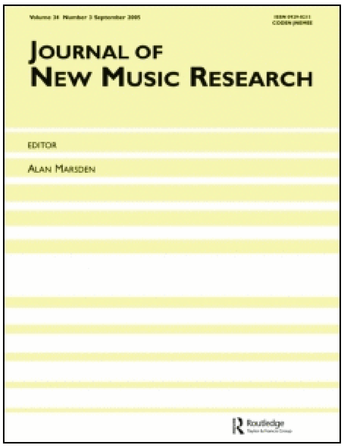

Journal of New Music Research
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713817838

The Processing of Chords in Tonal Melodic Sequences

Erik Jansen; Dirk-Jan Povel

Online publication date: 09 August 2010

To cite this Article Jansen, Erik and Povel, Dirk-Jan(2004) 'The Processing of Chords in Tonal Melodic Sequences', Journal of New Music Research, 33: 1, 31 — 48
To link to this Article: DOI: 10.1076/jnmr.33.1.31.35396
URL: http://dx.doi.org/10.1076/jnmr.33.1.31.35396

Journal of New Music Research
2004, Vol. 33, No. 1, pp. 31–48

The Processing of Chords in Tonal Melodic Sequences

Erik Jansen and Dirk-Jan Povel

Nijmegen Institute for Cognition and Information, Nijmegen, The Netherlands

Abstract

A model is proposed for the On-Line Harmonic Processing (OLHP) of tonal melodic sequences in which each incoming tone is described in terms of its features *Fittingness*, compliance with the previous harmony, *Uncertainty*, ambiguity of a new harmony, and *Chord Change*, goodness of the connection between previous and new harmony. To test this model, in Experiment 1 listeners rated the musical logic of 10-tone sequences presented with an induced segmentation in tone groups of 3-3-3-1, and following an harmonic progression of I-target-V-I, respectively, with the harmonic functions I, II, III, IV, V, or VI inserted as target fragment. The results support the Chord Change feature of the model. In Experiment 2 these sequences were rated as tone-by-tone increasing fragments, starting from the initial 3 tones up to the complete sequence. The ratings of the incremental sequences supported the findings of the first experiment. The three features in the model explained 46.4 % of the variance in the target ratings, although Uncertainty seemed to have no effect. In a comparison with two other models OLHP model performed best. Finally, an aposteriori model consisting of Chord Change and a variable quantifying pitch proximity between consecutive tones accounted for a major part of the explained variance. It is concluded that listeners employ OLHP's features in their representation of the sequences and that both harmony and pitch height are indispensable factors in a model of melody perception.

1. Introduction

Perceptually, a chord change in music can be viewed as an exchange of one mental state for another. Different harmonies, of which the functions are determined by their location in a key, have different musical stabilities, and each harmony comes with its own set of musical expectations. Thus, traversing in time from one harmony to the next creates changing stabilities (Krumhansl & Kessler, 1982; see Krumhansl, 2000) and expectation-related tensions (Bigand & Parncutt, 1999; Schmuckler, 1989) that are essential to musical experience. The listener may experience this as floating in a dynamic field of musical forces (Zuckerkandl, 1956).

Closely related to this is the idea that listeners track the "logic" of harmonic changes in order to mentally connect consecutive elements in the flow of musical events. Schoenberg (1967, p. 1; see also Dunsby & Whittall, 1988, pp. 74–77) introduced this notion of musical logic, characterising it as the key aspect of musical coherence. Although Schoenberg does not confine the concept to harmonic relations only, musical logic may apply to harmony in particular as it provides an explanation for the perceived coherence of harmonic progressions. Moreover, the musical logic of an harmonic change can be viewed as the perceived quality of the harmonic relation, i.e., the connection between one harmony and the next.

Theoretically, it should make no difference whether these chords consist of a group of simultaneous tones, constituting an *explicit* harmony, or consist of a group of successive tones, creating an *implied* harmony. In this view, the musical logic of the chord change depends on the exchange of one harmonic function for another, regardless of how the chords are induced.

The principal aim of the present study is to evaluate a descriptive perceptual model for the induction of harmony underlying tonal melody. In this model the mental states are harmonies, which the listener aims to identify as a sequence of tones is coming in. In the case of accompanied melodies simultaneous sounding tones can readily be interpreted as harmonies because the harmony can be directly related to the chords, but for unaccompanied melodies a number of extra perceptual operations need to be performed before a harmony can be inferred from the successive tones (Jansen & Povel, submitted; Holleran, Jones, & Butler, 1995).

A number of studies have emphasized that harmonic factors play an important role in the perception of melody.

Accepted: 24 July, 2003

Correspondence: Dirk Povel, Nijmegen Institute for Cognition and Information, P.O. Box 9104, 6500 HE Nijmegen, The Netherlands. Tel.: +31 24 3612635. E-mail: povel@nici.kun.nl

0929-8215/04/3301-031$16.00

Cuddy, Cohen, and Mewhort (1981) found that the disruption of the harmonic structure in a tone sequence drastically decreased listeners' ratings of tonal structure. A study by Povel and Jansen (2002) showed that whether or not a tone sequence is perceived as a melody depends on whether the listener succeeds in discovering the underlying harmony. The occurrence of non-chord tones appeared to be one of the main factors affecting harmonic induction, such that non-chord tones that could not be linked (anchored) to a following chord tone seriously disrupt the underlying harmonic structure. Furthermore, Holleran, Jones, and Butler (1995) and Trainor and Trehub (1994) found that melodic pitch changes that also change the implied harmony but do not violate the key are more easily identified than pitch changes preserving the harmony. Bigand (1990) found that listeners were capable of correctly grouping tone sequences with the same harmonic structure, suggesting that they had made a representation of the chord progression. In a study by Sloboda and Parker (1985) in which respondents were required to recall a melody by singing, the reproduced melodies preserved the harmonic structure of the original melody or yielded a new but consistent harmonic structure. Jansen and Povel (submitted-b) performed a study in which listeners responded to tone sequences with different combinations of underlying chords. It was found that both ratings and continuation tones were affected by the implied harmonic structure. The latter study also showed that tone sequences with more common underlying chord progressions tended to be judged as more wellformed than sequences with less common progressions.

Several models for harmonic analysis have been proposed, but the majority of these models take a music theoretic or informatics approach rather than a perceptual one. For instance, Temperley (1997, 2001), Leman (1995), and Parncutt (1989) emphasize the bottom-up processes in harmonic analysis, although they start from different lower levels: Whereas Temperley assumes an input signal in which the pitches are discrete elements, both Leman and Parncutt employ a continuous acoustical input signal from which the pitches still have to be extracted. The present endeavour aims at specifying some of the processes in the evolving model for the perception of tonal melodies by Povel (2002), which includes a significant top-down influence of harmonic expectations on an input level consisting of a string of pitches. Whereas some studies found evidence for an important role of harmonic factors in the perception of melody (Povel & Jansen, 2001, 2002; Jansen & Povel, in press) the model presented below describes the tone-to-tone operations by which harmonic factors affect the perception of tonal melodies. First, the OLHP model of harmonic induction will be described, after which two experiments are reported that test some aspects of the model.

2. Harmonic processing model

In light of the above mentioned considerations a model is being developed that describes the On-Line Harmonic Processing (OLHP) of a tone in a tone sequence by way of its relevant features. A previously established tonal context, which includes the activated harmony, and a metric organization are assumed to affect the incoming tones in a top-down fashion. With each tone the model evaluates three aspects implemented as features: (1) *fittingness* of the tone in the current chord; (2) *uncertainty* of the (new) harmony; and (3) the usualness of the *chord change*. Below, the theoretical and empirical background of each of these features is developed more thoroughly. Some restrictions apply to the model in its present form: First, the domain is limited to melodies consisting of only chord tones; the incorporation of non-chord tones is not yet accounted for. Second, chord changes can only occur at downbeats, i.e., at strong positions in the meter. Third, the processing or induction of top-down processes, such as key-finding and the formation of harmonic expectations is not implemented; key and associated harmonic functions are presently hard-wired into the model.

2.1 Fittingness

The first feature in the model is labeled Fittingness, and is simply whether a tone complies with the currently activated harmony. This concept is derived from the distinction of melody tones as being either chord tones or non-chord tones (Bharucha, 1984; Povel & Jansen, 2001; Temperley, 1997, 2001). From a theoretical perspective this is a necessary first step in the identification of a harmonic change: in order to recognize a new chord the listener first has to reckon that the previous harmony has ended. A study by Platt and Racine (1994) indicated that listeners can reliably detect whether in a sequence of tones an harmonic change has occurred. Preferred locations for chord changes are assumed to be suggested by the segmentation as induced by the metric organization and the articulation pattern.

The relation between chord and non-chord tones, is perceptually asymmetric rather than symmetric: chord tones can be taken up in a higher order representation, the chord unit. Non-chord tones, however, cannot be integrated causing some unwellformedness in a melody, unless they are linked to a following chord tone close in time and pitch (Povel & Jansen, 2001). The latter process is commonly referred to as melodic anchoring (Bharucha, 1984, 1996). In the present model, however, anchoring is not taken into account for reasons of conceptual simplicity.

2.2 Uncertainty

The second feature of the model, labeled Uncertainty, describes the harmonic ambiguity of the incoming tone(s). This step builds on the identification of a tone as not fitting in the current chord: If a tone does not fit the current harmony, it must be an element of a different harmony within the restrictions of the tonal frame. Depending on the tonal framework and the number of tones of which the harmonic identity remains yet to be determined, different chord candi-

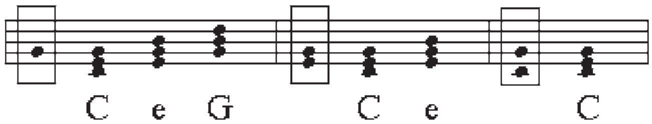

Fig. 1. Examples for Uncertainty. In each bar the note in the rectangle refers to the input, the other note combinations refer to possible triad interpretations in the key of C-major. In the first bar, a single tone, such as G4, occurs in three possible triads, in case a C-major triad, an e-minor triad, and a G-major triad; in the second bar, the major third tone combination, in case E4–G4, occurs in two triads, in case a C-major chord or an e-minor chord; likewise, in the third bar a perfect fifth, such as C4–G4, uniquely identifies the chord, in case a C-major chord, as it occurs in that chord only.

dates will be activated. For instance, a single tone can be a member of six different minor or major triads (it can either be the prime, the third or the fifth of a major or of a minor triad). Thus, uncertainty is maximal for a single tone. However, with new tones coming in, the number of harmonic candidates will decrease (on the assumption that the tones belong to the same chord). For instance, within a major key two tones forming an interval of a major third can either be the prime and third of a major triad or the third and fifth of a minor triad. In the same vein, two tones forming an interval of a fifth disambiguate the chord in a major key. If only one candidate chord remains, harmonic ambiguity has been reduced to a minimum, and the harmony has been identified. Examples of uncertainty are shown in Figure 1.

