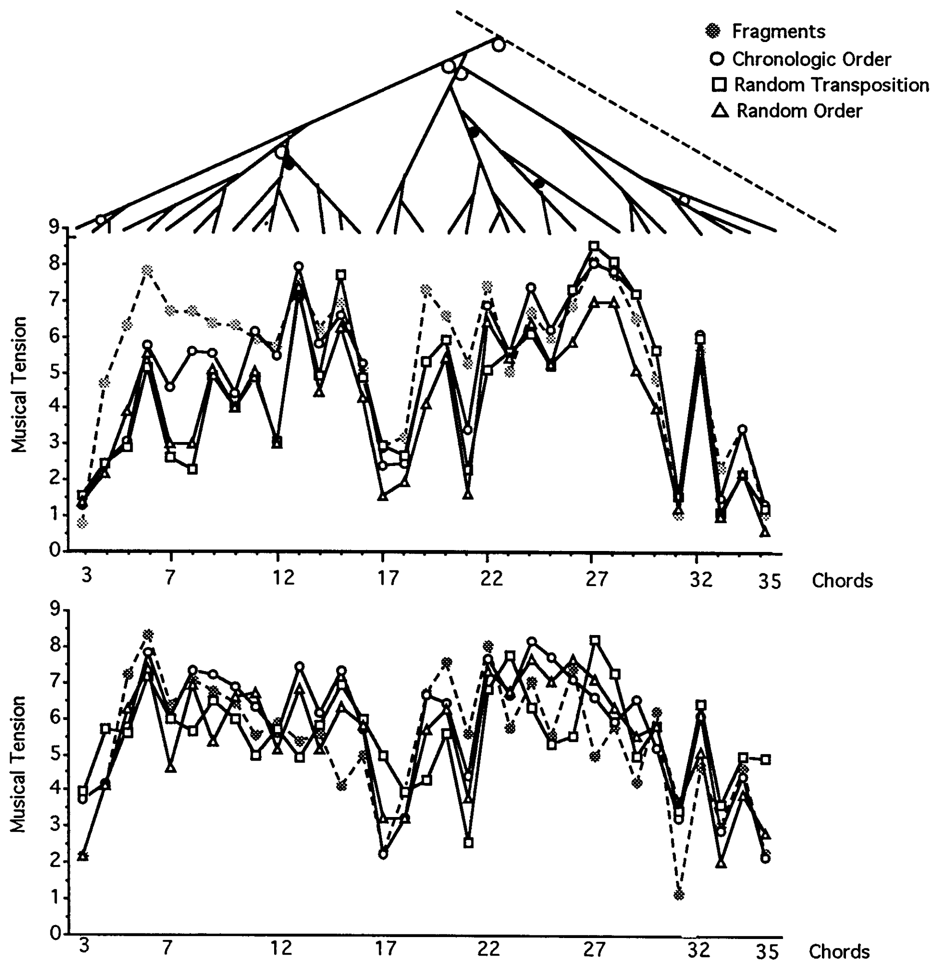


Fig. 7 Average tension perceived by musicians (*top*) and nonmusicians (*bottom*) for 33 chords of the Chopin Prelude. The stimuli used were either fragments of increasing length (Fragments of Exp. 2), pairs of chords played in Chronological Order, in chronological order with Random Transposition, or pairs of chords played in a Random Order (without transposition)

assumption (Table 11). In most cases, the hierarchic model entered as the first step in the stepwise regression. In fact, the hierarchic model tended to contribute more for pairs of chords than for longer musical fragments.

These data suggest that the hierarchic model was active in the previous experiments because it captured the influence of local harmonic structure rather than the influence of global structures. Therefore, the crucial point was to understand what sort of local structures may be at once correlated with the hierarchic predictions and yet not captured by the other local models. Figure 7 reveals that the average tension ratings are actually less varied than the tension values predicted by the hierarchic model, where tensions experienced fluctuated between low, medium, and high values. Strong relaxation systematically occurred when two adjacent chords formed a perfect cadence (V–I), the tension being very low each time the chords were in root position. Tension remained at a medium level on dominant chords and was high for all other kinds of harmonic progression. This suggests that participants may have been essentially sensitive to the presence of harmonic cadences. Since hierarchic structures in tonal music necessarily rely on cadences, a simple reaction to these cadences may produce a pattern of data that reasonably correlates to the hierarchic prediction. Such a correlation could appear even if the global structure of the piece is not at all perceived.

