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Intensity changes and perceived similarity: Inter-parametric analogies

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• **ABSTRACT**

Music theorists and psychologists have described diverse musical processes in terms of changes (increase or decrease) in "intensity". This paper examines the hypothesis that analogous intensity changes in different musical parameters can be perceived as similar, and discusses implications of such perception for music analysis. In the experiment reported, participants rated the degree to which members of pairs of musical stimuli were similar in character to a "standard" — a crescendo on a repeated tone. One member of each pair presented an "increase" in a specific musical parameter, while the other presented a "decrease" (e.g., pitch ascent vs. descent). Parameters investigated included melodic direction and attack rate and their combinations, pitch interval size, motivic pace, and harmonic tension. For most parameters, the intensifying figure was rated as closer to the standard (itself intensifying) than its abating counterpart. Perceived similarity was strongest between figures presenting intensification in dynamics (crescendo) and pitch direction (ascent), while similarity between intensification in dynamics and tempo (accelerando) was weaker, and perceived mainly by musically-trained subjects. Similarity between dynamic change and harmonic progression was perceived only when the latter involved manipulation of dissonance, and dynamic intensification and increase in pitch interval size were perceived as similar only for ascending intervals. Importantly, the combined effect of melodic direction and attack rate on similarity perception was additive, rather than interactive, though the effect of melodic direction was significantly stronger. This result supports models of "integrated intensity contours" (Berry, 1976; Todd, 1994), but suggests different weighting for different musical parameters.

In sum, results indicate that listeners can perceive intensity contours in different parameters as analogous, and thus suggest that intensity contours may serve as musical "gestures", regardless of the specific parameters depicting them. The implications of these results to music analysis are discussed with regard to motivic structure, thematic prototypicality, and structural functions of intensity contours.

BACKGROUND

Diverse musical parameters can be organized along a "quantitative" continuum, in which change in one direction is conceived as an increase, and change in the other as a decrease. Loudness, for example, can increase or decrease, as can temporal and textural density; pitch can ascend (increase) or descend (decrease); pitch intervals can become larger or smaller, and move towards more or less dissonance.

Such processes have often been described as changes in the level of "intensity" — either in the physical, or psychoacoustical sense, or in a metaphorical, conceptual sense (see below, pp. 41-43). Throughout the last century, a number of music theorists have suggested or implied that such intensity changes in different parameters can be conceived as analogous to each other (e.g., Berry, 1976; Hopkins, 1990; Kurth, 1991; Rink, 1999). The corollary of such an assumption is that the direction and contours of intensity changes may be depicted independently of the specific musical parameters that generated them, and conceived as structural or expressive features in a musical piece. For instance, a pattern consisting of a crescendo followed by a diminuendo and one consisting of an accelerando followed by a decelerando may both be conceived as instances of an "arched" (convex) intensity contour — a phase of intensification followed by a phase of abatement (Cohen, 1971).

Such notions have informed music theories from Kurth (1917/1971, 1931/1969, 1991), through Berry (1976) and Meyer (1989), to recent performance-oriented music analyses (Rink, 1999), raising a number of interesting implications. The overall change in intensity, or "integrated intensity flux" (Todd, 1994), generated by an interaction of the various musical parameters, has been used to depict aspects of the "shape" or structure of the piece. A clear example is the association of intensity contour with the piece's segmentation (e.g., Todd, 1994, 1995), and particularly with structural closure, enhanced by abatement in diverse parameters (Hopkins, 1990). Furthermore, patterns of intensity change, expressed in different parameters, were proposed as musical "motives", reproduced and varied throughout a specific piece (Rink, 1999; Eitan, 2003), or as "style structures", typical of the musical style of a specific composer such as Beethoven (Sheer, 1989) or a historical period such as nineteenth century Romanticism (Agawu, 1982; Eitan, 1997; Meyer, 1989).

A basic but often implicit assumption in many of the above studies is that intensifications in diverse musical domains are in some ways similar to each other, conceptually and perceptually. In the current study we set out to test this assumption. Specifically, we examine (1) whether, all other things being equal, two musical gestures sharing an intensity contour are perceived as more similar to each other than musical gestures contrasting in intensity contour, (2) which musical parameters create isomorphic intensity contours, and (3) whether perception of such isomorphic intensity contours is influenced by musical training.

In the following we review some literature attesting to the importance of intensity as a perceptual property across sensory modalities and within the auditory domain. This literature not only provides a general background against which we present our experimental hypotheses, but also serves to stress the importance we attribute to the concept of intensity contours in music perception and theory — an issue we return to in the conclusion section.

INTENSITY AS A CROSS-SENSORY AND CROSS-DIMENSIONAL PERCEPT

Intensity is one of the most salient properties of perceived objects. Physically, intensification is achieved by higher levels of energy. This in turn is coded at the neuronal level by an increase in overall discharge rates (e.g., Recce, 1999), although such increase is by no means the only mechanism for representing changes in intensity (e.g., Polley *et al.*, 2004). On the perceptual level, intensity is equated with changes in perceived sensory magnitude (brighter light, louder sound, etc.). In general, the subjective perceptual magnitude of intensity conforms to a power function, such that a constant percentage increase in the stimulus magnitude produces a constant percentage increase in the perceived effect (Stevens, 1975).

A rich body of empirical research suggests that the percept of intensity crosses and associates different modalities. Stevens and colleagues have demonstrated, for example, that subjects can associate the levels of auditory loudness and of visual brightness (Stevens, 1961, 1975; Stevens & Guirao, 1963). Furthermore, two concurrently presented dimensions in two different modalities may interact, so that changes in intensity of one, affects the perception of the other. For instance, when subjects classify values in one dimension, while the values of a second dimension are varied, as in Garner's speeded classification method (Garner, 1974), speed and accuracy may be enhanced if intensities in the two parameters concur (e.g., louder pitch with brighter light. For a summary see Marks, 2000, 2004).

Developmental studies also demonstrate what seems to be an inborn tendency to perceive intensity as a holistic property, over and beyond specific dimensions or even perceptual modalities. Lewkowicz and Turkewitz (1980), among others, show that young infants respond to auditory and visual stimuli as more or less similar depending on their intensity, rather than upon the specific modality. Furthermore, infants and parents often communicate through mutual imitation of cross-modal intensity contours, or time-shapes, involving auditory dimensions such as pitch inflection and dynamics, as well as touch and motion (e.g., Malloch, 2000; Papousek, 1996; Stern, 1985; Sullivan & Horowitz, 1983). The importance of a holistic sense of intensity is also observed in pre-school children's free classification of objects varying along two or more dimensions. For example, children three and four years old spontaneously group together big vividly-colored objects in contrast to small and pale objects (Smith, 1985). The criterion for the grouping seems to be the overall intensity or magnitude across the two dimensions, rather than similarity or even identity on a single dimension. Bahrick, Lickliter and Flom (2004) argue that intersensory redundancy, obtained through amodal properties such as intensity, guides attention to the redundant information, "foregrounding" amodal stimulus properties, at the expense of modality-specific properties.

That intensity associates information not only across sensory modes but also across different dimensions within the auditory modality, is attested to by various studies. Thus, for example, Neuhoff and McBeath (1996), and Neuhoff, McBeath and Wanzie (1999) found that changes in loudness (crescendo and diminuendo) create an illusion of congruent pitch changes (rise and fall), and vice versa (see also Nakamura, 1987). Tekman (1997) reported that pitch accents sound louder, and dynamic (loudness) accents sound longer. Pitch, however, was not affected by dynamic accents. In another study, Collier (2001) found an interaction between pitch and tempo: accelerations were perceived as faster in higher pitches, and decelerations perceived as slower in lower pitches. Interactions between pitch, loudness and timbre were also found by Marks and Melara (1990a, 1990b) in speeded discrimination tasks. Finally, Eitan and Granot (unpublished study)[1] found that listeners assess stimuli with isochronous IOIs (Inter-Onset Intervals) as accelerating in stimuli whose loudness or textural density are progressively increased, and as decelerating in stimuli whose loudness or textural density decrease. More complex intramodal crossovers were observed in a sound-induced motion imagery task (Eitan and Granot, 2004; 2006), in which intensity changes in one auditory dimension were associated with motion parameters related to other auditory dimensions. For example, an increase in loudness in a repeating-tone figure was associated with images of accelerated motion (typically related to changes in tempo), whereas decrease in loudness was associated with images of spatial descent (typically associated with pitch).

Several researchers have attempted to design empirical models of cross-dimensional intensity in music. Of these, models suggested by Todd (1994, 1995, 1999), Clynes (1983), and Cohen (1971) are particularly relevant to the present study. Analyzing music performance, Todd proposes a model in which musical expression as well as aspects of musical structure, are equated in performed music with the changing profile of the psychoacoustic energy level over time. His model integrates intensity changes in various psychoacoustic dimensions, including tempo, dynamics, articulation, pitch register, timbre, and vibrato, into a single "integrated energy flux" (Clarke, 1995). The hierarchic intensity contours obtained by way of his model from performed music closely concur with traditional analyses of grouping structure.

An even broader view of the role of intensity contours in musical expression is proposed by Clynes (1983) who incorporated into his model of musical expression other sensory modes, suggesting that cross-modal intensity contours — "essentic

(1) A report on the study is currently being prepared for publication. Results are available from the authors upon request.

forms" — are the archetypical icons of basic human emotions (Clynes & Nettheim, 1982).These contours may be depicted aurally through pitch and loudness, as well as through other sensory modes, such as touch and visual curvature. Examining how "essentic forms" apply to music, Clynes asked subjects to apply rhythmical pressure to a sentograph (a touch-sensitive device) while listening to musical pieces. The average intensity curves conform, according to Clynes, to essentic forms, thus depicting the music's emotional progression.

