Intensity and Cross-Dimensional Interaction in Music: Recent Research and its Implications for Performance Studies

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Abstract

This article surveys empirical and theoretical studies (including recent empirical studies by the author and associates), suggesting that intensity-based analogies linking different dimensions of audition are instrumental in music perception. Based on this research, the article then suggests several lines of empirical investigation into the roles of intensity-based analogies between musical dimensions in the *performance* of music.

Intensity and Intensity Contours

We perceive the world, music included, by distinguishing specific dimensions in separate sense modalities, such as pitch, loudness, and timbre in audition, or hue, lightness, and size in vision. However, we can also relate different sense modalities, or different dimensions within a single sensory mode, through a-modal percepts, such as temporal congruence or intensity.

Diverse stimuli in different sense modalities, such as visual brightness, muscular tension, tactile roughness, or auditory loudness, may be organized along a bipolar “quantitative” continuum, in which change in one direction (e.g., brightening, crescendo) is conceived as an increase, and change in the other (e.g., darkening, diminuendo) as a decrease. Such changes may be described in terms of intensity – as intensifications or abatements in the stimulus level. Physically, intensification is achieved by higher levels of energy, presumably coded at the neuronal level by an increase in overall discharge rates (e.g., Recce, 1999).[1] Perceptually, intensity is equated with changes in sensory magnitude (brighter light, louder sound, etc.).

The course of intensity changes over time creates *intensity contours*. At least conceptually, different sensory modes may present analogous intensity contours, associated through similar patterns of increase or decrease in magnitude or frequency: an auditory accelerando followed by ritardando is thus analogous to a gradual visual brightening followed by gradual darkening. Comparable analogies can be described for musical dimensions: a crescendo, an accelerando, and a pitch rise (among other dimensions), all intensify, while their opposites (diminuendo, ritardando, pitch fall) abate.

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Perceptual and cognitive studies of intensity-based equivalence

Cross-modal analogy

Experiments using different experimental paradigms suggest that intensity is a cross-dimensional quality. Cross-modally, it associates perceived magnitudes in different sensory modes (e.g., loudness and brightness). Unimodally, it associates different dimensions within the auditory mode (e.g., pitch and loudness).

Developmental studies suggest that intensity may be a primeval sensory dimension, preceding sensory specification in infancy. “The newborn perceives changes over space and time in the quantity of energy, not the sense through which it arose” (Maurer, 1993). Hence, “infants respond to stimuli as equivalent based on the degree of similarity of the stimuli with regard to their intensity: A bright light and a loud sound are responded to as similar, whereas a bright light and a dim light are responded to as different.” (Lewkowicz & Turkewitz, 1980). Infants indeed transfer habituation responses from visual brightness to auditory loudness (ibid.), and 3.5 year old children match auditory loudness and pitch to brightness (Marks, Hammeal & Bornstein, 1987). Coordinated intensity contours, matching changes in auditory dimensions (pitch and loudness) with analogous, concurrent changes touch and motion, are also important in infant-parent communication (e.g., Maurer 1993, Papousek 1996, Stern 1985, Sullivan & Horowitz 1983).

Though sensory discrimination is fully developed in adults, intensity analogies do affect adults’ perception as well. In his pioneering psychophysical experiments, S. S. Stevens asked adult subjects to match the perceived intensity in one dimension to that of another (e.g., alter the loudness of a sound until it matches a given visual brightness). Subjects easily and consistently matched intensity in one dimension to that of another (e.g., tactile force, loudness, visual brightness). Moreover, different dimensions across sensory modes conformed to a power function (Stevens's power law), such that a constant percentage increase in the stimulus magnitude produces a constant percentage increase in the perceived effect (Stevens, 1975).

Another experimental paradigm suggesting intensity-based analogies involves speeded classification: subjects are asked to rapidly classify values in one dimension (e.g, distinguish between a bright and dim light), while the values of a second dimension (e.g, loud and soft sound) are varied. For some dimensions (e.g., louder sound or higher pitch with brighter light), speed and accuracy of performance are enhanced if intensities in the two parameters concur, and hindered if parameters are incongruent (see Marks, 2004, for a summary).