Table 10 Correlation between average ratings for musical tension observed in Exps. 2 and 4. In Exp. 2. musical fragments to be evaluated were of increasing length; in Exp. 4. pairs of chords were played either (1) in chronological order (C.O.), (2) in chronological order with random transposition (R.T), or (3) in random order without transposition. (R.O). Nonmusicians' data are in italics

	Fragment	Pairs C.O	Pair R.T
Pairs C.O.	r = .87		
	r = .76		
Pairs R.T.	r = .74	r = .90	
	r = .48	*r = .60*	
Pairs R. O	r = .83	r = .94	.93
	r = .76	*r = .91*	*.65*

To further this interpretation, a new variable (referred to hereafter as "cadential model" in Table 6) was defined, and several post-hoc analyses were performed. The cadential model assigns a 0 value to an authentic cadence (whatever the referential key), a value of 1 to half cadence, and a value of 2 in all other cases. This simple model correlates to the hierarchic model, $r = .63$,

Table 11 Summary of a stepwise regression analysis predicting the average ratings for musical tension obtained in Exp. 2 (Fragments) and in the three conditions of Exp. 4

	Musicians			Nonmusicians	
	Step	R^2		Step	R^2
Fragments					
Hierarchic values	1	.35	P.C. ($n-1$)	1	.26
P.C. ($n-2$)	2	.53	Hierarchic values	2	.51
P.C. ($n-1$)	3	.64			
Sequential harmonic dist.	4	.73			
Alto motion	5	.79			
Chronological order					
Hierarchic values	1	.46	Hierarchic values	1	.38
Local stability	2	.57	PC ($n-1$)	2	.49
Sequential harmonic dist.	3	.63	Sequential dist.	3	.62
Random transposition					
Hierarchic values	1	.41	P.C. ($n-1$)	1	.12
Local stability	2	.49	Hierarchic values	2	.23
Sequential harmonic dist.	3	.58	Sequential dist.	3	.35
Random order					
Hierarchic values	1	.40	Hierarchic values	1	.47
Local stability	2	.52	P.C. ($n-1$)	2	.62
Sequential dist.	3	.60	Sequential dist.	3	.68

Table 12 Summary of a stepwise regression analysis predicting the average ratings for musical tension obtained in Exp. 2 (Fragment) and in each condition of Exp. 4 using the cadential model

	Musicians			Nonmusicians	
	Step	R^2		Step	R^2
Fragments					
Cadential model	1	.75	Cadential model	1	.57
P.C. ($n-1$)	2	.79	PC ($n-1$)	2	.68
Chronological order					
Cadential model	1	.53	Cadential model	1	.67
Local stability	2	.62			
Bass voice	3	.67			
Random transposition					
Cadential model	1	.41	Cadential model	1	.21
Hierarchic dist.	2	.50			
Random order					
Cadential model	1	.54	Cadential model	1	.64
Local stability	2	.62	Hierarchic dist.	2	.69
			P.C. ($n-1$)	3	.75

$df=31$, $p<.01$. Several stepwise regression analyses were re-run (Table 12). For both groups and for each experimental situation, the cadential model always explained a substantial part of variance in tension ratings. Post-hoc analyses were also performed with the data of Exp. 3. As displayed in Table 13, the cadential model entered at the first (and often only) step in the model and provided a good fit to musical tension in all experimental situations. The success of the cadential model is consistent with Riemann's (1877) idea of internalized harmonic functions and with Eberlein's (1994) concept of the cadence as a temporal-harmonic pattern learned from music and depending on musical syntax rather than on pitch-perceptual principles.