A different approach to the role of multi-parametric intensity contours is suggested by Cohen's theory of musical expression and style (e.g., Cohen, 1971). Relating intensity and tension contours, Cohen discusses the roles of two contrasting archetypical intensity curves: an inverted U (convex) curve, used to attain an emotionally balanced, calm musical expression, and a U-shaped (concave) curve which represents a model of excited, unpredictable expression. Both shapes may be realized by different musical parameters, including pitch, dynamics, melodic intervals, and attack rate. Drawing on examples from diverse musical cultures, as well as from speech intonation, birdsong, and ERP (Event-Related potential) studies, Cohen and Granot (1995) suggest that the expressive functions of these contrasting intensity shapes are innate and universal.

AIMS AND HYPOTHESES

Though the studies surveyed above suggest that intensity changes in different musical dimensions may affect the perception of each other, it does not necessarily follow that intensity isomorphism affects perceived similarity, i.e., that analogous intensity changes in different musical dimensions (e.g., a crescendo and an accelerando) are, other things being equal, perceived as similar. Furthermore, most of the empirical studies surveyed have examined responses to basic psychoacoustic dimensions, like loudness or density. Musicians, however, often refer to intensity with regard to music-specific domains like harmonic progression (e.g., Berry, 1976), far removed from such basic sensory domains. Our aim, then, was to test specifically whether analogous patterns of intensity change, realized by different parameters, are perceived as similar, while applying this test to both basic psychoacoustical domains, like dynamics (loudness), and to higher-level aspects of musical organization, like tonal harmonic structure.

To address this issue, we examined whether listeners, varying in their musical training, perceive isomorphic intensity contours in different musical dimensions as more similar to each other than nonisomorphic intensity contours. We focused on the simplest and possibly most widely used contour — linear increase or decrease in intensity. Participants' task was to decide which of two musical gestures, contrasting in their intensity contours with respect to a specific dimension (e.g., an accelerando versus a ritardando) was more "similar in character" to a reference gesture of a crescendo (i.e., an intensification in loudness)[2].

We tested this general hypothesis with regard to a number of specific musical parameters, each of which can be organized along an axis of increase or decrease, as suggested by empirical findings or by music-theoretical models. Below, we specify our hypothesis with regard to each musical parameter examined, and present some of the empirical or theoretical work suggesting that changes in this parameter may be conceived as intensifications and abatements. For each parameter, we present two contrasting stimuli, one (hypothetically) increasing in intensity, the other – decreasing.

1. Pitch Direction. *A pitch ascent (hypothetically, an increase in intensity) would be perceived as more similar to a crescendo (intensification in the domain of loudness) than a pitch descent (hypothetically, a decrease in intensity).*

As mentioned above, Neuhoff and McBeath, (1996) and Neuhoff, McBeath and Wanzie, (1999) have shown that changes in loudness may create an illusion of a change of pitch and vice versa, while Eitan and Granot (2006) have demonstrated that decrease in loudness evokes images of spatial descent (usually associated with pitch fall). Todd's notion of "integrated energy flux" (1994) supports such associations, suggesting that changes in pitch, like changes in dynamics (as well as in other parameters, such as tempo) modulate the overall energy level along a musical segment, since the integrated energy of a high frequency is greater than that for a low frequency" (quoted from Clarke, 1995, p. 24). As Cox (1999) notes, the perception of such "energetic" analogies may be enhanced by the experience of vocal production, in which greater quantities and magnitudes of air, effort, and tension are needed to produce higher notes.

2. Pitch Intervals. *A succession of pitches in which the pitch intervals progressively increase would be perceived as more similar to a crescendo than a succession of pitches whose intervals progressively decrease.*

Larger F_0 shifts and wider pitch range have been associated with the dimension of increasing activity, and with active emotions like anger and happiness, in perceived tone sequences (e.g., Scherer & Oshinski, 1977) and in emotional speech (Paeschke & Sendlmeier, 2000; Scherer, 1986). This association may be due to the increased effort and muscular tension demands in vocal (as well as most instrumental) production as pitch intervals increase. Furthermore, pitches separated by large intervals may demand a higher mental effort, since they are harder to integrate into a single stream (Bregman, 1990). This increased effort may also contribute to a sense of intensification.

(2) The expression "similar in character" (rather than simply "similar") was used in the experiment's instructions to avoid confusion, since some of the musical stimuli were acoustically disparate from each other.

3. Inter-Onset Intervals (temporal density). *A succession of pitches whose inter-onset intervals progressively decrease would be perceived as more similar to a crescendo than a succession of pitches whose inter-onset intervals progressively increase.*

Change in the temporal density of sound events involves change in the quantity of acoustic energy per unit of time, and thus may be perceived as intensity change, analogous to change in loudness. Note also that velocity and intensity are associated in sound production: faster motion would, other things being equal, produce a stronger impact and thus louder sound. Indeed, increase in tempo has been shown to be associated with increase in loudness in piano performance (Palmer, 1996), a result of increased amplitude of vertical finger motion (Palmer & DallaBella, 2004). More generally, louder and faster sounds both require the investment of more energy (Todd, 1992, 1994). As Todd proposes, the tempo-loudness association may arise not only from experience with environmental stimuli, but from shared physiological mechanisms.

The effect of changes in loudness on perceived duration has been demonstrated in several studies, both in general auditory contexts (Hirsch, Bilger & Deathrage, 1956) and in specifically musical ones (Tekman, 1997). Specifically, a sequence of increasingly louder isochronous notes tends to be perceived as accelerating, i.e., as progressively decreasing in duration (Eitan & Granot, unpublished study; see footnote 1).

4. Motivic Pace. *A succession of melodic figures whose durations progressively decrease (intensifying) would be perceived as more similar to a crescendo than a succession of melodic figures whose inter-onset intervals progressively increase (abating).*

Changes in motivic pace are conceptually analogous to changes in temporal density: they present change in the rate of an event per unit of time, though this event is not a single note, but an entire grouping unit. In eighteenth and nineteenth century music such changes, often involving the gradual "liquidation" of a prominent musical motive (Schoenberg, 1967: 58), are frequent in transitional or development sections, and often involve other intensifying processes such as a crescendo or a continuous rise in pitch (Sheer, 1989).

5a. Harmonic progression: tonal stability. *Within a context of consonant diatonic triads, an idiomatic progression (I-vi-IV$_6$-ii$_6$-V), leading from tonic (stable) to dominant (unstable), would be perceived as more similar to a crescendo than its reverse, leading from dominant to tonic.*

5b. Harmonic progression: dissonance. *Within a tonal, diatonic context, a gradual motion from consonant chords towards increasingly dissonant ones (i-VI$_6$-iv$_6$-iv$_5^6$- ii$_5^6$- II$_3$4$^{6\#}$-V$_7^{13}$) would be perceived as more similar to a crescendo than its reverse - motion from dissonant to consonant chords.*

Most theories of harmonic tonality, their differences notwithstanding, agree that changes in harmonic tension can be produced by motion away from or toward the tonic, and by the generation and resolution of harmonic dissonance. The contribution of both these factors to perceived "musical tension" has been examined in several recent studies, involving short and long harmonic phrases (Bigand, Parncutt, & Lerdahl, 1996; Bigand & Parncutt, 1999) and actual musical contexts (Smith & Cuddy, 1997). As mentioned, some music theorists (e.g., Kurth, 1991; Berry, 1976; Rink, 1999; see pp. 40-41 above) have integrated harmonic motion and dissonance with other parameters, such as dynamics and pitch contour, in a general additive concept of musical intensity or "energy".

6. Parametric additivity: Pitch direction and IOI change combine additively (rather than interact) in the similarity rating task. *(For instance, a stimulus combining intensifications in these two parameters would produce higher similarity ratings with the crescendo figure than intensifications in each of these two parameters alone.)*

Theoretical models of intensity contours often assume, implicitly or explicitly, that the overall intensity contour can be obtained as some form of a linear summation of the intensity contours of each of the underlying musical parameters (Berry, 1976; Todd, 1995; Rink, 1999). Additivity is manifested also in musical accents, where "joint accent structure", combining dynamics, duration and pitch, additively shapes perceived or preformed accentuation (see, e.g., Jones & Pfordresher, 1997; Tekman, 1997 for perceptual studies; Palmer, 1989, regarding performance; Eitan, 1997; Huron & Royal, 1996, for statistical studies of joint accents in musical repertories). Partial additivity has been found in the auditory system, in detection of deviants in simple acoustical features such as frequency, stimulus onset asynchrony, and intensity (Paavilainen, Valppu & Näätänen, 2001). However, no such additivity effect has been found to deviants in higher order abstract features, such as intensity or pitch change in pairs of tones varying in the absolute pitch or intensity values (Paavilainen et al., 2003), suggesting that the additivity hypothesis may not be valid within more complex musical contexts.

Musicians and non-musicians. We do not present specific hypotheses regarding differences between musicians and non-musicians for each of the investigated parameters. Rather, we propose that differences in performance as a function of training would emerge more clearly where the analogy between the compared stimuli involves conceptual, music-specific domains, such as the proposed analogy between intensification and abatement in loudness and changes in harmonic stability and consonance, rather than perceptual relationships prominent in extra-musical auditory experience, such as the analogy of loudness and temporal density.