The notion that the extent of harmonic ambiguity of a tone (or tone combination) acts as a negative perceptual feature of the tones is derived from Riemann (1916, p. 6/7). According to Riemann, listeners strive to overcome this ambiguity in order to obtain a clear harmonic interpretation. In his view the harmonic quality of a tone is its primary characteristic and listeners tend to hear tones and dyads as representers (Klangvertreters) of the triads in which they occur. This idea is confirmed by research of Parncutt and Bregman (2000), and Thompson and Parncutt (1997) showing that when listeners are confronted with two different simultaneously played tones of a triad, they tend to imagine the missing one. Temperley (2001) also applies this principle in his algorithm for harmonic analysis.

Whereas the literature referred to above mainly concerns the perception of simultaneous tones, i.e., explicit harmony, in the present research the Uncertainty feature is applied to the induction of implied harmony.

2.3 Chord change

If the Uncertainty of a tone (combination) has been eliminated, the result of which is a new chord unit, the third feature in the model is formed by the result of the evaluation of the relation between the newly identified chord and the previous one. Perceptually this evaluation may be analogous to a meaningful qualification of the chord relation, enabling the new information to be linked in the mental representation. This feature is the result of a higher-order mental operation, because it involves the analysis of induced mental units (chords). In the operation of the model, the chord change evaluation is followed by a replacement of the previous active chord with the new chord, and therefore a completion of the processing cycle by a return to the evaluation of the fittingness of new tones to the new harmony.

Table 1. Table of usual root progressions (adapted from Piston, 1987).

Chord	Next chord			
	Most often	Sometimes	Less often	Rarely
I	IV or V	VI	II or III	VII
II	V	IV or VI	I or III	VII
III	VI	IV	I, II or V	VII
IV	V	I or II	III or VI	VII
V	I	VI or IV	III or II	VII
VI	II or V	III or IV	I	VII
VII	III	I	–	II, IV, V, VI

Note. The chords are symbolized by Roman numerals indicating the scale degree that forms the chord root. The table displays categorically the likelihood that a chord in the first column is followed by another chord. The fifth column is not present in Piston's original table.

Empirical support for the perception of implied chord changes is found in most of the studies on the perception of implied harmony (see, e.g., Cuddy, Cohen, & Mewhort, 1981; Trainor & Trehub, 1994; Holleran, Jones, & Butler, 1995). Our own studies also confirm the existence of a chord change evaluation process (Jansen & Povel, submitted-b). In the latter study the usualness of a chord progression was determined applying Piston's table of usual root progressions (displayed in Table 1). Support for the validity of this table was also found by Krumhansl (1990, p. 195), and Schmuckler (1989), although both studies applied the table to explicit chord progressions.

3. Experiment 1

In Experiment 1 both the harmonic structure and the contour structure of artificial tone sequences are manipulated. The main hypothesis tested in Experiment 1 is that the goodness ratings of the tone sequences are determined by the underlying harmony as well as by the contour of the sequence. It is predicted that more usual chord changes are rated higher than less usual ones based on Piston's (1987) table of usual root progressions: a chord change of the first category receives a penalty of 1, one of the second category a penalty of 2 and one of the third category a penalty of 3; if there is no chord change the penalty is 0; the prediction for the entire progression is simply the sum of the penalties for the individual chord changes. It is further predicted that simple contours are rated higher than less simple ones.

3.1 Method

3.1.1 Participants

Twenty listeners, students and staff of the University of Nijmegen participated in the experiment, 10 women and 10 men. Age ranged between 19 and 60 years (median: 25 years). All listeners had extensive experience playing an instrument (median: 12.5 years), in particular piano and guitar; most of them had also followed formal musical lessons, with a median of 6.5 years. Twelve listeners also played or had played a second instrument. Most participants had a background in classical or pop music. Listeners were volunteers and received course credit for their participation if they wished.

3.1.2 Stimulus materials

Thirty-six 10-tone sequences were constructed each divided into three consecutive groups of 3 tones and a final tone as shown in Figure 2. The second group (tones 4–6) formed the target fragment; the first and third groups and the final tone (tones 1–3, tones 7–9, and tone 10, respectively) formed the context sequence. The tones 1 to 3 were C4 E4 G4 (a C-major triad implying a harmonic function of I in the key of C-major), tones 7 to 9 were G4 D4 B3 (a G-major triad implying V in C-major), and the final tone was C4 (implying a return to I in C-major). In other words: The context tones strongly implied the chord progression I-V-I in the key of C with the target fragment embedded before V (denoted *a* in Fig. 2).

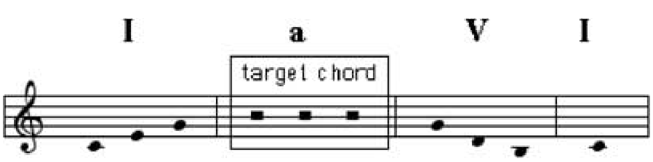

Fig. 2. Experiment 1: Stimulus construction: context into which the target fragments are embedded. The bar lines indicate an induced triple meter, appearing before each accented tone. Above each measure the harmonic function implied by the tones it contains is displayed; the target fragment is indicated by “a”.

To control for the metrical interpretation and to facilitate the perceptual grouping of the tones as described above, each sequence was presented in a triple meter in which the tones 1, 4, 7, and 10 coincide with stressed beats. The parameter values for stimulus presentation, shown in Table 2, were derived from the recorded timing and tone intensities of a tone sequence played in a triple meter.

The tones in the target fragment contained all three tones of one of the triads I, II, III, IV, V, or VI in C-major. Note that VII was not used as a target, because listeners tend to perceive it as a V7 chord with a missing root (Cuddy, Cohen, & Mewhort, 1981). The pitches for each of these triads were selected in the range between A3 to G4, as were the context tones. Each target triad was realized with 6 different contours (up-up and down-down; up-down [2×]; down-up [2×]) as shown in Figure 3. The progression categories and the consecutive predictions in terms of usualness are shown in Figure 4. Table 3 shows a complete listing of the entire stimuli ordered according to the predicted usualness, and also indicates the contour categorisation.

3.1.3 Apparatus

All tones were generated by a Yamaha PSR-620 keyboard set to the Grand Piano 1 timbre with slight built-in reverb added to obtain a realistic piano sound. The sounds were played through Sennheiser HD-250 linear II closed headphones at a comfortable listening level. Listeners were seated in front of the PSR-620 and a Macintosh PPC 4400, running a computer program that controlled stimulus presentation and response collection.

3.1.4 Procedure

A trial started when a listener clicked the “play/repeat” button on the computer screen or pushed the “0” key on the numeric keypad of the computer keyboard. After presentation of a stimulus the listener was asked to rate its melodic goodness on a scale from 1 (bad) to 7 (good). This rating was given by either clicking a button on the screen, or by pushing the appropriate numbered key on the keypad. A listener could repeat a stimulus by again clicking the “play/repeat” button. To proceed with the next trial, listeners clicked the “Next” button on screen or pushed the “Enter” key on the keypad. There were no time limitations imposed on a trial and the number of repetitions of a stimulus was not restricted.

Table 2. Parameter values of the tones for stimulus presentation. IOI = interval in ms until next tone; Dur = duration of the tone in ms; Vel = velocity (intensity) of the tone expressed as a value between 1–127.

	Tone 1	Tone 2	Tone 3	**Tone 4**	Tone 5	Tone 6	**Tone 7**	Tone 8	Tone 9	**Tone 10**
IOI	**519**	496	504	**519**	496	504	**519**	496	504	–
Dur	**519**	496	170	**519**	496	170	**519**	496	170	**519**
Vel	**90**	66	59	**90**	66	59	**90**	66	59	**90**

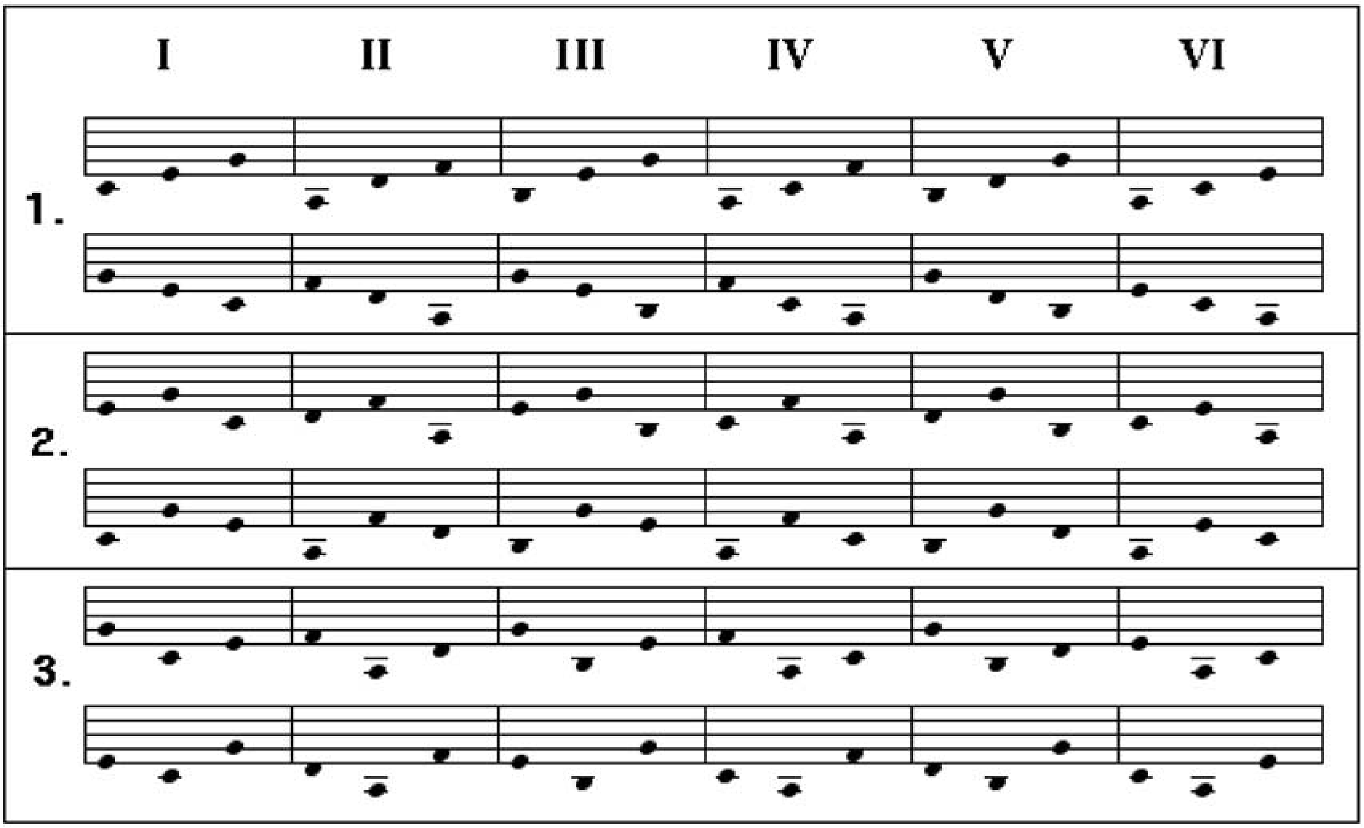

Fig. 3. Experiment 1: Stimulus construction: Factorial design of the target fragments that are inserted in the context sequence of Figure 2. Across rows the three contour categories are indicated (top 2 rows = contour category 1; middle 2 rows = contour category 2; lower 2 rows = contour category 3); across columns the six implied chord functions within the context are indicated.