Cross-dimensional effects on auditory perception

Different dimensions within the auditory domain can be conceived as increasing and decreasing in intensity. These may include dynamics (crescendo-diminuendo), tempo (accelerando-ritardando) or attack rate, pitch contour (rise-fall), as well as various types of event density, both temporal (progressive changes in the duration of events of a certain type), and "spatial" (e.g., the number of concurrent attacks). Studies based on diverse research paradigms suggest that some such dimensions are indeed perceptually and cognitively related through intensity analogies. Pitch, loudness, and timbre interact in speeded classification tasks (Melara & Marks, 1990a, b). For instance, congruence of pitch and loudness (higher pitch and louder intensity; lower pitch and softer intensity) results in faster pitch and loudness discrimination than non-congruence (higher pitch and softer intensity; lower pitch and louder intensity).

In a different line of research, intensity change in one auditory dimension created or enhanced a perception or illusion of corresponding changes in another. 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. Collier & Hubbard (2001) found an interaction between pitch and tempo: accelerations were perceived as faster in higher pitches, and decelerations perceived as slower in lower pitches. Correspondingly, Bond & Feldstein (1982) found that perceived speech rate is positively related to vocal frequency and intensity; they suggest that these perceptions stem from frequently experiencing such covariation in spontaneously occurring speech. Finally, note that ERP (Event-Related Potential) studies suggest that such perceptual correspondences may have a specific neural basis, as they indicate that the brain processes “abstract” intensity contours differently than the specific auditory stimuli that generate them (Paavilainen, Degerman, Takegata & Winkler, 2003).

A more complex interaction of musical dimensions, which may still be attributed to intensity analogies, is reported by Boltz (1998) with regard to pitch structure and tempo: tempi were perceived as slower when a melody contained larger melodic intervals and more changes in contour (as well as non-congruence between rhythmic and melodic accents). Thus, to be perceived as equivalent, tempo should accelerate as more contour changes, larger intervals, and more accentual non-congruence are introduced. Since these factors involve changes in the magnitude (intervals) and frequency (contour) of melodic change, they can be described as changes in melodic intensity.

Relevant studies by the author

Recent experiments by Eitan & Granot indicate that analogies of intensity contours associate auditory parameters in several musically meaningful realms, including the perception of musical motion, the perception of similarities and differences among musical figures, the perception of musical tempo, and assessing tension in music.

Eitan & Granot (2006) presented subjects with musical stimuli in which different musical dimensions either intensified (e.g., pitch rise, crescendo, accelerando) or abated, and asked them to imagine a moving human character, so that imagined motion would correspond to the music. Results indicate that intensity analogies between musical parameters affect their spatio-kinetic associations, as kinetic associations for one musical dimension “spill over” to another. For instance, both pitch descents and diminuendi evoke an image of spatial descent, and both accelerations and pitch rises are associated with speeding up of motion.

In a different experiment (Eitan & Granot, 2007), subjects were asked to rate the similarity between pairs of musical stimuli that were either congruent (e.g., pitch rise and crescendo) or incongruent (e.g., pitch fall and crescendo) in their intensity contours. Congruence of intensity contours resulted in greater perceived similarity between stimuli in different dimensions, including attack rate, pitch direction, and loudness, suggesting that these stimuli are perceived as analogous musical "gestures".