METHOD

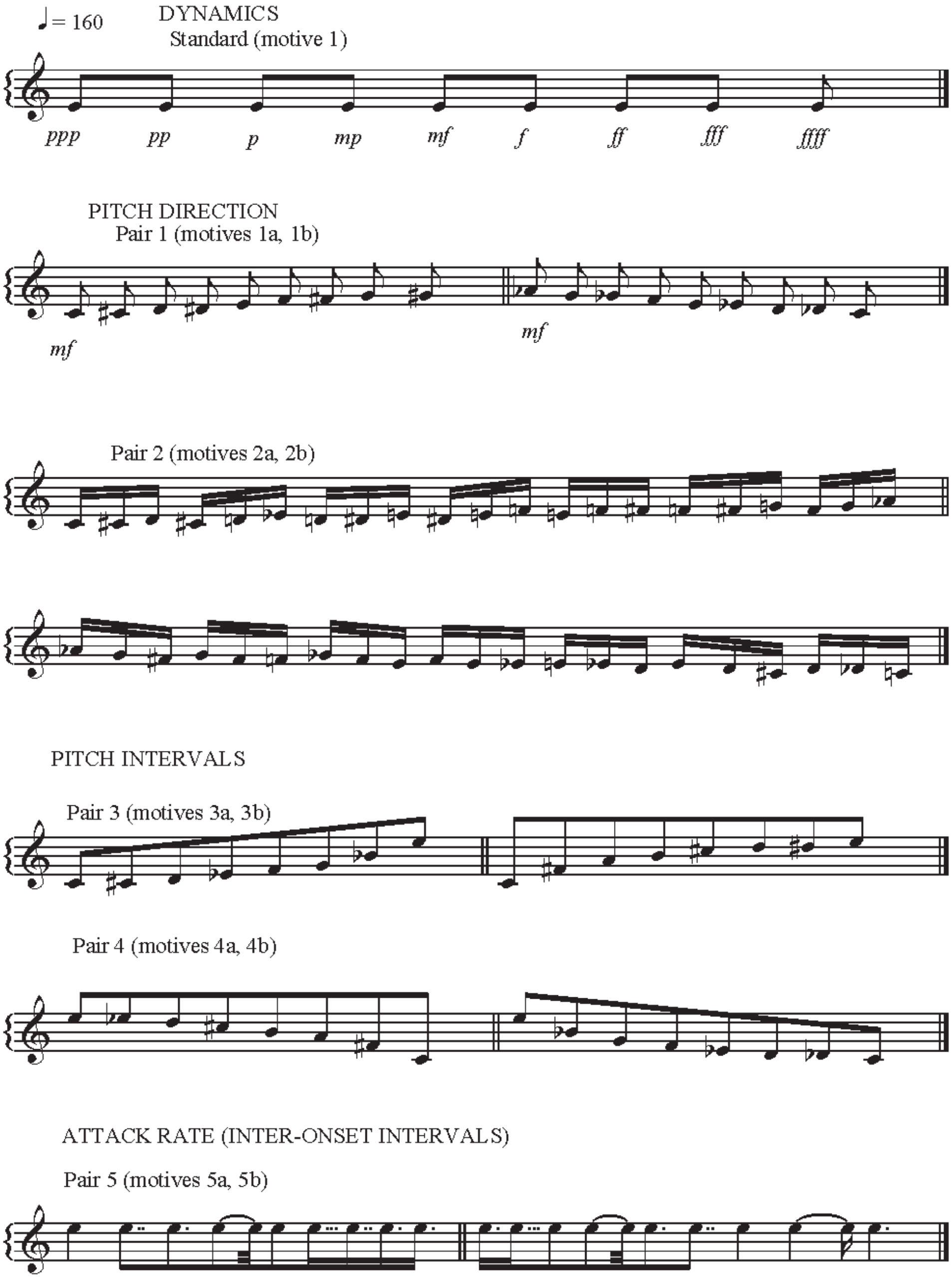
• **Participants.** Fifty nine college students participated in the experiment. Thirty three participants had little or no musical training (20 females, 13 males, mean age: 23.45 *SD* = 2.67) and the remaining 26 participants (12 females, 14 males, mean age: 25.3 *SD* = 5.65) had at least 7 years of formal training on an instruments or 5 years of playing on an instrument + 2 semesters of studies of music theory (mean period of training = 10.5 years, *SD* = 3.9).

• **Materials.** The musical stimuli included a "standard" musical figure — a crescendo of 9 isochronous monotones increasing gradually in intensity from *ppp* to *ffff*[3] as defined by the Sibelius 1.2 notation program, and 14 pairs of musical figures (see Figure 1)[4]. One member of each pair presented an intensity "increase" in a specific musical parameter, while the other presented a "decrease" (see above, "aims and hypotheses" for specific descriptions of increase or decrease in intensity for each parameter). Other parameters were held constant for each pair. The investigated variables were pitch direction (ascending vs. descending), size of pitch intervals (increase vs. decrease), temporal density (acceleration vs. deceleration of attack rate or of motivic pace), and harmonic progression (increasing vs. decreasing stability or dissonance). In addition, we examined the interaction between pitch direction and IOI (pairs 9-14). We did not examine in this study other types of interactions due to considerations of participants' attention and fatigue. For each individual parameter, two different pairs of motives were used. For *pitch direction* we used a simple chromatic scale (pair 1), and a chromatic sequence (pair 2). For *pitch intervals,* ascending (pair 3) and descending (pair 4) progressions were used. For temporal density we used a repeating tone figure (pair 5), and a chromatic motive, whose overall duration was progressively increased or decreased by adding or omitting notes ("motivic pace", pair 6). For harmonic progression, we used a pair of consonant triadic progressions, one moving from tonic to dominant, the other — its inverse (pair 7; see hypothesis 5a, p. 45 above), and a pair of contrasting progressions that either increase or decrease in harmonic dissonance (pair 8; see hypothesis 5b, p. 45).

• **Apparatus.** Musical Stimuli were created through *Sibelius 1.2* music software, using the software's Grand Piano sound, and recorded onto an audio CD using two identical tracks (i.e., a monophonic recording).

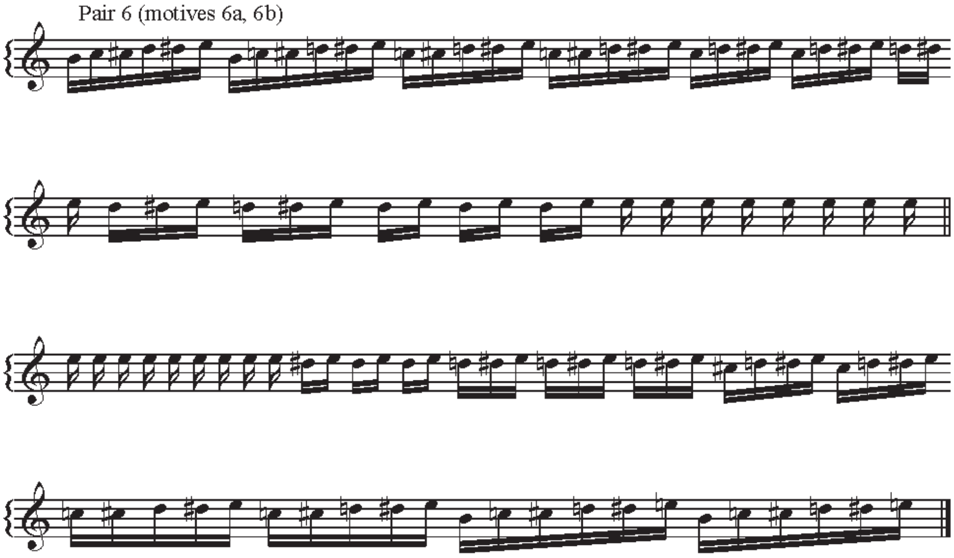
(3) An important addition to the experiment (which could not be implemented for practical constraints) would use a diminuendo as an additional standard. Comparing results for the two standards (crescendo and diminuendo) may enable the discovery of directional asymmetries, analogous to those reported by Eitan & Granot (2006).

(4) A MIDI file of the musical figures may be obtained from the authors.


♩ = 160
DYNAMICS
Standard (motive 1)
ppp pp p mp mf f ff fff ffff
PITCH DIRECTION
Pair 1 (motives 1a, 1b)
mf
mf
Pair 2 (motives 2a, 2b)
PITCH INTERVALS
Pair 3 (motives 3a, 3b)
Pair 4 (motives 4a, 4b)
ATTACK RATE (INTER-ONSET INTERVALS)
Pair 5 (motives 5a, 5b)

MOTIVIC PACE

Pair 6 (motives 6a, 6b)



♩ = 84 HARMONIC PROGRESSION (CONSONANT TRIADS)

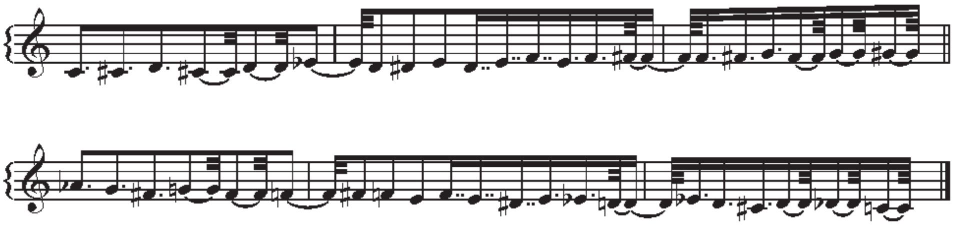
Pair 7 (motives 7a, 7b)

HARMONIC PROGRESSION (INCLUDING DISSONANT SONORITIES)

♩ = 160

Pair 8 (motives 8a, 8b)

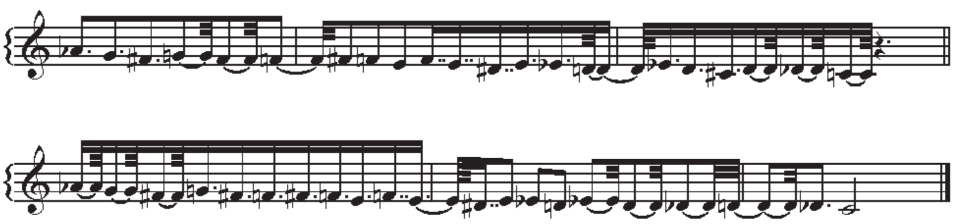
Pair 9 (motives 9a, 9b)



Pair 10 (motives 10a, 10b)

Pair 11 (motives 11a, 11b)

Pair 12 (motives 12a, 12b)



Pair 13 (motives 13a, 13b)

Pair 14 (motives 14a, 14b)

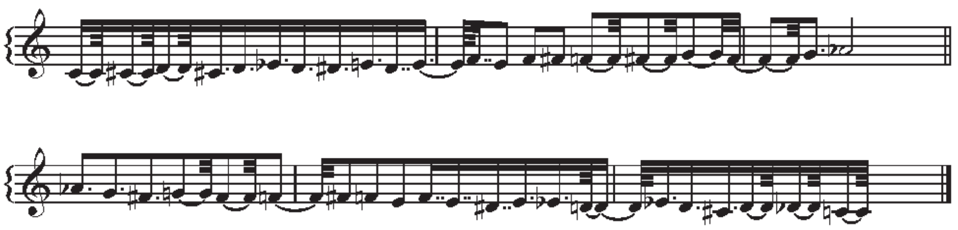


Figure 1.
Musical stimuli: One member of each pair presents an intensity "increase" in a specific musical parameter, while the other presents a "decrease". Other parameters are held constant for each pair.