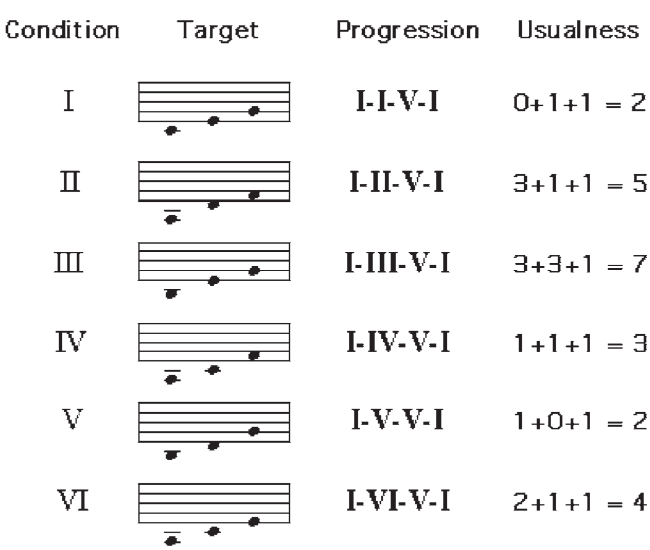

Fig. 4. Experiment 1: Predictions for the progression categories. For each Condition the tones in the Target fragment, the resulting Progression and the summed Usualness of the individual chord changes is shown. The usualness of an individual chord change is determined by its indexation in terms of Table 1, in which a first category chord change receives a penalty of 1, a second category chord change a penalty of 2, a third category chord change a penalty of 3 and a fourth category chord change a penalty of 4.

The stimuli were presented in a random order for each respondent. From trial to trial sequences were presented at a pitch height quasi-randomly selected from a range of 6 semitones around C4, such that consecutive trials were never in the same key. Respondents practiced with 12 training trials that were similar to the experimental stimuli, but which did not appear in the experiment proper. They were told that the range of goodness in the experimental sequences was approximately the same as in the training stimuli, and were encouraged to use the whole rating scale.

3.2 Results and discussion

In general, listeners found the task rather difficult, because they found differences between sequences small, but all of them were able to complete the experiment. The individual responses of each of the 20 listeners were correlated with the responses of the other 19 participants. The average of these correlations ranged between 0.23 and 0.39; the overall mean correlation between listeners' responses was 0.32. Cronbach's alpha of the responses was 0.90, indicating high agreement among listeners.

The mean ratings for the 6 Progression conditions are shown in Figure 5A. Target chord I was rated highest, closely followed from high to low by V, IV, II, and at some distance

Table 3. Complete list of stimuli ordered by summed Usualness.

Nr.	Tones	Progression	Usualness	Contour
1	C4 E4 G4 B3 E4 G4 G4 D4 B3 C4	I-III-V-I	7	1
2	C4 E4 G4 E4 G4 B3 G4 D4 B3 C4	I-III-V-I	7	2
3	C4 E4 G4 G4 B3 E4 G4 D4 B3 C4	I-III-V-I	7	3
4	C4 E4 G4 E4 B3 G4 G4 D4 B3 C4	I-III-V-I	7	3
5	C4 E4 G4 B3 G4 E4 G4 D4 B3 C4	I-III-V-I	7	2
6	C4 E4 G4 G4 E4 B3 G4 D4 B3 C4	I-III-V-I	7	1
7	C4 E4 G4 A3 D4 F4 G4 D4 B3 C4	I-II-V-I	5	1
8	C4 E4 G4 D4 F4 A3 G4 D4 B3 C4	I-II-V-I	5	2
9	C4 E4 G4 F4 A3 D4 G4 D4 B3 C4	I-II-V-I	5	3
10	C4 E4 G4 D4 A3 F4 G4 D4 B3 C4	I-II-V-I	5	3
11	C4 E4 G4 A3 F4 D4 G4 D4 B3 C4	I-II-V-I	5	2
12	C4 E4 G4 F4 D4 A3 G4 D4 B3 C4	I-II-V-I	5	1
13	C4 E4 G4 A3 C4 E4 G4 D4 B3 C4	I-VI-V-I	4	1
14	C4 E4 G4 C4 E4 A3 G4 D4 B3 C4	I-VI-V-I	4	2
15	C4 E4 G4 E4 A3 C4 G4 D4 B3 C4	I-VI-V-I	4	3
16	C4 E4 G4 C4 A3 E4 G4 D4 B3 C4	I-VI-V-I	4	3
17	C4 E4 G4 A3 E4 C4 G4 D4 B3 C4	I-VI-V-I	4	2
18	C4 E4 G4 E4 C4 A3 G4 D4 B3 C4	I-VI-V-I	4	1
19	C4 E4 G4 A3 C4 F4 G4 D4 B3 C4	I-IV-V-I	3	1
20	C4 E4 G4 C4 F4 A3 G4 D4 B3 C4	I-IV-V-I	3	2
21	C4 E4 G4 F4 A3 C4 G4 D4 B3 C4	I-IV-V-I	3	3
22	C4 E4 G4 C4 A3 F4 G4 D4 B3 C4	I-IV-V-I	3	3
23	C4 E4 G4 A3 F4 C4 G4 D4 B3 C4	I-IV-V-I	3	2
24	C4 E4 G4 F4 C4 A3 G4 D4 B3 C4	I-IV-V-I	3	1
25	C4 E4 G4 B3 D4 G4 G4 D4 B3 C4	I-V-V-I	2	1
26	C4 E4 G4 D4 G4 B3 G4 D4 B3 C4	I-V-V-I	2	2
27	C4 E4 G4 G4 B3 D4 G4 D4 B3 C4	I-V-V-I	2	3
28	C4 E4 G4 D4 B3 G4 G4 D4 B3 C4	I-V-V-I	2	3
29	C4 E4 G4 B3 G4 D4 G4 D4 B3 C4	I-V-V-I	2	2
30	C4 E4 G4 G4 D4 B3 G4 D4 B3 C4	I-V-V-I	2	1
31	C4 E4 G4 C4 E4 G4 G4 D4 B3 C4	I-I-V-I	2	1
32	C4 E4 G4 E4 G4 C4 G4 D4 B3 C4	I-I-V-I	2	2
33	C4 E4 G4 G4 C4 E4 G4 D4 B3 C4	I-I-V-I	2	3
34	C4 E4 G4 E4 C4 G4 G4 D4 B3 C4	I-I-V-I	2	3
35	C4 E4 G4 C4 G4 E4 G4 D4 B3 C4	I-I-V-I	2	2
36	C4 E4 G4 G4 E4 C4 G4 D4 B3 C4	I-I-V-I	2	1

Note. For each stimulus is indicated the stimulus number (first column), the tones it contains (second column), the implied progression (third column), the resulting summed usualness (fourth column) and the contour category (fifth and final column).

III, and VI. In Figure 5B the mean ratings for the Contour categories are shown. Contour category 1 is clearly rated higher than both Contours 2 and 3. Figure 6 shows the interaction of Contour within Progression. It can be seen that targets I, IV, and V display a similar pattern across Contours, and likewise does the pattern across targets II, III, and VI.

The data were analysed using a Repeated Measures ANOVA with Progression (I, II, III, IV, V, VI) and Contour category (category 1, no contour change; category 2, up-down contour change; and category 3, down-up contour change) as within factors. The main effects for both Progression, $F(5, 15) = 15.24$, $p < 0.0001$, and Contour, $F(2, 18) = 35.42$, $p < 0.0001$, were significant. Because the interaction was also significant, $F(10, 10) = 17.61$, $p < 0.0001$, it will be discussed first.

As can be seen in Figure 6, combinations of the least complex contour category 1 with the harmonic functions I, IV, and V were rated highest. As noted above there are two different response patterns of contour category across the levels of progression: In both patterns contour category 1 is rated higher than both categories 2 and 3. On the one hand contour category 2 is rated higher than category 3 for targets I, IV, and V; on the other, category 2 is rated lower than category 3 for targets II, III, and VI. Thus, a simple contour structure leads to higher ratings than a complex contour structure for the same progression. Specific effects of contour

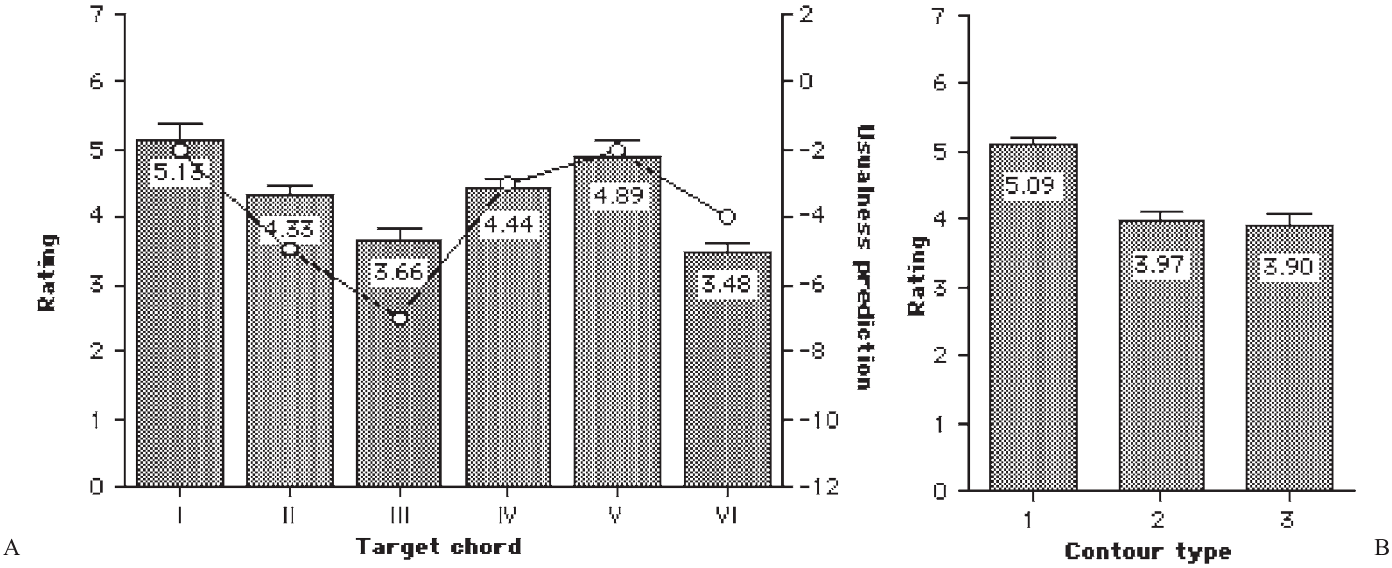

Fig. 5. Experiment 1: Main effects for Progression (panel A) and Contour (panel B). In panel A the bars indicate mean ratings (with regard to left side axis) as notated within each bar, and the linegraph indicates the usualness prediction according to Piston's table (with regard to right side axis); the latter values are plotted as negative values, as the higher the value, the lower the predicted rating should be. The error bars signify the standard errors associated with the mean ratings.