Interactions between attack rate, pitch direction, and loudness were also shown in two additional experiments, recently concluded. In one (Eitan & Granot, Manuscript in preparation a), subjects were asked to evaluate whether musical stimuli accelerate or decelerate. In fact, attack rate was isochronous in all stimuli, but other dimensions (e.g., loudness, pitch, textural density) increased or decreased. Subjects perceived crescendi, pitch rises, and increases in textural density as accelerating, and their opposites as decelerating, suggesting that intensity changes in non-temporal parameters may induce an illusion of analogous changes in tempo.[2]

Finally, Eitan & Granot (Manuscript in preparation, b), asked subjects to rate the degree of tension change in short musical stimuli that increased or decreased in tempo, pitch, or loudness, and their different combinations (e.g., an accelerating diminuendo, or a descending crescendo). In most cases, the relationships of intensity changes in different parameters to perceived tension were additive, such that adding one intensifying change to another (e.g., a crescendo and an accelerando) increased the degree of perceived tension, while combining an increase and a decrease in tension (e.g., a diminuendo and an accelerando) resulted in a lesser degree of perceived tension, "subtracting" the tension conveyed by one dimension from the detention conveyed by the other. This suggests that intensity changes in different parameters (e.g., accelerando, crescendo, and pitch rise) add up to a general percept of musical tension.

Two general points regarding Eitan & Granot's experiments above should be noted. First, three of these experiments used both parameters "naturally" encountered in extra-musical audition (like loudness or temporal density), and music-specific parameters, like tonal harmonic progression or melodic intervals. Decisively, "natural" auditory parameters were better associated with intensity than musically-specific parameters like harmony and melodic intervals. Second, differences between musically-trained and untrained participants were small in all four experiments. These findings both suggest that the main source of analogies of intensity contours is not music-specific experience and training, but general, extra-musical factors – either "natural," everyday auditory experience, or innate determinants.

Integrated intensities in music

The above studies suggest that cross-dimensional intensity contours may shape perceived musical structure and expression in meaningful ways. They may affect the sense of musical "motion" and continuity. They may affect the perception of similarity in music, and thus take part in shaping perceived motivic and thematic structure, or in constructing "gestures" typically associated with specific structural functions, such as transition or conclusion. Intensity-based analogies may also take part in the perception of musical style, by constructing gestures related to a specific style (e.g., progressively "stretching" values in different dimensions, a typical 19th century gesture; see Meyer, 1989). Perceived musical "spaces," such as tonal pitch space (Lerdahl, 2001), or contour space (Morris, 1987), may also be affected by cross-parametric intensity contours.

Indeed, studies of diverse musical repertories have revealed that structures that correlate congruent intensity changes in different parameters are common, and may serve important structural functions. Of these, the most important is perhaps the arched (convex) shape, in which a relatively long intensification, which may integrate various parameters (e.g., pitch contour, dynamics, textural and temporal density, or harmonic tension) is followed by abatement. Such structure, widely found in Western and other musics, is often associated with a progression of tension and release (Agawu, 1982; Berry, 1976; Cohen, 1971; Meyer, 1989).

Related manifestations of intensity correlations in musical repertories were found in several recent studies. Huron (1990a, 1990b, 1992) found that in 18th and 19th century repertories, dynamics, texture, and pitch contour all tend to build up gradually but subside quickly ("ramp archetype"). Hopkins (1990) shows that complex, multi-phased abatements correlating many musical dimensions characteristically lead to closure in Mahler's symphonies. Eitan's study of melodic peaks in Haydn, Chopin, and Berg (1997) indicates that such peaks (the highest tones in a piece or segments) tend to correlate with peaks of intensity in other dimensions, such as dynamics or the size of melodic intervals. Finally, Cohen, in a series of studies (e.g., Cohen, 1971; Cohen & Granot, 1995; Cohen & Wagner, 2000), 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. These studies, drawing on examples from diverse musical cultures, as well as from speech intonation, birdsong, and ERP studies, suggest that the expressive functions of these contrasting intensity shapes are innate and universal.[3]

Correlated intensities in music performance

How would intensity-based correlations of different musical dimensions, such as those reported above, affect the performance of music? One may examine such correlations in (at least) three different contexts. First, how different dimensions (such as duration and loudness) are associated in performing the various musical *accents* and emphases suggested by the score. Second, whether, within a grouping unit such as a phrase, the *contours* of different musical parameters (e.g., melodic contour and progressive tempo change) are correlated in performance. Third, examining whether the *overall level* in one parameter (e.g., pitch) affects that of another (e.g., tempo). Below, I survey some of the empirical studies examining such associations (for further discussion, see Gabrielsson 1999, 2003).