• **Task and procedure.** Each participant initially completed a questionnaire regarding musical training, gender and age. Participants were first presented with the standard musical figure (a crescendo) four times for general acquaintance. Then, for each of the 14 pairs of musical motives, participants performed two related and consecutive tasks. In *Task 1*, they heard the standard followed by a pair of musical motives, and indicated which of the two members of the pair was more similar in character to the standard. Five seconds of silence separated the presentation of the standard and the first member of each pair, and five seconds separated consecutive pairs. The standard was presented before each pair of the compared musical motives. In Task 2, a "fine tuning" of Task 1, the same pair of stimuli was presented again, and participants were required to rate on a scale ranging from 1 (most distant) to 7 (most similar) the degree to which each of the stimuli was similar in character to the standard. Altogether, each of the 14 pairs of motives was heard twice (once for each task), and the standard was heard 18 times (once before each pair, plus 4 times preceding the tasks). The stimuli were presented over speakers at a comfortable intensity. Participants were tested in small groups (4-8 participants per group) either during music classes or in the lab. The order of the pairs of stimuli was randomized for each group and the order of stimuli within pairs was counterbalanced by producing a different version of the experiment CD with different track ordering for each group.

RESULTS

• **Task 1.** Table 1 presents results of a chi-square analysis of participants' responses in Task 1 (specifying which motive in each pair is more similar to the standard). For each pair of compared motives, the table indicates the manipulated parameter, the motives compared (numbered as in Figure 1), the number of participants who selected the intensifying (1) and the abating (2) motive in each pair as more similar to the standard, the results of chi-square tests and their p-values, and the respective False Discovery Rate (FDR), used to account for multiple testing[5].

Significant tendencies to match intensification in different musical parameters (i.e., match the standard with the intensifying figure in a pair) are exhibited in 10 of the 14 pairs. As Table 1 suggests, intensifications in pitch direction (i.e., pitch ascents) were most consistently judged to be similar to the standard crescendo figure. Participants chose pitch ascent over descent as more similar to the standard in diverse conditions: a simple isochronous chromatic figure (pair 1 in Table 1), an isochronous chromatic sequence (pair 2), a decelerating chromatic sequence (pair 10), and (marginally) an accelerating chromatic sequence (pair 9). IOI change significantly affected participants' choices only when pitch changed as well, either ascending (pair 11) or descending (pair 12), but not in the context of a repeated, unchanged pitch (pair 5). When pitch direction was combined with IOI congruently (ascent with acceleration and descent with deceleration; pair 13) participants significantly matched the intensifying figure (ascent plus acceleration) with the standard; when the two parameters did not concur (ascent with deceleration and descent with acceleration; pair 14), participants did not exhibit a significant preference. Changes in melodic interval size significantly affected participants' choice in ascent (pair 3), but not in descent (pair 4). Harmonic progression in a consonant setting (pair 7) did not significantly affect participants' choices; harmonic progressions involving the manipulation of dissonance, however, exhibited a marginally significant tendency to influence participants' selection such that more participants chose the intensifying progression (i.e., the progression that increased in dissonance) as more similar to the

(5) Benjamini and Hochberg (1995) introduced the *False Discovery Rate* (FDR) as a new approach to multiple inference problems. A false discovery is a true null hypothesis that is rejected. The idea behind the FDR is to control the fraction of false discoveries from among all null hypotheses that are tested. Older approaches, such as the Bonferroni method, are designed to control the probability of falsely rejecting even one null hypothesis. When all the null hypotheses are true, FDR-based methods will be very cautious about rejecting any hypotheses, just like the Bonferroni method. If, however, many of the null hypotheses are false, FDR-based methods will tolerate a small fraction of false rejections among the large collection of correctly rejected null hypotheses. As a result, FDR-based methods enjoy a substantial increase in power for detecting true effects. In recent years, use of the FDR has achieved widespread acceptance and application and is a standard method in, for example, the analysis of genetic microarray experiments.

Table 1

Chi-square tests for Task 1 (all participants)

PAIR NO.	PARAMETER	MOTIVES	A[a]	B[a, b]	CHISQ (*df* = 1)	P	FDR (M = 14)[c]
1	Pitch direction (chromatic scale)	1a vs. 1b	42	16	11.65517	***0.00064***	0.007143
2	Pitch direction (chromatic sequence)	2a vs. 2b	40	16	10.28571	***0.001341***	0.017857
3	Pitch intervals (ascending pitch)	3a vs. 3b	39	20	6.118644	***0.013376***	0.025
4	Pitch intervals (descending pitch)	4a vs. 4b	28	31	0.152542	0.696118	0.046429
5	IOI (no pitch change)	5a vs. 5b	35	23	2.482759	0.1151	0.042857
6	Motivic pace	6a vs. 6b	43	15	13.51724	***0.000236***	0.003571
7	Harmony (consonant tonal progression)	7a vs. 7b	30	28	0.068966	0.792849	0.05
8	Harmony (tonal prog. + dissonance)	8a vs. 8b	36	21	3.947368	*0.046945*	0.035714
9	Pitch direction (IOI speeding up)	9a vs. 9b	37	21	4.413793	*0.035649*	0.032143
10	Pitch direction (IOI slowing down)	10a vs. 10b	40	18	8.344828	***0.003868***	0.021429
11	IOI (ascending pitch)	11a vs. 11b	42	17	10.59322	***0.001135***	0.014286
12	IOI (descending pitch)	12a vs. 12b	37	20	5.070175	***0.024341***	0.028571
13	Pitch direction + IOI (congruence)[d]	13a vs. 13b	42	16	11.65517	***0.00064***	0.010714
14	Pitch direction + IOI (non-congruence)[d]	14a vs. 14b	35	22	2.964912	0.085089	0.039286

(a) A = number of participants who indicated that the presumed intensifying figure was more "similar in character" to the standard (a crescendo) as compared to the abating figure.
B = number of participants who indicated that the presumed abating figure was more "similar in character" to the standard (a crescendo) as compared to the intensifying figure.

(b) The total number of entries is sometimes smaller than our overall sample (59) due to missing values.

(c) FDR = False Discovery Rate used to account for multiple testing (see also footnote 5).

(d) Congruence: pitch ascent and accelerando, pitch descent and ritardando. Non-congruence: pitch ascent and ritardando, pitch descent and accelerando.

Table 2

Chi-square tests for Task 1: musicians vs. nonmusicians

PAIR NO.	PARAMETER	MOTIVES	TRAINING	A[a]	B[a, b]	CHISQ (*df* = 1)	P	FDR[c]
1	Pitch direction (chromatic scale)	1a vs. 1b	Musicians	19	7	5.538462	*0.018603*	0.017857
			Non-Mus	23	9	6.125	0.013328	0.007143
2	Pitch direction (chromatic sequence)	2a vs. 2b	Musicians	19	6	6.76	***0.009322***	0.014286
			Non-Mus	21	10	3.903226	0.048193	0.017857
3	Pitch intervals (ascending pitch)	3a vs. 3b	Musicians	18	8	3.846154	0.04986	0.025
			Non-Mus	21	12	2.454545	0.117185	0.021429
4	Pitch intervals (descending pitch)	4a vs. 4b	Musicians	11	15	0.615385	0.432768	0.042857
			Non-Mus	17	16	0.030303	0.861804	0.05
5	IOI (no pitch change)	5a vs. 5b	Musicians	18	8	3.846154	*0.04986*	0.028571
			Non-Mus	17	15	0.125	0.723674	0.042857
6	Motivic pace	6a vs. 6b	Musicians	18	8	3.846154	*0.04986*	0.032143
			Non-Mus	25	7	10.125	***0.001463***	0.003571
7	Harmony (consonant progression)	7a vs. 7b	Musicians	11	14	0.36	0.548506	0.046429
			Non-Mus	19	14	0.757576	0.384088	0.035714
8	Harmony (tonal prog. + dissonance)	8a vs. 8b	Musicians	16	9	1.96	0.161513	0.039286
			Non-Mus	20	12	2	0.157299	0.025
9	Pitch direction (IOI speeding up).	9a vs. 9b	Musicians	19	7	5.538462	***0.018603***	0.021429
			Non-Mus	18	14	0.272727	0.601508	0.039286
10	Pitch direction (IOI slowing down)	10a vs. 10b	Musicians	17	9	2.461538	0.116665	0.035714
			Non-Mus	23	9	6.125	0.013328	0.010714
11	IOI (ascending pitch)	11a vs. 11b	Musicians	22	4	12.46154	***0.000415***	0.007143
			Non-Mus	20	13	1.484848	0.223018	0.028571
12	IOI (descending pitch)	12a vs. 12b	Musicians	20	6	7.538462	***0.00604***	0.010714
			Non-Mus	17	15	0.125	0.723674	0.046429
13	Pitch direction +IOI (congruence)	13a vs. 13b	Musicians	23	3	15.38462	***8.77E-05***	0.003571
			Non-Mus	19	13	1.125	0.288845	0.032143
14	Pitch direction +IOI (non-congruence)	14a vs. 14b	Musicians	13	12	0.04	0.841481	0.05
			Non-Mus	22	10	4.5	0.033895	0.014286

(a) A = number of participants who indicated that the presumed intensifying figure was more "similar in character" to the standard (a crescendo) as compared to the abating figure.
B = number of participants who indicated that the presumed abating figure was more "similar in character" to the standard (a crescendo) as compared to the intensifying figure.
(b) The total number of entries is sometimes smaller than our overall sample (59) due to missing values.
(c) FDR = False Discovery Rate used to account for multiple testing (see also footnote 5).

standard. Finally, there is a highly significant tendency to match an acceleration of motivic pace (pair 6) with the standard.