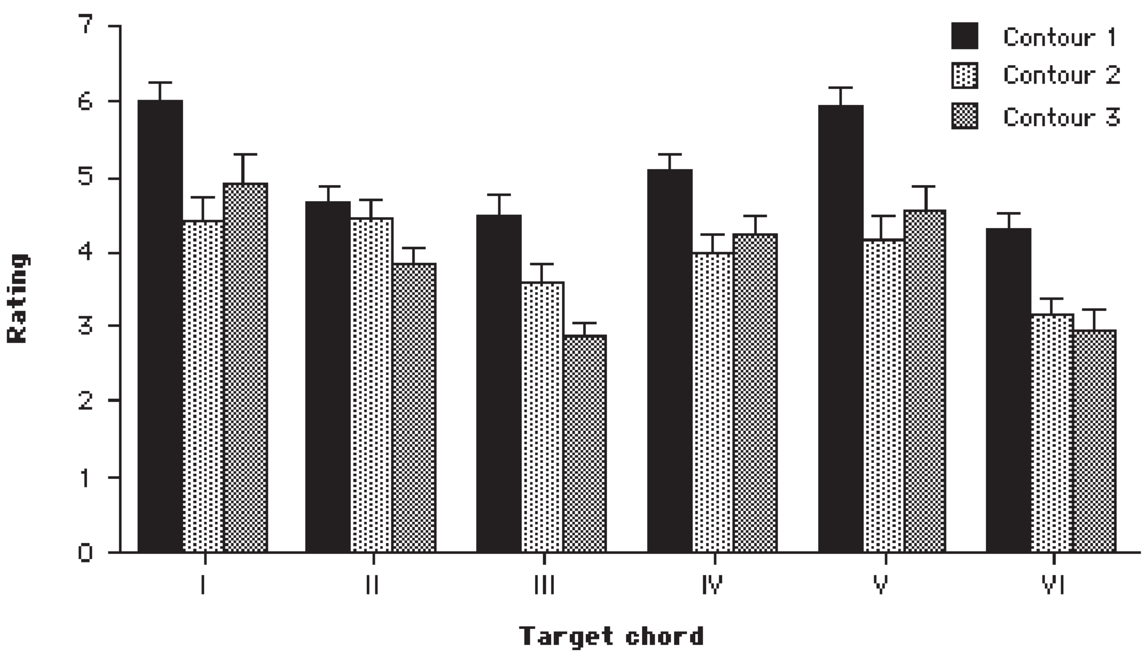

Fig. 6. Experiment 1: Interaction effect of Contour within levels of Progression. Error bars signify standard errors of the means.

structure may depend on the tone content of the implied chord, possibly as a function of differences between the major (I, IV, and V) versus the minor chord targets (II, III, VI).

To follow-up on the Progression main effect, statistical tests for pairwise differences of Progression conditions were performed (listed in Table 4). These tests revealed that I, IV and V each differed significantly from VI, and III. I also differed significantly from II, from which V differed only marginally. IV, however, could not statistically be distinguished from II. Both the target chords I and IV did not differ significantly from V, but differ marginally from each other.

Further tests of the predictions were performed employing specific planned contrasts of Progression conditions. First, the conditions with the targets I, IV and V differed sig-

Table 4. Pairwise comparisons of the progression conditions.

	Condition				
	I-II-V-I	I-III-V-I	I-IV-V-I	I-V-V-I	I-VI-V-I
I-I-V-I	12.59 0.002*	27.84 <0.001*	9.10 0.007	0.87	59.99 <0.001*
I-II-V-I		10.70 0.004	0.80	8.74 0.008	26.12 <0.001*
I-III-V-I			15.66 <0.001*	21.13 <0.001*	0.68
I-IV-V-I				3.24	38.33 <0.001*
I-V-V-I					35.66 <0.001*

Note. Statistical testing of the comparisons of the conditions was performed against a Bonferroni-corrected alpha of 0.003.

nificantly from the progressions with II, III, and VI, $F(1, 19) = 70.25$, $p < 0.0001$. This was in line with the predictions because the progressions with targets I, IV and V involve only category 1 chord changes, whereas II, III, and VI also contain less usual changes.

Second, target IV was rated significantly lower than a combination of I and V, $F(1, 19) = 7.77$, $p < 0.05$. This was also according to the predictions because the progression I-IV-V-I employs one chord change more than the progression I-V-I, which is effectively the progression of both I-I-V-I and I-V-V-I. In fact, the targets I and V do not differ.

Third, according to the predictions condition VI (usualness of 4) would be rated higher than condition III (usualness of 7). However, condition VI was not rated higher. Even condition II (usualness of 5) was rated higher than condition VI, $F(1, 19) = 26.12$, $p < 0.0001$, whereas the reverse effect was predicted. Thus, particularly the low rating for VI is not in accordance with the predictions.

In sum, the effects for progression are reasonably well predicted by the usualness of the implied chord progression, but the results do not completely conform to the predictions derived from Piston's table: The results with regard to targets I, IV, and V are in line, whereas those regarding II, III, and VI are to some extent in conflict with the predictions.

The main effect for Contour was examined further using planned pairwise comparisons. Simpler contours are rated higher than less simple contours: both category 2 and category 3 differ significantly from category 1 (at a Bonferroni corrected alpha of 0.0167), $F(1, 19) = 50.66$, $p < 0.0001$, and $F(1, 19) = 52.85$, $p < 0.0001$, respectively. The difference between categories 2 and 3 is non-significant. This lack of difference may be explained by the fact that category-2 and category-3 contours both have one contour change, and are similar in terms of contour complexity.

The results are interpreted in terms of the hypotheses as follows: First, the results support the hypothesis that implied harmony plays an important role in the perception of the sequences. This corroborates results reported in Jansen and Povel (in press) and Povel and Jansen (2001, 2002). Second, the effect for contour structure confirms the hypothesis that simpler contours lead to higher goodness ratings. Finally, the observed interaction suggests that the contour sometimes affects the processing of implied harmony. In sum, the findings support the hypothesis that the evaluation of underlying chord changes plays an important role in the perception of the sequences.

4. Experiment 2

In order to monitor the chord identification process while the tone sequence unfolds the stimuli of Experiment 1 were presented as increasing initial fragments and rated for melodic goodness. Each sequence was presented as a series of 8 initial fragments the first one consisting of the initial 3 tones, the final one consisting of all 10 tones. The results are analysed in terms of the stimulus features Fittingness, Uncertainty, and Chord Change.

4.1 Method

4.1.1 Participants

Twenty students and staff members of the University of Nijmegen, 8 women and 12 men, volunteered to participate in the experiment, 16 of which had also participated in Experiment 1. Ages ranged from 19 to 60 years, with a median of 26. All listeners had experience playing an instrument, mainly piano and guitar, for a median 11.5 years. Seventeen had received formal instruction for a median 6 years. Twelve listeners also played a second instrument. Listeners' backgrounds varied, but were mainly in classical and pop music. If they wished, they received course credit for their participation.

4.1.2 Stimulus materials and apparatus

The stimuli were the same 10-tone sequences as employed in Experiment 1. Of each sequence 8 initial fragments were formed in length increasing from three to 10 tones. The stimuli were presented using the same experimental setup in the same timing and velocity patterns as in Experiment 1.

4.1.3 Procedure

In each trial, a respondent first listened to the initial fragment of three tones and provided a goodness rating as in Experiment 1. When the listener clicked the "Next" button on the computer screen, or pushed "enter" on the numeric keypad of the computer keyboard, a fourth tone was added to the sequence and the entire fragment presented. After the listener had provided a rating the fifth tone was added, and so forth, until the entire 10-tone sequence was presented. The listener could repeat each fragment by clicking the "repeat" button

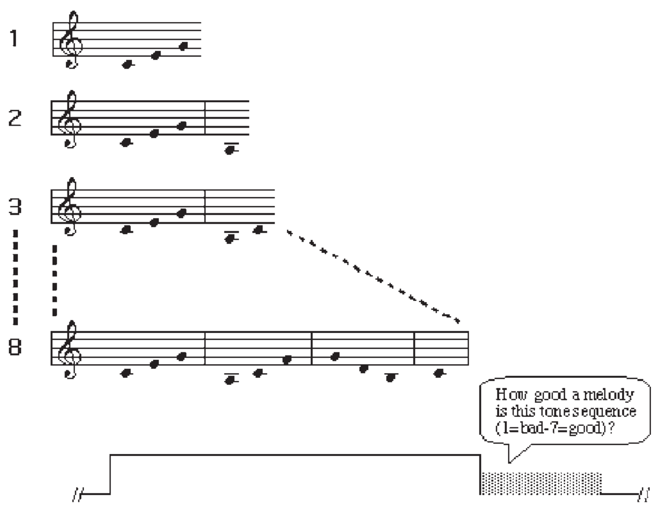

Fig. 7. Experiment 2: Gating paradigm. In each trial a listener responds to tone-by-tone increasing fragments by rating the perceptual goodness on a scale from 1 (bad) to 7 (good) of each sequence fragment. The first fragment consists of the initial three tones; the final fragment consists of the entire 10-tone sequence.

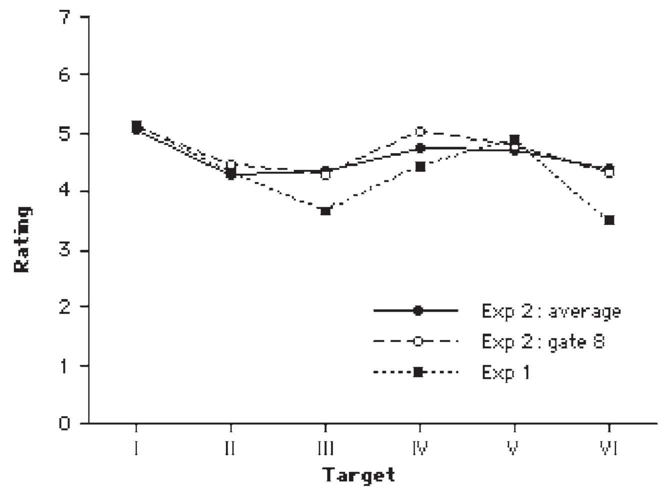

Fig. 8. Experiment 2: Combined results of derived measures of Experiment 1. Indicated are the ratings of Experiment 1, the mean ratings for each target chord averaged over all gates, and the ratings at gate 8. Note that the profiles are similar, although those of Experiment 2 are somewhat flattened.

on screen or by pushing the “0” key on the numeric keypad. The paradigm is shown schematically in Figure 7.

With each new initial fragment of three tones the key of presentation was varied as for consecutive stimuli in Experiment 1. Respondents listened to incremental gates of each sequence in their successive order. The order of presentation of the 10-tone sequences was determined randomly. Prior to the experimental trials, listeners practiced with four 10-tone training sequences of which all fragments were presented in the same way as with the experimental stimuli. The training trials did not appear in the experiment proper. The experiment took about forty minutes to perform.