Table 13 Summary of a stepwise regression analysis predicting the average ratings for musical tension in Exp. 3 with the cadential model

	Musicians			Nonmusicians	
	Step	R^2		Step	R^2
Original version					
Cadential model	1	.77	Cadential model	1	.75
			Sequential dist.	2	.83
First listening					
Cadential model	1	.79	Cadential model	1	.51
Fourth listening					
Cadential model	1	.81	Cadential model	1	.50

General discussion

The main purpose of this study was to investigate musical tension perceived in long chord sequences. With long sequences, tension ratings of chords may be governed by their functional and/or acoustic relations to the immediately surrounding chords or by their function inside the global harmonic structure. In Exps. 1 and 2, the influence of local and global variables was assessed by comparing the contribution of several cognitive and sensory-psychoacoustic models. In Exps. 3 and 4, these influences were tested by manipulating the way the musical stimuli were presented to participants.

The first outcome was that the global harmonic structure only weakly contributed to musical tension. Significant effects of global structure were observed when pairs of chords (vs. fragments) were presented in Exp. 4. However, these effects remained weak, given the strength of the manipulation performed. The weakness of the global harmonic structure was also reported in Exps. 1 and 2: when a modulation occurred, the influence of the previous key lasted over a short time span but did not transpire until the end of the sequence. The findings of Exp. 2 notably show that a return to the main key was perceived as a departure from the local tonic, generating *tension* rather than the music-theoretically expected *relaxation*. Experiment 3 confirmed that the return to the main key was experienced as an increase in tension, even if the listeners knew from previous exposure to the piece that this return would occur at the end. Finally, the fact that the data of musicians never strongly differed from those of nonmusicians suggested that the processing of hierarchical structure is difficult for all levels of musical expertise. These findings are consistent with other recent findings that demonstrate a weak influence of global structures on music perception (Cook, 1987; Tillmann & Bigand, 1996) for both musicians and nonmusicians (Karno & Konecni, 1992; Deliège, Melen, Stammers, & Cross, 1996; Tillmann et al., 1998a). It seems likely that, at least in these somewhat artificial laboratory settings, musical events are perceived through the frame of a short window sliding along a sequence, so that events perceived at a given time are negligibly influenced by events outside the window (Fraisse, 1957; Michon, 1977).

The present study suggests that the duration of this temporal window is quite short, especially when a sudden modulation to far keys occurs in the sequence. Further evidence for this conclusion was recently obtained with a different procedure (Tillmann, Bigand, & Pineau, 1998b). Participants were asked to decide as quickly as possible whether a target chord following a seven-chord sequence was in tune (harmonic priming procedure). The harmonic relationship between the target and the sequence was factorially manipulated at a global and a local level. The global harmonic context was defined by the first six chords of the sequence, and the local context was defined by the single chord played before the target. For example, when the target chord was a C-major chord, the first six chords of the sequence were either in the key of C major (globally related condition) or in the key of D-flat major (globally unrelated condition). The chord preceding the target was either a G chord (locally related condition) or an A-flat chord (locally unrelated condition). A change in global context was expected to have a stronger effect of the processing of the target than a change in local context. The data contradicted this hypothesis: the processing of the target tended to be more facilitated in the globally unrelated-locally related condition than in the globally related-locally unrelated condition. This finding provides new evidence that a single, harmonically unrelated chord is sufficient to disrupt the influence of a previous key context. We do not wish to deny altogether the possibility that long-term hierarchic structure might have some cognitive reality in music. First, it is possible that the size of the temporal window might increase when musical sequences modulate smoothly to closely related keys (see Bigand, Madurell, Tillmann, & Pineau, 1999). Second, other parameters (change in intensity, expressive variations of tempo) that were kept constant in the present study may help the listener to grasp the overall hierarchical structure of a musical piece (see Krumhansl, 1996).