Accents. Different parameters correlate to enhance musical emphasis in performance. In emphasizing metrical downbeats, agogic, dynamic, and articulation (i.e., more legato) accents usually correlate (Sloboda 1983, 1985; Gabrielsson, 1974). Melodic accents (jumps and turns) involve increase in loudness (Drake & Palmer, 1993). Such correlations also affect memory for melody, as tunes are reconstructed most accurately when melodic, agogic, and dynamic accents coincide (Drake, Dowling & Palmer, 1991). Further-more, different parameters (duration, loudness, and articulation) sometimes substitute for one another in creating accent (Clarke, 1988). Correspondingly, Edlund (1994) found that articulation was used by harpsichord players to create emphasis where pianists used dynamics.

Contours. Experimental results and theoretical models suggest some correlation among different intensity contours (such as tempo and loudness change) in performance, and among such performed contours and facets of the written score, such as pitch contour or the progression of harmonic tension. However, such correlations are far from being simple or straightforward.

Some studies indeed indicate that tempo and loudness contours along a performed musical phrase correlate in both vocal (Gjerdingen, 1988) and instrumental (piano) performance (Gabrielsson, 1987; Palmer, 1996). Loudness was also shown to change congruently with pitch contour, both in classical singing (Gabrielsson & Johnson, 1985) and in piano playing (Gabrielsson, 1974). To account for such correspondences, Todd (1992) proposed a simple model relating tempo and loudness variations in performance to phrase structure. The model suggests that musical dynamics and tempo are coupled, such that “the faster the louder,” so creating together a compound “energy” profile. This profile (which, according to Todd, is also analogous to velocity change in physical movement) correlates with grouping structure, such that tempo and dynamics typically increase towards the middle of phrases and decrease toward their ends, creating an overall cross-dimensional curve. Note that since other (notated) aspects of musical intensity, such as pitch contour or harmonic tension, often create analogous curves, Todd’s model implicitly suggests correlation among intensity contours in several musical dimensions, both composed and performed, not only in tempo and loudness.

A number of experiments examining Todd's model indicate, however, that the simple "faster-louder, slower-softer" relationship he suggests does not adequately describe the actual relationship of tempo and dynamics along a performed musical phrase (Palmer, 1996; Windsor & Clarke, 1997; Repp, 1999; Clarke & Winsdor, 2000). Clarke & Winsdor (2000) suggest that such simple tempo-dynamics relationships may serve as a basis for idiosyncratic deviations in performance. These deviations, or "residuals," may be measured against the model's predictions, such that the model generates implications against which specific performances are assessed (see Palmer, 1997; Gabrielsson, 2003; Widmer & Werner, 2004, for discussions of alternative models of performance expression).

Relationships of parametric levels in performance

While the effect of (hypothetical) intensity analogies on the performance of accents and on performed tempo and dynamic contours has been investigated empirically, there is little direct research investigating how overall (or mean) level in one musical parameter affects that of another in performance. Some studies suggest that an integrated representation of dimensions such as loudness and tempo levels plays a significant part in assessing musical performance. Timmers (2005) found that a compound feature, integrating overall tempo and loudness, is significantly associated with listeners' ratings of similarity among different performances of the same music, while loudness *per se* was rarely significant as a separate feature. Do performers' choices of the level of a specific parameter, then, affect their choices in other parameters? For instance:

(1) How would changing the tempo affect a performer's choices of dynamics?

(2) How would a transposition, or choosing a different pitch level (e.g., A4=415 vs. A4=440) affect tempo?

(3) How would an instrument's loudness limitations affect the frequency of ornamentation (e.g., clavichord vs. pianoforte)?

(4) How would the choice of tempo affect ornamentation?