4.2 Results

4.2.1 Exploratory analysis

The responses of each listener were correlated with the responses of the 19 other listeners. The mean correlations of each listener with all other listeners ranged between 0.20 and 0.44. The overall average between-listener correlation was 0.32. Cronbach’s alpha for the responses was 0.91, indicating high agreement among listeners.

First, the responses were analysed in terms of the Target categories of Experiment 1 to investigate the convergence of the experimental methods. For this purpose the average rating over gates was determined for each of the 36 stimulus sequences separately. Next the mean ratings for the 6 Progression categories were determined yielding a correlation of 0.82, $p < 0.05$, with the Progression category ratings of Experiment 1. Similarly, the mean ratings at Gate 8 (final gate, or complete sequence) were also examined in terms of the 6 Progression categories, yielding a correlation of 0.86, $p < 0.05$, with the Progression category ratings of Experiment 1. Ratings across Progression Target categories for both derived measures can therefore be considered similar to those of Experiment 1 (as can also be seen in Fig. 8).

Next, the ratings at separate gates per stimulus were examined. Note that, although contexts are equal for all stimuli, all 10-tone stimuli are unique because each target category consists of 6 sequences, with the same target tones but in a different order. For this reason, the average ratings per gate of each of the 36 stimuli were inspected sequence by sequence. Two typical examples of rating profiles are presented below.

The first example is shown in Figure 9, and regards a comparison between stimuli 4 and 34, with as target fragments E4 B3 G4 and E4 C4 G4, respectively. Both sequences are rated high at gate 1, and somewhat lower at gate 2, even though the added tone E4 fits with the active harmony I as indicated in the roman numeral notation below the score (this lower rating at gate 2 is found for virtually all stimuli). At gate 3 of stimulus 4 a non-fitting B3 comes in and the rating drops considerably. The chord search which is initiated at this increment, yields a III chord after reconsidering all tones from the latest segment boundary onward (in case E4 and B3). For stimulus 34, however, the incoming tone at gate 3 is a C4, which is indeed a chord tone of the I-chord. Consequently, its rating remains equally high. In fact, it remains fairly stable until gate 8. Contrastingly, the low rating for gate 3 of stimulus 4 increases slightly over gates 4–8. This example clearly suggests that the differences in gating profile for two sequences almost equal in pitch height structure are affected by the on-line chord recognition processes.

The second example, shown in Figure 10, is a sequence with as target tones C4 E4 A3 yielding a rating pattern with similar effects as the sequences in Figure 8: it is rated high at gate 1, and drops somewhat at gate 2, even though the

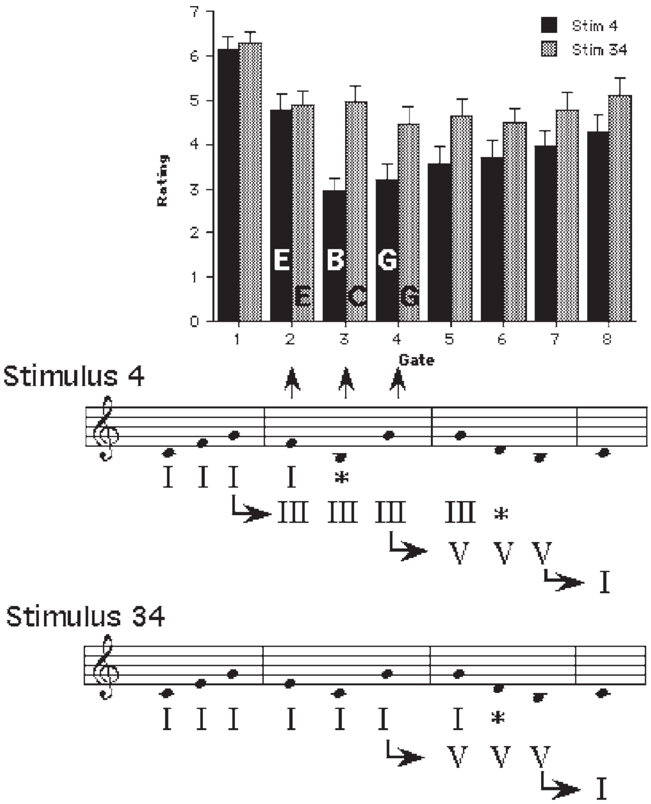

Fig. 9. Experiment 2: Example of the rating profile across gates for two typical stimuli (4 and 34). An asterisk indicates a chord search procedure; Roman numerals indicate the active harmonic function, which may have been identified by taking previous tones in the segment into account. Error bars signify standard errors of the means. See text for further details.

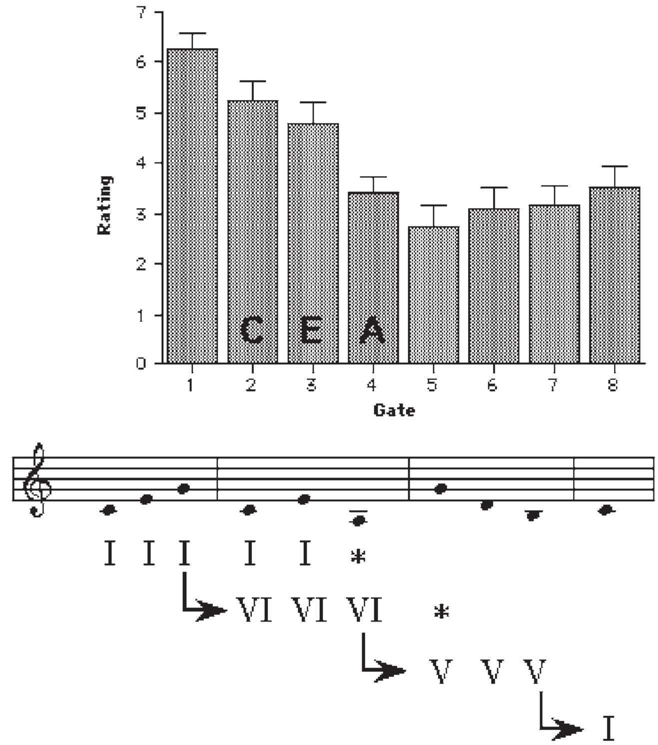

Fig. 10. Experiment 2: Another example of the rating profile across gates for a typical stimulus. See Figure 9 and text for further details.

incremented tone fits with the active tonic harmony as indicated in the roman numeral notation below the score. This is also the case for gate 3 at which the rating remains fairly stable. However, with the incoming A3 at gate 4 the rating suddenly drops: This may be explained by assuming that, as it does not fit with the active I chord, a search procedure is initiated for a new chord, yielding VI after reconsidering all tones in the current segment. Whereas in most cases the rating increases after gate 4, for the current sequence it decreases even further, even though the incremented tone is the highly expected G4 (because it is the first tone of the identical contexts across sequences). The reason for this may be the large pitch leap between the incremented tones at gate 4 and gate 5 (A3 to G4). From gate 6 on the rating increases as in the first example. Thus, apart from harmonic processing the rating patterns also suggest an influence of pitch height related factors.

Since with all stimuli the tones that were added at gate 1 and at gates 5 to 8 were identical (forming the context sequence), listeners may have regarded them as less interesting. If this assertion holds true, ratings for these gates should reveal a more or less uniform pattern. In fact, the ratings for these context gates are indeed similar across sequences: (a) a high rating is given for gate 1 (C4 E4 G4); (b) an increasing or stable rating across gates 5–8 (G4 D4 B3 C4), starting from the rating level at gate 4.

The exploratory analysis from which the above examples were taken led to the hypothesis that an on-line chord recognition account of the tone-by-tone incremented stimulus can explain the gating profiles of the stimuli. A more systematical examination of the gating ratings in terms of this hypothesis is reported in the next section.

4.2.2 Modeling

The On-Line Harmonic Processing (OLHP) model as presented in the introduction section was tested using a multiple regression approach, with the mean ratings for gates 2 to 4 of each stimulus as dependent variable. The rationale for only taking into account the ratings at gates 2, 3, and 4 is based on two general results of the exploration: (1) the stimuli and their respective ratings do not differ at gate 1 (i.e., always CEG, and always around 6); (2) the tones added at gates 5 to 8 are the same for all stimuli (GDBC) and their respective ratings increase towards gate 8 for virtually all stimuli. Thus, based on sequence characteristics as well as on the responses, the unique features of a sequence can be considered mainly to lie in its target tones.

Three additional assumptions with regard to the on-line chord recognition process were made (apart from the theoretical assumptions described in the introduction). First, at gate 2 the key is assumed to be C-major, and the local harmony is assumed to be the tonic chord in C-major. Second, the accentuation pattern is assumed to induce a preferred segmentation with new segments starting on accented tones. Thus, a new segment starts at gate 2, and it ends after gate 4. Third and finally, although the model is constrained to take only incoming information up to the current gate into account, it is allowed to perform some kind of "backtracking," revising its harmonic interpretation of the segment so far. Thus, if gate 4 adds a tone that is not consistent with the previous harmonic interpretation, and if it leads to the recognition of a different chord in combination with the tones added at gate 2 and gate 3, the model yields the new recognized chord. In sum, starting from a C-major harmony what is modeled is the development of the harmonic interpretation of the unfolding stimulus across gates 2–4.

The model was operationalized using three ordinal predictor variables. The first variable *Fittingness* applies to the tone-to-harmony matching. Gates are assigned a value of 0 for Fittingness if the incoming tone fits with the active harmony, and a value of 1 if it does not fit. If a value of 1 is assigned to a gate, the next gates in the segment also receive this value to account for the now undefined harmony.

The second variable *Uncertainty* reflects the chord search procedure. In this variable the cognitive strain of the chord search procedure is assumed to be the higher, the more chord interpretations are possible. The number of interpretations allowed is presently constrained by those chords appearing naturally in the major key. Thus, each gate fragment may be assigned one of the following values for Uncertainty: If the target fragment fits with three different chords it is assigned a value of 3 (only a single tone not fitting the current harmony can be assigned this value for the present stimuli). If the target fragment contains a third, or its inverse interval, a sixth, there are two possibilities: In case of a major third (e.g., *CE*), the chord can be the lower third of a major triad (e.g., *CE*-G, C-major triad), or the upper third of a minor triad (e.g., A-*CE*, A-minor triad); in case of a minor third the reverse applies (e.g., *EG* can appear as *EG*-B, E-minor triad, or as C-*EG*, C-major triad). With two possible interpretations a value of 2 is assigned to the fragment. If one unique candidate is determined, the chord is identified. This occurs on the one hand if two successive tones form a fifth, or its inverse a fourth, which fixes the chord in the key (e.g., in C-major *CG* or *GC* is possible within the triad CEG only), or on the other hand if the three tones in the segment form the complete triad. If a chord is identified an uncertainty value of 1 is assigned to the gate.

The third variable *ChordChange* expresses the chord change evaluation process as described in the introduction. To quantify the goodness of the latest chord change this variable is assigned the penalty values according to the categories of Piston's Table of usual root progressions. If no chord change is detected (yet), the value assigned is 0, as soon as a chord is uniquely identified the chord change can be rated and is assigned a value of 1 if it is a first category change, 2 if it is of the second category, and 3 if it is a change of the third category. Once a value for the chord change is assigned, this value "sticks" with the next gates within the segment: it keeps the value across the following gates. The model predictions for the stimulus fragments are shown in Table 5.