Table 2 compares the results of Task 1 for musicians and non-musicians. Musicians significantly matched intensification in pitch direction (pairs 1, 2, & 9), IOI (pairs 11, 12 and marginally 5), and the congruent interaction between pitch direction and IOI (pair 13) with the intensifying standard motive. For non-musicians, the only significant result concerns motivic pace (pair 6), where accelerating pace was significantly matched with the crescendo standard. In pairs based on contrast in pitch direction (pairs 1, 2, 10 and 14) non-musicians' choices are on the margin of significance. Nonetheless, the trends exhibited by the non-musicians are similar overall to those of the musicians. Indeed, the average fraction of "correct" matching (i.e., matching the intensifying figure with the standard) was 0.68 for musicians versus 0.62 for non-musicians, but this difference did not reach statistical significance (Wilcoxon rank sum test, p = 0.16). We also compared musicians' and non-musicians' choices in each of the 14 pairs of motives directly through a chi-square analysis (two-sided p-values; df = 1). Differences were found with regard to pairs 11 (accelerating vs. decelerating IOI in ascent; chi-square = 4.087; p = 0.0487; marginally significant under correction for multiple testing) and 13 (congruent IOI and pitch direction; chi-square = 6.075; p = 0.0137). In pair 11, musicians significantly associated intensifications across the domains of dynamics (the standard) and temporal density (22 vs. 4 in columns "1" & "2" respectively in Table 2), while non-musicians did not (20 vs. 13). Training-based differences for pair 13 suggest that musicians react additively to the interaction of IOI and pitch direction (as their choices overwhelmingly opt for the combined intensification: 23 vs. 3), while non-musicians do not (19 vs. 13). Similar trends of additivity are suggested by pairs 12 & 14, though in these pairs differences were not statistically significant.

• **Task 2.** Table 3 presents the similarity ratings assigned to paired motives (Task 2). The comparison between the ratings of the two motives in the pairs is based on the Wilcoxon test for paired samples, and uses FDR to account for multiple testing (see footnote 5). In most respects, results parallel those of Task 1 (see Table 1). The only difference between the results of the two tasks relates to the interaction between IOI and pitch direction. Unlike results in Task 1, here ascending motives were rated significantly higher than descending in both congruent (pair 13: 3.7 vs. 2.7) and non-congruent (pair 14: 3.3 vs. 2.78) combinations of IOI and pitch contour. This may suggest that in determining intensity-based similarity for these motives, pitch direction was a more prominent dimension than IOI change. The next table (Table 4) allows us to examine whether this effect is related to musical training.

Table 4 presents Task 2 results while comparing the results for musicians and non-musicians. Note that in pairs presenting contrast in IOI change (5, 11, & 12) musicians' results are significant, while those of non-musicians are not. Note also the

Table 3

Wilcoxon paired tests for Task 2 (all participants)

PAIR NO.	PARAMETER	MOTIVES	RATING A[a]	RATING B	Z	P	FDR (M = 14)[b]
1	Pitch direction (chromatic scale)	1a vs. 1b	3.446	2.649	– 3.57986	***0.000344***	0.01071429
2	Pitch direction (chromatic sequence)	2a vs. 2b	3.673	2.614	– 4.35363	***0.000013***	0.00357143
3	Pitch intervals (ascending pitch)	3a vs. 3b	2.949	2.593	– 2.09085	*0.036542*	0.03571429
4	Pitch intervals (descending pitch)	4a vs. 4b	2.351	2.482	– 0.70319	0.481939	0.04642857
5	IOI (no pitch change)	5a vs. 5b	4.825	4.339	– 1.46365	0.14329	0.04285714
6	Motivic pace	6a vs. 6b	3.857	2.964	– 3.5301	***0.000415***	0.01785714
7	Harmony (consonant tonal progression)	7a vs. 7b	2.930	2.821	– 0.29401	0.768748	0.05
8	Harmony (tonal prog. + dissonance)	8a vs. 8b	3.071	2.403	– 2.78348	***0.005378***	0.025
9	Pitch direction (IOI speeding up)	9a vs. 9b	3.603	3.127	– 2.04692	*0.040666*	0.03928571
10	Pitch direction (IOI slowing down)	10a vs. 10b	3.526	2.643	– 4.00426	***0.000062***	0.00714286
11	IOI (ascending pitch)	11a vs. 11b	3.719	2.833	– 3.33728	***0.000846***	0.02142857
12	IOI (descending pitch)	12a vs. 12b	3.345	2.737	– 2.45397	***0.014129***	0.02857143
13	Pitch direction + IOI (congruence)	13a vs. 13b	3.702	2.714	– 3.54075	***0.000399***	0.01428571
14	Pitch direction + IOI (non-congruence)	14a vs. 14b	3.304	2.782	– 2.41121	***0.0159***	0.03214286

(a) Mean rating of the degree to which the assumed intensifying (Rating A) and abating (Rating B) motives are similar in character to the standard.

(b) FDR = False Discovery Rate used to account for multiple testing (see also footnote 5).

Table 4
Wilcoxon paired tests for Task 2: musicians vs. nonmusicians

PAIR NO.	PARAMETER	MOTIVES	TRAINING	RATING A[a]	RATING B	Z	P	FDR (M = 14)[b]
1	Pitch direction (chromatic scale)	1a vs. 1b	Musicians	3.440	2.958	– 1.82404	0.06815	0.03571429
			Non-Mus	3.451	2.424	– 3.10343	***0.00191***	0.00714286
2	Pitch direction (chromatic sequence)	2a vs. 2b	Musicians	4.125	2.720	– 3.68384	***0.00023***	0.00357143
			Non-Mus	3.323	2.531	– 2.47606	***0.01328***	0.01428571
3	Pitch intervals (ascending pitch)	3a vs. 3b	Musicians	2.731	2.348	– 2.34273	*0.01914*	0.025
			Non-Mus	3.121	2.774	– 1.20735	0.2273	0.03214286
4	Pitch intervals (descending pitch)	4a vs. 4b	Musicians	2.240	2.833	– 2.0704	*0.03484*	0.03214286
			Non-Mus	2.437	2.219	– 0.81661	0.41415	0.04285714
5	IOI (no pitch change)	5a vs. 5b	Musicians	5.480	4.375	– 2.65049	***0.00804***	0.01428571
			Non-Mus	4.312	4.312	– 0.261	0.79409	0.04642857
6	Motivic pace	6a vs. 6b	Musicians	4.167	3.240	– 2.55792	***0.01053***	0.01785714
			Non-Mus	3.625	2.733	– 2.48214	***0.01306***	0.01071429
7	Harmony (consonant tonal progression)	7a vs. 7b	Musicians	3.000	2.720	– 0.31735	0.75098	0.05
			Non-Mus	2.879	2.903	– 0.09413	0.92501	0.05
8	Harmony (tonal prog. + dissonance)	8a vs. 8b	Musicians	3.083	2.520	– 1.45789	0.14487	0.04285714
			Non-Mus	3.062	2.312	– 2.44071	***0.01466***	0.01785714
9	Pitch direction (IOI speeding up)	9a vs. 9b	Musicians	3.720	3.125	– 2.07657	*0.03784*	0.02857143
			Non-Mus	3.515	3.129	– 0.89826	0.36905	0.03928571
10	Pitch direction (IOI slowing down)	10a vs. 10b	Musicians	3.400	3.400	– 1.72203	0.08506	0.03928571
			Non-Mus	3.625	2.437	– 3.73271	***0.00019***	0.00357143
11	IOI (ascending pitch)	11a vs. 11b	Musicians	4.080	2.667	– 3.35954	***0.00078***	0.00714286
			Non-Mus	3.437	2.967	– 1.33018	0.18346	0.02857143
12	IOI (descending pitch)	12a vs. 12b	Musicians	3.652	2.600	– 2.41063	***0.01593***	0.02142857
			Non-Mus	3.125	2.843	– 1.08511	0.27787	0.03571429
13	Pitch direction + IOI (congruence)	13a vs. 13b	Musicians	3.840	2.625	– 2.88207	***0.00395***	0.01071429
			Non-Mus	3.594	2.781	– 2.19454	*0.0282*	0.025
14	Pitch direction + IOI (non-congruence)	14a vs. 14b	Musicians	3.160	2.917	– 0.95256	0.34081	0.04642857
			Non-Mus	3.419	2.677	– 2.34347	***0.01911***	0.02142857

(a) Mean rating of the degree to which the assumed intensifying (Rating A) and abating (Rating B) motives are similar in character to the standard.
(b) FDR = False Discovery Rate used to account for multiple testing (see also footnote 5).

difference between the groups with regard to interaction between IOI and pitch direction (pairs 13, 14), which will be discussed later below (p. 60) where we focus on the pitch and IOI combinations.

To directly compare musicians and non-musicians with respect to their ratings of closeness to the standard we used the Mann-Whitney test. Differences were found in pair 5, consisting of IOI changes in a repeated tone (Mann Whitney U = 222; $p < 0.01$). While nonmusicians rated both figures in this pair as similar in character to the standard (4.26 versus 4.35), musicians rated the intensifying (accelerating) figure as significantly more similar to the standard as compared to the decelerating figure (5.43 versus 4.39).

• **Motive groups.** To account for the effect of the manipulated parameters on similarity ratings across various contexts, we compared, using two-tailed paired samples tests, mean ratings for groups of motives that differ with respect to these parameters (Table 5). Thus, *pitch contour* (Table 5 first row) compares ratings for the ascending motives (1a, 2a, 3a, 3b, 9a, 10a) with those of their descending counterparts (1b, 2b, 4a, 4b, 9b, 10b); *IOI* compares ratings for motives presenting accelerations (i.e., increasing temporal density; motives 5a, 6a, 9a, 9b) and decelerations (5b, 6b, 10a, 10b); *Pitch intervals* compares ratings for motives presenting increase (motives 3a, 4a) and decrease (3b, 4b) in pitch intervals; and *Harmony* compares harmonic intensifications (motives 7a, 8a) and abatements (7b, 8b).