The second main outcome of the present study is that the current models of musical tension that provided a good fit with short chord sequences (Bigand et al., 1996) were only moderately active with longer chord sequences. The model for horizontal motion was active in Exp. 1 only, and the pitch-commonality values contributed to the tension ratings only for the Chopin sequence. Of all the experiments, the hierarchic and local stability models were those that generally fit best to tension ratings. This finding is consistent with recent ones reported by Krumhansl (1996). However, the present study raises a problem for these models, since their contribution did not change when several factors were manipulated in Exps. 3 and 4. Notably, when the global structure of the Chopin Prelude was broken down (Exp. 4), the contribution of the local models did not increase, and the hierarchic model remained the most active factor. This suggests, somewhat paradoxically, that the local structures that strongly governed participants' responses were captured by the hierarchic model more than by any of the local models. Post-hoc analysis indicated that participants' judgements depended upon the occurrence of harmonic cadences. Whatever the referential tonic, the authentic cadence tended to produce the lowest tension ratings. By reacting to harmonic cadences, the tension ratings roughly fit the hierarchic model, although the participants seem to have been insensitive to the global harmonic structure of the pieces. In addition, Exp. 4 raises an important methodological point: the fact that a hierarchical model provides a good fit to tension ratings does not imply that musical structures are perceived in a hierarchical way. To reach such a conclusion necessitates first that systematic changes in the global structure provoke systematic changes in listeners' behaviours. Experiment 4 did not provide a straightforward support for this prediction.

Conclusion

The present results are consistent with the idea that cadences (i.e., harmonic progressions that establish or reaffirm musical keys) and modulations (i.e., harmonic progressions that precipitate key changes) constitute important reference points for the perception of longer chord sequences. However, the present study provided no evidence that these structures may be integrated into larger forms by the listeners. Other recent studies involving different experimental tasks and musical pieces have similarly failed to provide evidence of higher-level perceptual organization. For example, Tillmann, et al., (1998a) showed that listeners failed to differentiate the role played within a given piece (a short minuet from the classical period) by a perfect cadence in the main key and a perfect cadence in the dominant key. Both produced a marked decrease in tension ratings and so were presumably perceived as a mark of definite ending. This suggests that listeners understand the syntactic function of cadence in general but have difficulty differentiating their specific music theoretic functions within a given piece. In other words, the local role of the cadence prevails over its function in the global structure.

Of course, it may be argued that the experimental procedures used in most of these experiments were not subtle enough to capture the influence of hierarchic structure in music. However, if – as our study suggests – quite subtle experimental procedures would be required to provide evidence for hierarchical structure, it is clear that hierarchical structures have a relatively weak or subtle influence on music perception. In any case, local structures seem to play a stronger role than global ones in the perception of tonal forms.

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Appendix 1 Horizontal motion values computed for each voice for the 30 chords of the composed sequence

Chords	Bass	Tenor	Alto	Sopr.
2	3	0	2	0
3	2	2	0	2
4	5	5	2	0
5	7	3	4	2
6	5	2	1	0
7	7	0	1	1
8	2	2	3	1
9	4	2	4	0
10	2	0	2	1
11	5	2	0	1
12	8	3	3	0
13	1	2	1	0
14	2	5	5	2
15	2	0	1	2
16	1	5	5	2
17	2	1	3	2
18	3	1	2	3
19	1	0	0	1
20	2	1	2	2
21	7	1	2	0
22	1	1	3	2
23	5	1	0	1
24	2	1	0	1
25	2	1	0	1
26	3	4	2	0
27	2	2	2	1
28	2	2	3	1
29	4	2	5	0
30	2	0	2	1
31	5	2	0	1

Appendix 2 Horizontal motion values computed for each voice for the 30 chords of the Chopin sequence

Chords	Bass	Tenor	Alto	Sopr.
3	5	1	2	0
4	5	0	1	2
5	3	2	0	0
6	0	0	0	2
7	7	0	1	0
8	0	2	0	0
9	2	0	0	1
10	8	2	2	0
11	10	0	2	0
12	0	0	0	1
13	2	2	3	0
14	5	0	2	2
15	3	2	1	0
16	0	0	0	2
17	1	2	1	0
18	5	1	2	0
19	4	1	1	0
20	10	0	0	0
21	1	2	0	1
22	2	7	3	2
23	2	0	0	2
24	2	0	2	0
25	1	2	1	0
26	2	5	3	4
27	2	1	0	0
28	1	2	0	0
29	1	1	1	2
30	0	1	2	2
31	5	4	2	1
32	3	0	1	1
33	5	1	1	0
34	5	1	2	0
35	5	1	2	0

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