Fittingness, Uncertainty and ChordChange were entered in a regression analysis. In Figure 11 the correlations between the predictor variables and Rating are shown. All correlations are highly significant, but for that of Uncertainty with Rating. R for the model is 0.68, which is significantly different from 0, $F(3, 104) = 30.06$, $p < 0.001$. The proportion explained variance, as indicated by R^2, is 0.46 (R^2 *adjusted* = 0.45).

With regard to the predictor variables, Table 6 shows that the (standardized) beta weights for ChordChange and Fittingness are significant, but that of Uncertainty is not significant. The unique contributions of ChordChange and Fittingness, as indicated by their squared semipartial correlations (sr^2), are 5.9% and 4.6% of the total variance, respectively. These unique contributions are not large, because of the relatively high first-order correlations between the variables: the variance shared by the predictors is 35.9% of the total variance. The complete model explains 46.4% of the variance (44.9% adjusted).

The high correlations between predictors suggests that a smaller set of predictors in the model may be sufficient to account for the variance of the ratings. To specifically investigate the contributions of the predictors three hierarchic regression analyses were performed in which the order of entry of the predictors was varied. In the first analysis ChordChange is initially entered yielding an explained variance of 31.4% (30.7% adjusted). If Fittingness is added the explained variance increases to 46.2% (45.2% adjusted): an increase of 14.9% ($p < 0.001$). If in the final step Uncertainty is added the explained variance increases 0.2% only (not significant). A second analysis employing the reverse order of entry (i.e., Uncertainty, Fittingness added, ChordChange added) does not yield better results for Uncertainty as its contribution is still only 0.3% (not significant) even though it is allowed to account for the largest part of the shared variance. The third analysis shows that if Fittingness is entered in the first step, followed by ChordChange in the next, the amounts of explained variance by the model are 35.7% (35.1% adjusted) and 46.2% (45.2% adjusted), respectively: an increase of 10.5% ($p < 0.001$) in explained variance due to the addition of ChordChange after the variance overlap with Fittingness has been accounted for first. Thus, whereas ChordChange and Fittingness compete for the largest influence, Uncertainty appears to be a redundant parameter of the model. Summaries of these hierarchic regression analyses are shown in Table 7.

Table 5. Quantification of the OLHP-predictions in the regression analysis.

Nr.	On-Line Harmonic Processing									Rating		
	Fittingness			Uncertainty			Chord Change					
	g^2	g^3	g^4	g^2	g^3	g^4	g^2	g^3	g^4	g^2	g^3	g^4
1	1	1	1	3	1	1	0	3	3	4.2	4.3	5
2	0	0	1	1	1	1	0	0	3	5.15	4.55	3
3	0	1	1	1	2	1	0	0	3	5.85	3.85	3.5
4	0	1	1	1	1	1	0	3	3	4.8	2.95	3.2
5	1	1	1	3	2	1	0	0	3	4.15	4.2	4.05
6	0	0	1	1	1	1	0	0	3	5.65	5.15	2.9
7	1	1	1	3	1	1	0	3	3	3.85	3.4	4.6
8	1	1	1	3	2	1	0	0	3	4.65	4.3	3
9	1	1	1	3	2	1	0	0	3	5.4	3.55	4
10	1	1	1	3	1	1	0	3	3	5	2.2	3.05
11	1	1	1	3	2	1	0	0	3	3.6	3.75	4.15
12	1	1	1	3	2	1	0	0	3	5.15	5.15	3.1
13	1	1	1	3	2	1	0	0	2	4.2	4.9	5.45
14	0	0	1	1	1	1	0	0	2	5.25	4.8	3.4
15	0	1	1	1	1	1	0	2	2	5.05	3.1	3.6
16	0	1	1	1	2	1	0	0	2	5.35	3.8	3.8
17	1	1	1	3	1	1	0	2	2	3.95	3.75	4.15
18	0	0	1	1	1	1	0	0	2	5.15	5.15	4
19	1	1	1	3	2	1	0	0	1	3.95	4.75	4.6
20	0	1	1	1	1	1	0	1	1	5.3	5.3	3.6
21	1	1	1	3	2	1	0	0	1	5.5	3.6	4.2
22	0	1	1	1	2	1	0	0	1	5.15	3.75	3.9
23	1	1	1	3	2	1	0	0	1	4.2	4.3	3.9
24	1	1	1	3	1	1	0	1	1	5.5	4.1	4.45
25	1	1	1	3	2	1	0	0	1	4.15	4.3	5.05
26	1	1	1	3	1	1	0	1	1	4.6	4.25	3.8
27	0	1	1	1	2	1	0	0	1	6.1	4	4.45
28	1	1	1	3	2	1	0	0	1	4.2	4.25	3.9
29	1	1	1	3	2	1	0	0	1	4.2	4	4.05
30	0	1	1	1	1	1	0	1	1	5.85	5.4	5.5
31	0	0	0	1	1	1	0	0	0	5.4	5.05	5.3
32	0	0	0	1	1	1	0	0	0	4.8	4.5	4.7
33	0	0	0	1	1	1	0	0	0	5.95	4.5	4.3
34	0	0	0	1	1	1	0	0	0	4.9	4.95	4.45
35	0	0	0	1	1	1	0	0	0	5.1	4.65	4.7
36	0	0	0	1	1	1	0	0	0	5.85	5.65	5.9

Note. For each stimulus as indicated by Nr in the first column, the prediction values of the model variables Fittingness, Uncertainty, and Chord Change, and the Ratings at the target gates g^2, g^3, and g^4 are shown in consecutive columns. The stimulus numbers correspond to the stimulus numbers in Table 3.

From a different perspective, the large negative correlation of Uncertainty with ChordChange,[1] may indicate that the former functions as a suppressor variable in the regression analysis. However, the non-significant standardized beta-weight of Uncertainty indicates that it is not (Tabachnik & Fidell, 2001, p. 148). Employing different quantifications for Uncertainty yielded slightly better results: If Uncertainty is interpreted as an all-or-none variable with only two levels, either uncertainty (0) or identification (1), the explained variance of the complete model increases to 47.9% (46.4% adjusted). The correlation of this adapted Uncertainty variable with Rating increases to −0.10, which is still not significant. Thus, Uncertainty is indeed an unnecessary predictor in the model.

[1] This negative correlation of Uncertainty with ChordChange can be explained as follows: If Uncertainty is minimal (i.e., 1) there is recognition of a chord, and thus a high likelihood at a penalty for ChordChange in the same gating step; if there is Uncertainty, there is no chord recognition and the penalty for the chord progression cannot yet be assigned.

In sum, the regression analysis indicates that the OLHP model explains a fair amount of variance in the melodic goodness ratings for the gating fragments, although the factor Uncertainty appears to be redundant. It should be noted that the model describes local harmonic factors only, as a result of which it cannot explain variance in the ratings due to pitch height characteristics. To investigate the influence of these and other melodic factors, the OLHP model was compared with alternative models of melody perception.

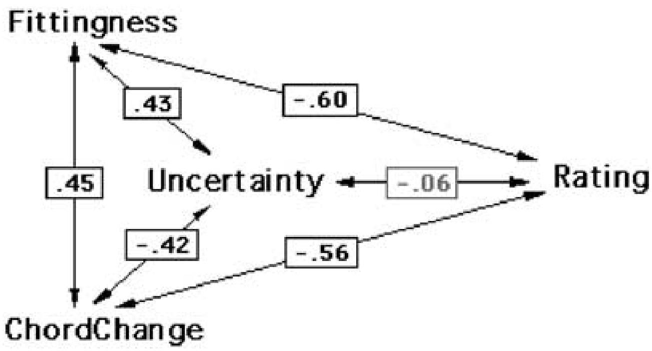

Fig. 11. Correlations of the (in)dependent variables in the OLHP model. Correlations printed in black are highly significant (n = 108; p < 0.0001); the correlation between Uncertainty and Rating (printed in grey) is nonsiginificant (n = 108; ns).

Table 6. Beta-weights and contributions of the individual predictors in the OLHP-model.

Variable	Unstand. Coeff.		Stand. Coeff.	t	sr^2
	B	*SE*	β		
Fittingness	−0.642	0.214	−0.375	−3.00**	0.046
Uncertainty	−0.077	0.128	−0.074	−0.61	0.0018
Chord Change	−0.303	0.089	−0.422	−3.39**	0.059

Note. * p < 0.05; ** p < 0.01.

4.2.3 *Comparison with alternative models*

To evaluate the overall strength of the OLHP model, it was compared with two other melody perception models: (1) a simplified version of the Implication-Realization model by Schellenberg (1997); (2) a model based on the major-key profile of Krumhansl-Kessler (1982). Following a similar approach as in Povel and Jansen (2002), a hierarchical regression analysis was performed to statistically evaluate the models. The gates of the target fragments used were quantified according to these models as described below (and shown in Table 8).

The Implication-Realization (IR) model (Narmour, 1990; 1992) in the strongly simplified version by Schellenberg consists of the principles Pitch Proximity and Pitch Reversal (Schellenberg, 1997). A fragment is assigned a penalty for Pitch Proximity equal to the size of the interval between the penultimate and the ultimate tone. The principle of Pitch Reversal assigns a value for the gate based on the fittingness of the final (realization) interval given the penultimate (implicative) interval. Note that the value assigned is a goodness value and not a penalty value. In brief, Pitch Reversal describes the tendency of large intervals (>6 semitones) to be followed by similarly large, or smaller intervals in a different direction, and the tendency of small intervals to be followed by small intervals in the same direction. Thus, Pitch Reversal incorporates gap-fill tendencies (large jumps, i.e., gaps in the pitch contour, followed by small steps in the opposite direction, i.e., events filling in the missing steps in the pitch leaps), and reversals (large jumps followed by directional changes) in the contour of a melody. The quantification of Pitch Reversal is described in more detail in Povel and Jansen (2002). In short, the IR-model predicts that the goodness of a gate will be determined by pitch height related factors, rather than harmonic considerations.

The second model (K&K) employed was based on the Krumhansl and Kessler (1982) stability profile of tones in a major-key. The goodness of a gate fragment was quantified as the stability value of the tone added in the fragment. Thus, this model predicts that the goodness of a gate fragment is determined by the stability of its final tone.

To investigate the degree of association between the model variables, the first-order correlations between the vari-

Table 7. Summary of the hierarchic regression analyses for the predictors of OLHP.

	Step	Predictor added	R^2	R^2 adjusted	R^2 incr.	*p*
Analysis 1	1	ChordChange	0.314	0.307	0.314	0.001
	2	Fittingness	0.462	0.452	0.149	0.001
	3	Uncertainty	0.464	0.449	0.002	>0.5
Analysis 2	1	Uncertainty	0.003	−0.006	0.003	>0.5
	2	Fittingness	0.405	0.394	0.402	0.001
	3	ChordChange	0.464	0.449	0.059	0.001
Analysis 3	1	Fittingness	0.357	0.351	0.357	0.001
	2	ChordChange	0.462	0.452	0.105	0.001

Table 8. Predictor values for the alternative models.