Results for all participants, regardless of musical training (Table 5, rows using white background) demonstrate that "increase" in pitch, temporal density, and harmony significantly affected similarity ratings, while pitch intervals did not. In other words, stimuli featuring pitch rises, temporal accelerations, and tensing harmonic progression were rated as more similar to the standard crescendo figure than their abating counterparts — pitch descents, temporal decelerations, and abating harmonic progressions, while increase or decrease in the magnitude of pitch intervals did not significantly affect these ratings. Here again, the parameter of pitch contour is the one creating the strongest sense of similarity to the crescendo (the only parameter significant for both musicians and nonmusicians). The two groups also concur in their responses to pitch intervals: neither of the groups correlates increasing interval size with increased loudness. IOI, on the other hand seems to influence only the ratings of musicians, suggesting they are more sensitive to the possible analogies across dynamics and temporal density. Indeed, a direct comparison of the mean rating of the two groups (using an independent samples t-test for equality of means) shows that similarity ratings of accelerating figures with the standard crescendo figure are significantly different ($p = .003$). Finally, although the parameter of harmony did influence overall participants' rating in the expected direction, interestingly, it is the non-musicians' data which contributes more to this phenomenon.

Table 5
Paired samples tests for groups of motives in Task 2

Parameter	Type of change	Participants	Paired Differences 95% Confidence Interval of the difference: Lower	Upper	Std. Error Mean	t	df	Sig. (2-tailed)
Pitch Contour	Ascending vs. descending	All	.6194	1.1408	.130	6.8	56	***.0000***
		Musicians	.4273	1.121	.167	4.6	23	***.000***
		Non-Mus	.5703	1.344	.190	5.0	32	***.000***
IOI	Speeding vs. slowing	All	.2804	1.0295	.187	3.5	56	***.0009***
		Musicians	.7017	1.121	.283	4.5	24	***.000***
		Non-Mus	.2800	.5989	.2145	.75	31	.457
Pitch intervals	Increasing vs. decreasing	All	– .1270	.4127	.135	1.1	55	.2934
		Musicians	– .3989	.3155	.173	– .2	23	.811
		Non-Mus	– .1200	.6803	.196	1.4	31	.161
Harmony	Intensifying vs. abating	All	.0518	.6937	.160	2.3	54	***.0237***
		Musicians	– .2025	.9851	.286	1.3	22	.186
		Non-Mus	– .02	.7404	.187	1.9	31	*.064*

• **Pitch and IOI combinations.** For pairs 9-14, in which the parameters of pitch direction and IOI change are combined, we applied repeated measures analysis of variance, to examine the independent effect of pitch contour, IOI change, and their interaction, on similarity rating (Task 2). There are clear effects related to which of the musical parameters matched the standard in the direction of intensity change, as the four possible combinations of the two parameters (rising and accelerating, falling and decelerating, rising and decelerating, falling and accelerating) are significantly different from one another ($p < 0.001$). There are highly significant main effects for both pitch contour and IOI (P (contour) < 0.01; P (IOI) < 0.05), with no interaction between them ($p = 0.82$). This suggests that when pitch direction and IOI are combined, they contribute to the perceived affinity independently and additively. This finding lends some support to the implicit assumption underlying some models of intensity contours in music (see introduction), in which the intensity is integrated linearly across various parameters. Note, however, that the parameter of pitch direction has a stronger effect on the average ratings than does the parameter of IOI change. For instance, ascending motives were rated significantly higher than descending in both congruent (pair 13) and non-congruent (pair 14) interactions of IOI and pitch direction (see Table 3). This trend can be seen in the F-statistic for pitch direction and IOI change, as the former is about twice as large as the latter [$F(1,147) = 27.196$; $F(1,147) = 14.323$ for pitch direction and IOI respectively]. In other words: the average change in rating when pitch matches the standard (i.e., when pitch ascends) is larger than the effect of having IOI change match the standard (i.e., acceleration) by a factor equal to about the square root of 2.

Though there are no overall differences between musicians and non-musicians in similarity ratings of pairs 9-14 ($p = 0.59$), there is a significant interaction between IOI and musical training ($p = 0.048$), suggesting once more that musicians' ratings are more sensitive to the changes in IOI. For instance, in pair 14 (non-congruence), musicians' rating for the two motives are similar (Table 4: 3.16 vs 2.92;), suggesting an equally weighted effect. For non-musicians, however, ascent in ritardando is rated significantly higher than descent in accelerando (3.419 vs. 2.677), suggesting pitch direction has, for this group, a stronger effect than IOI change in determining intensity-based similarity across dimensions[6].

(6) Note that in pairs 9-14, each combination of pitch direction (ascent or descent) and IOI change (accelerando or ritardando) was presented thrice, each time with a different paired item. The identity of the other pair member played a significant role on rating when intensification in one parameter is counteracted by abatement in the other parameter (Friedmann test: $p < .001$). That is, the rated degree of similarity to the standard in figures representing incongruence between the direction of change in the two parameters (ascent in ritardando, descent in accelerando) varies according to the figure with which they are paired.

CONCLUSIONS AND DISCUSSION

What do our findings add to the diverse perceptual evidence (surveyed in the introduction) that parameters such as pitch height and loudness indeed interact in perception? The answer is threefold. First, unlike the extremely simple stimuli used in studies such as Stevens (1961, 1975), or Melara & Marks (1990a, 1990b, 1990c), we used relatively complex music-like stimuli, such as melodic sequences and motivic chains, to represent even basic dimensions like pitch contour or temporal density. Second, unlike most such studies (a few exceptions, e.g. Neuhoff, McBeath & Wanzie, 1999, notwithstanding) we used continuous dynamic processes, like a crescendo, an accelerando, or a pitch ascent, rather than single stimuli such as isolated pitches; and third, our task directly addresses listeners' perception of similarity between isomorphic intensity contours in these different dimensions. All these differences make the results of the present study more directly relevant to the perception of similarity relationships in music then those of most previous studies of cross-dimensional intensity relationships.

Our results mostly corroborate our main hypothesis: isomorphisms of intensity direction in different musical parameters (e.g., a crescendo and an accelerando) indeed affect the perceived similarity between musical figures. The results thus suggest that such similarity is affected not only by affinity within musical dimensions (e.g., shared pitches, pitch intervals, or timbres), but also by analogies across dimensions, based on isomorphic intensity contours.

Importantly, such cross-dimensional similarity is perceived not only where intensity in both dimensions directly results from changes in acoustic energy (e.g., dynamics and temporal density, as suggested by Todd, 1992, 1995); it also applies where the perception of intensity results from more complex sources, such as harmonic dissonance within a tonal framework, motivic pace, or pitch direction.

Indeed, the analogy between ***pitch direction*** and loudness change (see ***hypothesis 1***), has proved to be the most robust among the analogies suggested here. Participants, regardless of their musical training, perceived figures of rising pitches (with no loudness change) as more similar to a crescendo figure (with no change in pitch) than equivalent figures of falling pitches, and applied this perception to a variety of melodic figures (a simple chromatic line, a chromatic sequence, patterns of increasing and decreasing melodic intervals).

This analogy does not seem to stem from simple acoustic effects related to the Equal-loudness contours (Fletcher and Munson, 1933), since at the pitch ranges we used (C4 = 261.6 - E5 = 659) the equal loudness curve is nearly flat. Furthermore, the equal loudness contours used in the psychoacoustic literature refer to a specific matching task of two isolated tones, rather than a dynamic process such as that used here, and their exact shape differs as a function of the nature of the tones (sine versus complex tones) and the range of levels chosen for the matching (Moore, 1997). A more relevant context for our findings are studies by Neuhoff and McBeath (1996) and Neuhoff, McBeath and Wanzie (1999), showing that dynamic frequency change (e.g., a pitch glide) influences loudness perception such that increase in frequency is perceived as increase in loudness, and dynamic intensity change (a crescendo) is perceived as ascending pitch. This "higher is louder" effect was found even in ranges where equal loudness contours, comparing isolated tones, would have predicted the opposite effect. Neuhoff, McBeath & Wanzie (1999, p. 1050) suggest that "the interaction of dynamic pitch and loudness occurs due to an internalization or bias that reflects a correlation between naturally occurring changes in frequency and intensity". Correlations involving human sound production may particularly strengthen such bias, for instance, the tendency of a rise of subglottal pressure, the primary factor contributing to vocal loudness, to be accompanied by rises in fundamental frequency in speech (Titze, 1989), and more generally, the correlation of both rises in pitch and crescendi with increased vocal tension (Cox, 1999). When music-like stimuli are used, further bias may be created by the frequent association of changes in pitch and dynamics in music performance (e.g., Sundberg, Friberg & Frydén, 1991), or in notated music of the last centuries.

The primacy of the analogy between pitch contour and loudness in establishing intensity-based similarities is also revealed by the effect of pitch direction on the perception of analogies between loudness and other dimensions, particularly pitch intervals, motivic pace, and IOI. Thus for example, increase in the size of ***pitch intervals*** is perceived as more similar to a crescendo than a decrease ***(hypothesis 2)*** only when pitch is rising. This suggests that "weaker" intensity-based similarity, such as that between pitch intervals and change in loudness, is brought to attention only when a more prominent similarity (here, between pitch direction and loudness change) exists as well.

Pitch changes may have also influenced the strong affinity between ***increased motivic pace and crescendo (hypothesis 4)*** since in our motive of increased motivic pace (Figure 1, motive 6a) there is a confluence of intensification in IOI with intensification in pitch. This intensification in pitch, however, does not occur on the surface note-to-note level but rather results from a gradual rise of the initial notes of the motive, which accompanies its gradual truncation (hence shorter IOI).

Interestingly, the expected analogy between IOI changes and loudness ***(hypothesis 3)***, which could be explained by a common increase in acoustic energy (as suggested by Todd's model, 1992), albeit across different time-spans, turned out to be weaker than the less direct analogy between pitch rise and increase in loudness. Thus, for example, when pitch direction and IOI change are combined (pairs 9-14), the effect of the latter is significantly weaker (though, at least for musically-trained subjects, significant as well). Furthermore, the IOI-Loudness analogy seems to be more sensitive to musical training (see below) and turned out to be significant only when pitch changed as well, but not when IOI changes were applied to a repeated pitch (pair 5). This last result, however, may stem from the fact that the repeated pitch-class used (E) was identical to that in the standard crescendo motive. Possibly, this identity overrode the differences in the intensity contour of the speeding and slowing figures.

The relative weakness of the analogy between increased loudness and speed is primarily due to the performance of non-musicians (see below). Hence, the perception of such analogy may be based primarily on biases acquired through musical practice and extensive knowledge of musical repertories, where faster and louder often correspond (see Todd, 1992, for a relevant computational model).

When intensification occurs in both IOI and pitch (i.e., faster and higher) similarity ratings are higher (compared to ratings for each dimension separately), while combining an intensification in one dimension with abatement in the other lowers ratings, in comparison to those in the separate dimensions. This result supports the ***additivity*** hypothesis concerning IOI and pitch direction ***(hypothesis 6)***, and thus suggests that an additive model, combining intensifications and abatements in diverse parameters into an "integrated energy flux", whose ebbs and flows shape musical structure and guide expressive performance (Berry, 1976; Clarke, 1995; Rink, 1999; Todd, 1994, 1995), may be cognitively valid. It remains to be seen whether this conclusion can be generalized to broader and more complex contexts, involving more than the two dimensions examined. Nonetheless, our results clearly indicate that even within an additive model, different weights should be applied to different parameters.

Focusing on the music-specific parameter of harmony we found that intensifying ***harmonic progressions*** were perceived as more similar in character to the standard than abating ones (see ***hypothesis 5***) when the progression involved changes in the degree of harmonic dissonance. In contrast, when only consonant chords were involved, and harmonic intensification was based only on the succession of harmonic degrees, there was no difference in the similarity rating between intensifying and abating motives. These findings suggest that to be clearly perceived, harmonic intensity curves seem to require the support of perceptual dissonance. Such congruence between the harmonic function and perceptual dissonance is in fact prevalent in much of the eighteenth and nineteenth century musical practice. Thus, for example, a final tonic is a consonant triad, while dominant functioning chords are usually dissonant 7th chords, and (particularly in nineteenth century music, where the structural importance of intensity contours increases) often receive further dissonant embellishment.

Though no overall effect of ***musical training*** was found, such effect was demonstrated in the domain of tempo, as musically-trained participants were more sensitive to analogies between intensification in temporal density (acceleration) and dynamics (crescendo). This is somewhat surprising, since musically trained subjects have demonstrated little superiority over untrained ones in tasks involving the detection of tempo or timing changes (Repp, 1999; Wang, 1983; Yee, Holleran, & Jones, 1994). However, musical experience can be associated with the dynamics-tempo analogy in various ways: changes in dynamics and tempo are usually congruent in the classical repertory (e.g., "crescendo and accelerando"), more familiar to trained participants; moreover, in music performance, tempo and dynamics tend to be congruent (see Palmer, 1996, 1997; Palmer & Dala Bella, 2004, for empirical studies on tempo and loudness in piano performance). Thus, combination of performance and listening-related biases might have attuned musicians better to the tempo-dynamics analogy.

Surprisingly, no significant differences between trained and untrained participants were found with regard to analogies of dynamics and the specifically musical domain of harmony (in fact, untrained participants performed better, though not to a statistically significant degree, in this respect). The lack of significant training-based differences in this respect suggests that participants may have relied on their sensitivity to dissonance, sensitivity evident even in young infants (e.g., Trainor & Heinmille, 1998), rather than on an understanding of musical syntax per se. One notes, however, that the harmonic progressions we used are short, and their tonality was not pre-established by the preceding stimuli. It is possible that in actual listening conditions, where tonality is more strongly established, results would have been different.

Implications for music theory and analysis

This study suggests that isomorphic intensity contours in different parameters can, under specific circumstances, indeed be perceived as similar to each other, despite the diversity of their musical constituents. What may the possible implications of such findings for actual music materials be?

• **Intensity contours as motives.** The present results suggest an extension of motivic-thematic analysis, indicating that intensity contours, transferable from one parameter to another, may fulfill the unifying function usually ascribed to pitch or rhythmic motives (see, e.g. Cogan, 1984; Eitan, 2003; Hatten, 1993, 1997-2001 for relevant musical analyses). Although the present study does not necessarily show that listeners would categorize isomorphic intensity contours in different parameters as variants of each other, it does indicate that such categorization is cognitively possible, and thus suggests a new path for motivic analysis in music.

This path may be particularly useful for posttonal music, which does not provide the listener with the clear tonal structures supporting the perception of motivic similarity in eighteenth and nineteenth century music. While posttonal composers and theorists (e.g., Schoenberg, 1941/1984; Forte, 1973) have suggested other, pitch-class and interval-class based structures for such music, even trained musicians repeatedly fail to perceive such structures in studies of perceived motivic similarity (e.g., Bruner, 1984; Dibben & Clarke, 1997; Gibson, 1988, 1993). In light of these studies, and of studies suggesting that contour, rather than pitch intervals, is the main basis for the perception of similarity and identity in atonal melodies (Dowling & Fujitani, 1971; Dowling, 1982; Edworthy, 1985), it is conceivable that for posttonal music isomorphism of intensity contours plays a particularly important role in generating similarity perception and thematic categorization (such as cue abstraction and imprint formation; see Deliège, 2001a, 2001b). Indeed, the structural role of intensity contours is evident in diverse music of the twentieth century, from the excessive variants of nineteenth century intensity gestures, like series of "ramps" integrating pitch contour, textural and rhythmic density, and dynamics, used by expressionistic composers such as Alban Berg (e.g., *Lyric Suite*, 4th movement, mm. 1-16; See Eitan, 1997, chap. 5), to the density-based structures of composers such as Varèse, Xenakis, or Ligeti.

An approach relating contours in different parameters (pitch, duration) to each other, and presenting isomorphic contours in different parameters as equivalent, has been indeed suggested by several theorists of twentieth century music (Marvin & Laprade, 1987; Morris, 1993). Our results support the cognitive plausibility of such approaches.

• **Intensity and thematic prototypes.** Though our results do not directly show that cross-parametric intensity contours are perceived as musical motives, they do indicate that such contours could influence listeners' perception of musical similarity. One clear example of how this could manifest itself is in the degree to which motives are perceived as good or poor exemplars of their motivic category, as manifested in Zbikowski's analyses of motivic prototypes (1999, 2003). For instance, even when a motivic category is primarily characterized by its pitch intervals, a motive in crescendo may be perceived as a better example (closer to the prototype) of this category than the same motive in diminuendo, if the prototypic representation of the motive is one of intensification. Listeners' association of motivic prototypicality with specific intensity contours (or with levels of intensity) may partially explain the strong effect of surface parameters like temporal density, pitch contour, or dynamics (where intensity contours can be clearly depicted and compared, as our results suggest) on motivic-thematic perception, indicated in a number of empirical studies (e.g., Dibben & Clarke, 1997; Lamont & Dibben, 2001; Ziv & Eitan, this issue).

• **Intensity contours as style structures.** As mentioned above (pp. 40-41), a number of music theorists have described the characteristic intensity contours of specific musical styles (e.g., Agawu, 1982; Cohen, 1971; Kurth, 1991; Meyer, 1989). Our results support this approach and suggest that style analyses should take into account the role of such contours in shaping stylistically-typical gestures. Indeed, the prevalence of style structures based on inter-parametric intensity contours in Western music may have contributed to listeners' sensitivity to intensity-based analogies between different parameters, indicated by the results in this study.

• **Intensity contours as "rhetorical" prototypes.** Huron, Ch'ng, Rasmussen, and Stockwell (1997) show that listeners can correctly identify the "rhetorical" function (e.g., beginning, conclusion, transition) of musical fragments from 18th and 19th century pieces, isolated from their original context. Though Huron did not analyze the musical factors affecting his results, one of these factors may be intensity contours typically associated with specific rhetorical or structural functions. Relationships between intensity contours and structural functions in music have been demonstrated in musical analysis, for instance by Hopkins (1990), who discusses the role of multi-parametric abatements in shaping closure in Mahler's music. Listeners may identify structural functions of musical segments, then, by recognizing a typical intensity contour – an intensity contour that may be analogously depicted by diverse musical dimensions.

* * *

To conclude, in this study we have demonstrated that the concept of intensity contour is not only a useful theoretical construct but also represents an important aspect of our perception of musical materials. Listeners readily associate musical gestures which do not share specific pitches or pitch structures, but do share intensity contours. These associations may add another layer onto the complex web of relationships listeners create among the various parts of a piece as it unfolds in time. Moreover, intensity contours may not only associate different dimensions within the auditory domain but may also associate crossmodally with other sensory information — visual, tactile or kinetic (Calvert, 2001, Eitan & Granot, 2006). Thus, intensity-based similarities, such as those demonstrated here, could enrich both the experience of musical structure, and serve as a link between musical structure and its extra-musical meaning.