Nr.	Implication-Realization						Krumhansl-Kessler Stability		
	Pitch Proximity			Pitch Reversal					
	g^2	g^3	g^4	g^2	g^3	g^4	g^2	g^3	g^4
1	8	5	3	0	1	0	2.88	4.38	5.19
2	3	3	8	1.5	1.5	0	4.38	5.19	2.88
3	0	8	5	0	0	1	5.19	2.88	4.38
4	3	5	8	1.5	0	0	4.38	2.88	5.19
5	8	8	3	0	2.5	1	2.88	5.19	4.38
6	0	3	5	0	0	0	5.19	4.38	2.88
7	10	5	3	0	1	0	3.66	3.48	4.09
8	5	3	8	1.5	1.5	0	3.48	4.09	3.66
9	2	8	5	1.5	0	1	4.09	3.66	3.48
10	5	5	8	1.5	0	0	3.48	3.66	4.09
11	10	8	3	0	2.5	1	3.66	4.09	3.48
12	2	3	5	1.5	0	0	4.09	3.48	3.66
13	10	3	4	0	1	0	3.66	6.35	4.38
14	7	4	7	0	1	0	6.35	4.38	3.66
15	3	7	3	1.5	0	1	4.38	3.66	6.35
16	7	3	7	0	−1	0	6.35	3.66	4.38
17	10	7	4	0	1	1	3.66	4.38	6.35
18	3	4	3	1.5	0	0	4.38	6.35	3.66
19	10	3	5	0	1	0	3.66	6.35	4.09
20	7	5	8	0	2.5	0	6.35	4.09	3.66
21	2	8	3	1.5	0	1	4.09	3.66	6.35
22	7	3	8	0	−1	0	6.35	3.66	4.09
23	10	8	5	0	2.5	1	3.66	4.09	6.35
24	2	5	3	1.5	0	0	4.09	6.35	3.66
25	8	3	5	0	1	0	2.88	3.48	5.19
26	5	5	8	1.5	1.5	0	3.48	5.19	2.88
27	0	8	3	0	0	1	5.19	2.88	3.48
28	5	3	8	1.5	0	0	3.48	2.88	5.19
29	8	8	5	0	2.5	1	2.88	5.19	3.48
30	0	5	3	0	0	0	5.19	3.48	2.88
31	7	4	3	0	1	0	6.35	4.38	5.19
32	3	3	7	1.5	1.5	0	4.38	5.19	6.35
33	0	7	4	0	0	1	5.19	6.35	4.38
34	3	4	7	1.5	0	0	4.38	6.35	5.19
35	7	7	3	0	2.5	1	6.35	5.19	4.38
36	0	3	4	0	0	0	5.19	4.38	6.35

Note. For each stimulus indicated by number the value for the Pitch Proximity and Pitch Reversal variables of the Implication-Realization (IR) model (as simplified by Schellenberg, 1997) and the stability model (K&K) derived from the major key profile (Krumhansl & Kessler, 1982) are shown, in separate columns for the target gates g^2, g^3, and g^4. The stimulus numbers correspond to the stimulus numbers in Table 3.

ables were inspected (shown in Table 9). Rating correlates significantly with Fittingness and Chord Change (OLHP), Pitch Proximity (IR), and Stability (K&K). Note that Pitch Reversal (IR) does not correlate with any of the variables, nor with Rating. Fittingness and Uncertainty (OLHP) correlate significantly with Pitch Proximity (IR) and Stability (K&K), and Pitch Proximity (IR) correlates significantly with Stability (K&K), but not with Pitch Reversal (IR).[2] Chord Change (OLHP), however, is uncorrelated with any of the variables from the models.

To compare the models three hierarchic regression analyses were performed in which model variables were entered blockwise (summarized in Table 10). In the first analysis K&K was entered first, followed by IR, and OLHP. As can be seen in Table 10, the change in explained variance upon entering IR (23.3%; $p < 0.001$) is higher than the variance accounted for by K&K (17.1%; $p < 0.001$), but not so high as the change in explained variance due to OLHP (25.7%; $p < 0.001$). If entering the models in the order (1) IR, (2) OLHP, and (3) K&K (see Table 10), the picture is similar except for K&K which only adds 2.1% ($p < 0.05$) to the explained variance after IR (30.8%; $p < 0.001$) and OLHP (33.2%; $p < 0.001$) were entered first. Finally, an analysis was performed in which OLHP was entered first (44.9% explained variance; $p < 0.001$), followed by IR (change in explained variance of 17.6%; $p < 0.001$) and K&K (change of 2.1%; $p < 0.05$), respectively. In brief, irrespective of the order in which the models are entered in the analysis, OLHP always explains the largest portion of variance in the ratings.

Additionally, the betaweights and squared semipartial correlations for the model variables were inspected with all variables entered into a standard regression analysis (shown in Table 11). As can be seen in the table, the betaweights of Chord Change (OLHP), and Pitch Proximity (IR) are highly significant, and Fittingness (OLHP) and Stability (K&K) are also significant. The pattern of squared semipartial correlations indicates that Pitch Proximity (IR) has by far the largest unique contribution to the total explained variance. Chord Change (OLHP), Stability (K&K), and Fittingness (OLHP), respectively, have decreasing unique contributions, but this may be explained based on relatively large intercorrelations, particularly between Stability (K&K) and Fittingness (OLHP). In fact, the total proportion shared variability (40.3%) is much higher than the proportion unique variability (25.8%), indicating that there is considerable overlap between the variables, which is consistent with the pattern of correlations in Table 9. Finally, the betaweights for the variables as determined in the hierarchic regression procedures did not yield inconsistencies with the above results, nor were suppressor variables found in any of the procedures.

In sum, the most influential predictors are Chord Change (OLHP), Pitch Proximity (IR) and Stability (K&K). Three post-hoc models were constructed each consisting of a combination of two predictors to investigate whether a more parsimonious model could be formed. A regression analysis of the model consisting of Chord Change and Pitch Proximity

[2] This is in accordance with the results of Schellenberg (1996), who showed that his earlier implemented version of the IR-model consisting of 5 variables that were intercorrelated could be reduced to the present uncorrelated ones.

Table 9. Correlations between model variables of the OLHP model, the IR model, and the K&K model.

Model	Variable	Rating	IR		K&K Stab
			Prox	Rev	
OLHP	Fittingness	–0.598**	0.333**	0.010	–0.531**
	Uncertainty	–0.057	0.306**	0.118	–0.411**
	ChordChange	–0.560**	0.046	–0.132	–0.189
IR	PitchProximity (Prox)	–0.554**	–	–0.141	–0.198*
	Pitch Reversal (Rev)	0.101		–	0.056
K&K	Stability (Stab)	0.414**			–

Note. For all correlations n = 108; * $p < 0.05$; ** $p < 0.01$.

Table 10. Summary of the hierarchic regression analyses of the model comparison.

ANALYSIS 1		R^2	R^2 Adjusted	Standard Error	ChangeStatistics		
Step	Model				R^2 change	F Change	p
1	K&K	0.171	0.163	0.7313	0.171	21.896 (1, 106)	0.001
2	K&K, IR	0.404	0.387	0.6262	0.233	20.281 (2, 104)	0.001
3	K&K, IR, OLHP	0.661	0.640	0.4795	0.257	25.473 (3, 101)	0.001
ANALYSIS 2		R^2	R^2 Adjusted	Standard Error	ChangeStatistics		
Step	Model				R^2 change	F Change	p
1	IR	0.308	0.295	0.6715	0.308	23.346 (2, 105)	0.001
2	IR, OLHP	0.640	0.622	0.4913	0.332	31.378 (3, 102)	0.001
3	IR, OLHP, K&K	0.661	0.640	0.4795	0.021	6.113 (1, 101)	0.05
ANALYSIS 3		R^2	R^2 Adjusted	Standard Error	ChangeStatistics		
Step	Model				R^2 change	F Change	p
1	OLHP	0.464	0.449	0.5935	0.464	30.055 (3, 104)	0.001
2	OLHP, IR	0.640	0.622	0.4913	0.176	24.886 (2, 102)	0.001
3	OLHP, IR, K&K	0.661	0.640	0.4795	0.021	6.113 (1, 101)	0.05

Note. (see text for further details). The column headed “p” signifies that F Change has a p-value smaller than the indicated level.

yielded an explained variance of 59.4% (58.6% adjusted). This approximates the total explained variance of 66.1% obtained with all variables from the three models included, whereas the combinations Pitch Proximity and Stability, explaining 40.4% of the variance (39.2% adjusted), and Stability and Chord Change, explaining 41.2% of the variance (40.1% adjusted), perform markedly less good.

4.3 Discussion

The results of Experiment 2, based on the ratings obtained with the gating paradigm, were consistent with the results of Experiment 1 and the rating profiles across gates of individual stimuli clearly suggest harmonic influences. The findings can be summarized as follows: (a) the On-Line Harmonic Processing (OLHP) model explains a fair amount of variance in the ratings for the target gates, particularly by the influence of ChordChange and Fittingness, and Uncertainty appears to be a redundant variable; (b) in the comparison of OLHP with other models, it performs better than a simplified version of the Implication-Realization (IR) model, and a model based on tonal Stability ratings (K&K); and (c) a post hoc combination of the factors Chord Change from OLHP and Pitch Proximity from IR constitutes a very promising new model.

The model comparison procedure indicates that the OLHP model gives a good account of the ratings for the present stimuli, because it outperforms the alternative models even if it is allowed only to account for the variance unaccounted for by K&K and IR. Furthermore, the finding that Chord

Table 11. Betaweights and squared semipartial correlations of the model variables.

MODEL	Variable	Unstand. Coeff.		Stand. Coeff.	t	sr^2
		B	SE	β		
OLHP	Fittingness	–0.404	0.177	–0.236	–2.28*	0.017
	Uncertainty	0.118	0.110	0.113	1.07	0.004
	Chord Change	–0.255	0.074	–0.355	–3.46***	0.040
IR	Pitch Proximity	–0.145	0.020	–0.463	–7.26***	0.176
	Pitch Reversal	–0.031	0.061	–0.033	–0.55	0.001
K&K	Stability	0.130	0.053	0.178	2.47*	0.020

Note. * $p < 0.05$; *** $p < 0.005$; $R^2 = 0.661$; Unique variability = 0.258; Shared variability = 0.403.

Change is uncorrelated with any of the other variables from the (alternative) models indicates that it covers an aspect of the variance in Rating unaccounted for by the other models.Therefore, taking into account the local relations between successive chords appears an important feature of the present model.

The tests of various combinations of OLHP parameters indicated that the variables of the on-line harmonic processing model have some overlap: the regression analyses indicate that Fittingness, Uncertainty, and ChordChange have relatively high intercorrelations and Uncertainty appears to be a redundant parameter. This may be an effect of stimulus design: the stimuli were constructed primarily to yield an experimentally well-controlled set of tone sequences to compare perceptual ratings obtained in global and gating presentation paradigms. Because of this, multiple model steps were often applied at the same gating step in a tone sequence; ideally the addition of a tone yields the change of only a single model variable. Therefore, future work should employ stimuli specially designed to disentangle the effects of the model variables.

With regard to the comparison of OLHP with alternative melody perception models, the following issues are important. Firstly, the relatively high correlation between Fittingness and Stability can be understood by taking into account the local harmonic context: Fittingness evaluates whether the incoming tone fits the current (local) harmony of a C-major chord; Stability assigns a higher rating to tones that are higher in the tonal hierarchy (global), which in case are the elements of the C-major triad. Therefore, although Stability has more differentiation, it yields parameter values similar to the values for Fittingness. If the local harmony were to deviate from the tonic triad of the major key, Stability and Fittingness would probably lead to more differentiated predictions.

Secondly, although selected from different models, a combination of Chord Change and Pitch Proximity yields quite good results with respect to the explained variance. In spite of being formed aposteriori, this model is very parsimonious, as it consists of two parameters only, and theoretically quite plausible because it accounts for both harmonic and pitch height effects. Harmony and pitch height have often been considered to represent independent structural dimensions of melody. Moreover, in several experiments it was found that manipulation of a pitch contour variable does not necessarily interact with the manipulation of the underlying chord progression (Jansen & Povel, in press). Thus, both theoretically and empirically such a combination constitutes a quite plausible model of melody perception.

5. General discussion

The results of the experiments can be summarized as follows: (1) Listeners distinguish melodies with different underlying progressions. (2) The usualness of the chord changes underlying a tone sequence is a strong determinant of its judged melodic goodness. (3) The on-line induction of harmony implied by melody is a continuous process of evaluation of the input tones against the incrementally built harmonic representation, including its expectations. (4) A promising model of melody perception can be constructed of two factors one concerning the evaluation of underlying chord changes, and the other pertaining to the pitch proximity of consecutive tones.

The results of Experiment 1 corroborated previous research validating the hypothesis that chord progression underlying a tone sequence is perceptually relevant (Cuddy, Cohen, & Mewhort, 1981; Jansen & Povel, 2000; Povel & Jansen, 2002). Moreover, the use of the same tone sequences in both experiments allow for an analysis involving a direct comparison between the harmonic processes after they have occurred (Experiment 1), and those same processes while they are occurring (Experiment 2). As a consequence, the findings from Experiment 2 provide further evidence for the hypothesis that tone sequences are processed harmonically; however, they also allowed for a more specific analysis of the role of the recognition of chords and the evaluation of the chord progression by way of tests of the on-line harmonic processing model proposed in the introduction.

The findings from the modeling procedure raise some interesting issues. First, high correlations were found between the predictors Fittingness, Uncertainty, and Chord Change of the OLHP-model, as well as a redundancy of the predictor Uncertainty. In future experiments stimuli should be used that distinguish between the predictions from the three factors to verify whether a revision of the model is indeed necessary.

Second, the present quantification of the most powerful model predictor, Chord Change, was based on Piston's table of usual root progressions. Therefore, to a certain extent the results support previous tests of Piston's table for explicit chord progressions by Krumhansl (1990, p. 194/195), and Schmuckler (1989). There is, however, a growing sense among researchers that Piston's table is not entirely accurate as a description of the goodness of chord progressions and that there may be an alternative, better quantification (Temperley, 2001, p. 232; Jansen & Povel, in press). However, with such an alternative quantification the performance of a Chord Change variable in the model is most likely to increase rather than to decrease, because it will more closely approximate the actual perceived goodness of chord changes.

Third, the view that harmonic relations between consecutive tones play an important role in the perception of music, is stressed by the finding that the harmonic processing model did better than a simplified version of the IR model, and also better than a model based on the tonal stabilities as quantified by Krumhansl and Kessler (1982). In particular, the present findings reveal the relevance of sequential relations between higher-order mental units, in case chords. It should be noted that taking into account local harmonic relations, by way of chord membership of consecutive tones and underlying chord progressions, form the main distinctive features of the OLHP-model.

With respect to the gating paradigm, the following should be noted. First, the finding that the results of Experiment 2 are consistent with the results of Experiment 1 supports the idea that presentation in a gating paradigm and the presentation of entire sequences do not lead to different ways of processing. This is in accordance with gating studies indicating that successive presentation of gates does not differ from blockwise presentation, e.g., as shown for brief tone sequences by Povel and Jansen (2001), but also from the domain of spoken-word recognition (Grosjean, 1996). Second, across consecutive gates response "stickiness," a tendency of respondents to persevere in their response provided at the previous gate, was observed (see also Grosjean, 1996). This tendency appears asymmetrical: if a "bad" tone occurs, ratings suddenly drop, whereas if a sudden "good" revision of the interpretation occurs, the rating tends to restore only gradually. Third, whereas the ratings for the context gates are similar across stimuli, inter-stimulus rating differences are mainly located across the target gates suggesting that indeed the small-scale (note-to-note) regularities play an important role in the on-line processing of the stimuli. In sum, the present findings show that the gating paradigm is a tool well-suited to study on-line processes in melody perception.

In closing, the finding that a model consisting of a pitch height factor and a harmonic factor performs particularly well, supports the view that music perception consist of both general auditory principles (in case pitch proximity) and principles specific to music (in case harmonic factors; see also Bregman, 1990, p. 455). In the same vein, Thompson, Cuddy, and Plaus (1997) found support for a combination of pitch-height and tonal factors, although they did not include local harmonic regularities as tested here. This leads to the conclusion that a cognitive model of melody perception not taking into account local harmonic relations, should be considered incomplete. We therefore believe that future research in melody perception should disentangle the interaction between pitch height (melodic contour) and harmonic structure in the processing of tonal melodies.

References

Bharucha, J.J. (1984). Anchoring effects in music: The resolution of dissonance. *Cognitive Psychology*, *16*, 485–518.

Bharucha, J.J. (1996). Melodic anchoring. *Music Perception*, *13*, 383–400.

Bigand, E. (1990). Abstraction of two forms of underlying structure in a tonal melody. *Psychology of Music*, *18*, 45–59.

Bigand, E., & Parncutt, R. (1999). Perceiving musical tension in long chord sequences. *Psychological Research*, *62*, 237–254.

Bregman, A.S. (1990). *Auditory Scene Analysis: The perceptual organization of sound*. Cambridge, MA: MIT Press.

Cuddy, L.L., Cohen, A.J., & Mewhort, D.J.K. (1981). Perception of structure in short melodic sequences. *Journal of Experimental Psychology: Human Perception and Performance*, *7*, 869–882.

Dunsby, J., & Whittall, A. (1988). *Music analysis: In theory and practice*. London, UK: Faber Music Ltd.

Grosjean, F. (1996). Gating. *Language and Cognitive Processes*, *11*, 597–604.

Holleran, S., Jones, M.R., & Butler, D. (1995). Perceiving implied harmony: The influence of melodic and harmonic context. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*, 737–753.

Jansen, E.L., & Povel, D.J. (2000). The role of implied harmony in the perception of brief tone sequences. In: C. Woods, G. Luck, R. Brochard, F. Seddon, & J.A. Sloboda (Eds.), *Proceedings of the sixth International Conference on Music Perception and Cognition.* Keele, UK: Keele University, Department of Psychology.

Jansen, E.L., & Povel, D.J. (submitted-a). The influence of segmentation on the perception of perception of implied harmonic progressions. Manuscript submitted for publication.

Jansen, E.L., & Povel, D.J. (in press). Perception of arpeggiated chord progressions. *Musicae Scientae*, *7*.

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

Krumhansl, C.L. (2000). Rhythm and pitch in music cognition. *Psychological Bulletin*, *126*, 159–179.

Krumhansl, C.L., & Kessler, E.J. (1982). Tracing the dynamic changes in perceived tonal organization in a spatial representation of musical keys. *Psychological Review*, *89*, 334–368.

Leman, M. (1995). *Music and Schema Theory: Cognitive Foundations of Systematic Musicology.* Berlin/Heidelberg: Springer Verlag.

Narmour, E. (1990). *The analysis and cognition of basic melodic structures: The implication-realization model.* Chicago: University of Chicago Press.

Narmour, E. (1992). *The analysis and cognition of melodic complexity: The implication-realization model.* Chicago: University of Chicago Press.

Parncutt, R. (1989). *Harmony: A psychoacoustical approach.* Berlin, Germany: Springer Verlag.

Parncutt, R., & Bregman, A.S. (2000). Tone profiles following short chord progressions: Top-down or bottom-up? *Music Perception*, *18*, 25–57.

Piston, W. (1987). *Harmony* (Revised by M. DeVoto). London, Victor Gollancz Ltd.; (originally published 1941).

Platt, J.R., & Racine, R.J. (1994). Detection of implied harmony changes in triadic melodies. *Music Perception*, *11*, 243–264.

Povel, D.J. (2002). A model for the perception of tonal melodies. In: C. Anagnostopoulou, M. Ferrand, & A. Smaill (Eds.), *Music and artificial intelligence: Lecture notes in computer science.* Berlin: Springer Verlag.

Povel, D.J., & Jansen, E.L. (2001). Perceptual mechanisms in music processing. *Music Perception*, *19*, 169–198.

Povel, D.J., & Jansen, E.L. (2002). Harmonic factors in the perception of tonal melodies. *Music Perception*, *20*, 51–85.

Schellenberg, E.G. (1996). Expectancy in melody: Tests of the implication-realization model. *Cognition*, *58*, 75–125.

Schellenberg, E.G. (1997). Simplifying the implication-realization model of melodic expectancy. *Music Perception*, *14*, 295–318.

Schoenberg, A. (1967). *Fundamentals of musical composition.* In: G. Strang & L. Stein (Eds.), London: Faber & Faber.

Riemann, H. (1916). Ideen zu einer “Lehre von den Tonvorstellungen”. In: R. Schwartz (Ed.), *Jahrbuch der Musikbibliothek Peters für 1914/1915*. Leipzig: Peters Verlag.

Schmuckler, M. (1989). Expectation in music: Investigation of melodic and harmonic processes. *Music Perception*, *7*, 109–149.

Sloboda, J.A., & Parker, D.H.H. (1985). Immediate recall of melodies. In: P. Howell, I. Cross, & R. West (Eds.), *Musical Structure and Cognition*. London: Academic Press.

Tabachnik, B.G., & Fidell, L.S. (2001). *Using multivariate statistics.* Boston: Allyn & Bacon.

Temperley, D. (1997). An algorithm for harmonic analysis. *Music Perception*, *15*, 31–68.

Temperley, D. (2001). *The cognition of basic musical structures.* Cambridge, MA: Massachusetts Institute of Technology Press.

Thompson, W.F., Cuddy, L.L., & Plaus, C. (1997). Expectancies generated by melodic intervals: Evaluation of principles of melodic implication in a melody-completion task. *Perception and Psychophysics*, *59*, 1069–1076.

Thompson, W.F., & Parncutt, R. (1997). Perceptual judgments of triads and dyads: Assessment of a psychoacoustical model. *Music Perception*, *14*, 263–280.

Trainor, L.J., & Trehub, S.E. (1994). Key membership and implied harmony in Western tonal music: Developmental perspectives. *Perception and Psychophysics*, *56*, 125–132.

Zuckerkandl, V. (1956). *Sound and Symbol.* Princeton, NJ: University Press.