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• Cambios de intensidad y similitud perceptiva: analogías inter-paramétricas

Psicólogos y teóricos de la música han descrito diversos procesos musicales en términos de cambios (crecimiento o disminución) de "intensidad". Este trabajo examina la hipótesis de que cambios análogos en la intensidad de diferentes parámetros musicales pueden ser percibidos como similares, y discute las implicaciones de tal percepción para el análisis musical. Para llevar a cabo el experimento, los participantes midieron el grado de similitud de pares de estímulos musicales respecto a un modelo previo — un *crescendo* o una nota repetida —. Un miembro de cada par presentaba una disminución de un parámetro musical concreto, mientras que el otro presentaba un aumento — por ejemplo, un ascenso melódico frente a un descenso —. Los parámetros investigados incluían dirección melódica y ataque, así como sus combinaciones, amplitud melódica de los intervalos, diseño motívico y tensión armónica.
En la mayoría de los parámetros la figura que presentaba una intensificación fue considerada más parecida al modelo (una intensificación en sí misma) que su homólogo no intensificado. La percepción de similitud fue más fuerte entre las figuras que presentaban una intensificación dinámica — *crescendo* — y un ascenso melódico, mientras que la similitud entre la intensificación dinámica y el *tempo* — *accelerando* — fue más débil, y percibida principalmente por sujetos que poseían una educación musical. La similitud entre cambio dinámico y progresión armónica fue percibida únicamente cuando la última incorporaba el empleo de disonancia, y la intensificación dinámica y la disminución de la amplitud interválica fueron percibidos como similares solamente en el caso de intervalos ascendentes. Hay que destacar que el efecto combinado de la dirección melódica y ataque sobre la percepción de similitud resultó ser aditivo más que interactivo, pese a que el efecto de la dirección melódica fue significativamente más fuerte. Este resultado confirma modelos de "contornos de intensidad integrada" (Berry, 1976; Todd, 1994), pero sugiere diferentes resultados según el tipo de parámetros musicales.
En resumen, los resultados indican que los oyentes pueden percibir contornos de intensidad en diferentes parámetros como análogos, y también sugiere que los contornos de intensidad pueden servir como "gestos" musicales sin tener en cuenta los parámetros específicos representados por ellos. Se discuten implicaciones de estos resultados para el análisis musical en relación con la estructura motívica, los prototipos temáticos y las funciones estructurales de los contornos de intensidad.

• Cambiamenti d'intensità e similarità percepita: analogie inter-parametriche

I teorici e gli psicologi della musica hanno descritto diversi processi musicali in termini di cambiamenti (aumento o diminuzione) d'"intensità". Il presente articolo prende in considerazione l'ipotesi secondo cui cambiamenti d'intensità analoghi in parametri musicali diversi si possono percepire come simili, e discute le implicazioni di tale percezione sull'analisi musicale. Nell'esperimento riportato, i partecipanti

valutavano il grado in cui i membri di coppie di stimoli musicali somigliavano nel loro carattere ad uno "standard" — un crescendo su una nota ripetuta. In ciascuna coppia, un membro presentava un "aumento" di uno specifico parametro musicale, mentre l'altro presentava una "diminuzione" (ad esempio : altezze ascendenti *vs.* altezze discendenti). I parametri analizzati includevano direzione melodica, quota d'attacco e loro combinazioni, ampiezza degli intervalli, andamento motivico e tensione armonica.

Per la maggior parte dei parametri, la figura intensificante veniva giudicata più vicina allo standard (a sua volta intensificante) rispetto alla sua controparte decrescente. La similarità percepita era massima tra figure che presentavano un'intensificazione nella dinamica (crescendo) e nella direzione delle altezze (ascesa), mentre la similarità fra l'intensificazione dinamica e quella di tempo (accelerando) era più debole, e veniva percepita principalmente da soggetti musicalmente preparati. La similarità fra cambiamento dinamico e progressione armonica veniva percepita soltanto quando quest'ultima coinvolgeva la manipolazione della dissonanza ; l'intensificazione dinamica e l'aumento dell'ampiezza degli intervalli venivano percepiti come simili soltanto in caso di intervalli ascendenti. Aspetto importante, l'effetto combinato di direzione melodica e velocità d'attacco sulla percezione di similarità era di tipo additivo, e non interattivo, sebbene l'effetto della direzione melodica fosse significativamente più forte. Questo risultato avalla modelli di "contorni integrati d'intensità" (Berry, 1976 ; Todd, 1994), ma suggerisce un peso differente per ciascun diverso parametro musicale.

In sintesi, i risultati indicano che gli ascoltatori possono percepire contorni d'intensità in parametri diversi come analoghi, e suggeriscono quindi che i contorni d'intensità possano servire come "gesti" musicali, a prescindere dagli specifici parametri che li descrivono. Le implicazioni di questi risultati per l'analisi musicale vengono discussi in riferimento a struttura motivica, prototipicità del tema e funzioni strutturali dei contorni d'intensità.

• Changements d'intensité et similarité perçue : analogies inter-paramétriques

Les théoriciens et les psychologues de la musique ont décrit plusieurs processus musicaux en termes de changement (augmentation ou diminution) d'« intensité » . Nous examinons ici l'hypothèse selon laquelle des changements analogues d'intensité de différents paramètres musicaux peuvent être perçus comme étant semblables ; nous examinons ce qu'implique cette perception pour l'analyse musicale. Dans l'expérience décrite, nous avons demandé aux participants d'évaluer la mesure dans laquelle les membres de paires de stimuli musicaux étaient semblables à un « standard » : le crescendo d'une note répétée. Un membre de chaque paire présentait l'« augmentation » d'un certain paramètre musical, alors que l'autre présentait une « diminution » (par exemple, une hauteur montait et l'autre descendait). Les paramètres étudiés étaient la direction mélodique, la vitesse de l'attaque et leurs combinaisons, la largeur de l'intervalle, la rapidité motivique et la tension harmonique.

Pour la plupart des paramètres, la figure en augmentation était considérée comme étant plus proche du standard (qui lui-même augmentait) que celle qui est en diminution. La similarité perçue était plus forte entre les figures où il y avait augmentation de dynamique (crescendo) et de direction (hauteur montante) ; la similarité entre l'augmentation de dynamique et de tempo (accelerando) était plus faible et n'était en général perçue que par les sujets ayant une formation musicale. La similarité entre les changements de dynamique et de progression harmonique n'était perçue que lorsque les derniers comportaient l'utilisation de dissonances ; l'intensification de la dynamique et l'augmentation des intervalles n'étaient perçues comme étant similaires que dans le cas d'intervalles ascendants. Il est important de noter que l'effet combiné de la direction mélodique et de la vitesse de l'attaque sur la perception de la similarité était additive plutôt qu'interactive, bien que l'influence de la direction mélodique était nettement plus marquée. Ce résultat corrobore les modèles de « contours d'intensité intégrés » (Berry, 1976 ; Todd, 1994), mais il semble exiger une pondération différente pour les différents paramètres musicaux. Pour résumer, ces résultats indiquent que l'auditeur peut percevoir les contours d'intensité de différents paramètres comme étant analogues, ce qui suggère que ces contours servent peut-être de « gestes » musicaux, quel que soit le paramètre en question. Nous examinons ce qu'impliquent ces résultats pour l'analyse musicale du point de vue de la structure motivique, de la prototypicalité thématique et des fonctions structurelles des contours d'intensité.

• Intensitätsänderungen und wahrgenommene Ähnlichkeit : Interparametrische Analogien

Musiktheoretiker und Psychologen beschreiben unterschiedliche musikalische Prozesse als Änderungen (Zunahme oder Abnahme) von „Intensität". Dieser Artikel untersucht die Hypothese, dass analoge Intensitätsänderungen in verschiedenen musikalischen Parametern ähnlich wahrgenommen werden können ; Implikationen solcher Wahrnehmungen für die Musikanalyse werden diskutiert. In dem beschriebenen Experiment beurteilten Versuchsteilnehmer das Ausmaß, bis zu welchem jeweils zwei musikalische Stimuli im Charakter einer Referenz (Crescendo auf einem wiederholten Ton) ähneln. Einer der zwei Stimuli war durch eine „Zunahme" in einem spezifischen musikalischen Parameter gekennzeichnet, während der jeweils andere Stimulus eine „Abnahme" (z.B. Tonhöhenanstieg und -abstieg) präsentierte. Die untersuchten Parameter umfassten melodische Richtung und Attack-Rate und ihre Kombinationen, Tonhöhenintervallgröße, motivisches Voranschreiten sowie harmonische Spannung. Der Stimulus mit Intensitätssteigerungen wurde bei den meisten Parametern als ähnlicher im Vergleich zur Referenz (selbst mit Intensitätssteigerung) bewertet als der jeweils konträre Stimulus. Die wahrgenommene Ähnlichkeit zeigte sich am stärksten für die Stimuli, die Intensitätssteigerungen in der Dynamik (Crescendo) und in der Tonhöhenrichtung (Anstieg) präsentierten, während die Ähnlichkeit zwischen Dynamik und Tempo (Accelerando) schwächer bewertet wurde und vor allem von musikalisch gebildeten Versuchsteilnehmern wahrgenommen wurde. Ähnlichkeiten zwischen Änderungen in der Dynamik und harmonischer Fortschreitung wurden nur wahrgenommen, wenn letztere durch Manipulationen der Dissonanz geprägt war. Dynamische Intensitätssteigerungen und Vergrößerungen der Tonhöhenintervalle wurden nur für aufsteigende Intervalle als ähnlich wahrgenommen. Wichtig ist, dass der Kombinationseffekt zwischen Melodierichtung und Attack-Rate hinsichtlich der Ähnlichkeitswahrnehmung additiv anstatt interaktiv war, obwohl der Effekt für Melodierichtung signifikant stärker war. Dieses Ergebnis unterstützt das Modell „integrierter Intensitätskonturen" (Berry, 1976 ; Todd, 1994), verweist jedoch auf verschiedene Gewichtungen für unterschiedliche musikalische Parameter. Insgesamt zeigen die Ergebnisse, dass Hörer Intensitätskonturen in verschiedenen Parametern als analog wahrnehmen können. Daher könnten Intensitätskonturen als musikalische „Gesten" dienen, unabhängig von den verschiedenen Parametern, durch die sie dargestellt werden. Die musiktheoretischen Implikationen dieser Ergebnisse werden hinsichtlich der motivischen Struktur, der thematischen Prototypenbildung und der strukturellen Funktion von Intensitätskonturen diskutiert.