Comparable questions may address listeners' evaluation of performance. For instance, in assessing the most adequate tempo for a given music, would increasing the pitch level result in listeners' preference for a faster tempo? Would changing overall dynamic level affect listeners' tempo preference?

Two conflicting hypotheses may be proposed concerning such parametric correlations. A *congruence hypothesis* would suggest that changing the level of parameter x in a specific direction would affect parameter y in the same direction (e.g., a faster tempo would generate louder overall dynamics), thus creating congruent changes in overall intensity, comparable to those found for accentuation. In contrast, a *compensation hypothesis* would suggest that changing the level of parameter x in a specific direction would affect parameter y in the opposite direction (e.g., a faster tempo would generate a softer overall dynamics), so that overall intensity level would remain constant. Palmer (1997), summarizing results of several empirical studies (Drake, 1993; Drake & Palmer, 1993; Kurakata, Kuwano & Namba, 1993; Palmer, 1996), suggests that performed expressive deviations may compensate for modulations, engendered by musical structure, in perceptual sensitivity to temporal and intensity changes. For instance, performers instructed to play a sequence of tones with no change in intensity may play a note louder because in its context it is heard as softer. Thus, pianists played the second tone in each group louder (rather than the first, as expected), presumably to compensate for the higher perceived loudness of the preceding opening note (Kurakata, Kuwano & Namba, 1993). Similarly, when the perceived level of one parameter is affected by another (e.g. when, as Collier & Hubbard, 2001, indicate, perceived tempo change is modulated by pitch register) performers may compensate for the effect by altering values in the opposite direction (e.g., slowing down the pace of a melodic sequence when played a higher pitch register).

Note that in examining dimensional interaction in music performance, perceived values, rather than physical (acoustical) ones, are investigated. This distinction is important since perceived levels of auditory dimensions are often themselves affected by the interaction of several acoustic parameters. For instance, as is well known, the same sound-pressure level (in dB) may produce different levels of perceived loudness in different pitch registers (Fletcher & Munson, 1933). Such relationships should be controlled for (for instance, by using a relatively "flat" area of the equal-loudness curve) in experiments examining parametric interaction.

A tentative research plan

Below, I sketch some ideas for a research plan examining how changing the level of one musical parameter may affect that of another in performance. The proposed plan utilizes three experimental paradigms: analyzing relationships among parametric levels in recorded performances; controlling the level of a specific musical parameter in performance while examining the ensuing effect on the level of other parameters; and examining the effect of different interactions of parametric levels on listeners' evaluation of performed music.

Several musical parameters may be investigated in the proposed experiments. Most may serve (in different experiments) as both independent and dependent variables. These include overall (or mean) dynamic level, as well as the degree of dynamic variability; mean tempo, and the degree of tempo variability (rubato); overall or average pitch range; and the extent of using ornamentation (e.g., measuring the number of performer-added ornaments per unit of time).

Analyzing recorded performances. Recordings of the same piece of music may considerably differ in choices of overall tempo, dynamics, and even pitch level (as historically-informed performances often use pitch levels lower than the modern A4=440 standard). The availability of a large number of recordings of well-known compositions enables a statistically reliable examination of the relationships among performers' choices in these domains. For instance:

- Is the mean tempo of recordings using a lower pitch level different from that of recordings using higher pitch levels?
- Are recordings using a lower pitch level different from higher-pitched ones with regard to their average dynamics?[4]
- How does the choice of tempo relate to dynamics in recordings?
- How does tempo variability (the degree of rubato) relate to dynamic variability (the degree of dynamic contrast) in recordings?

Controlling a performance parameter. A different approach to examining how the level of one parameter affects those of others would involve controlling the level of a specific parameter in actual performance. In this line of experiments, a performer is asked to play the same piece several times, in several conditions. In each condition, the level of a specific parameter would be set differently. The effect of these alterations on other performance parameters will be examined. For instance:

- A violinist is asked to perform a piece for violin and keyboard several times, in different tempi (tempo is forced in each performance by a pre-recorded accompaniment). The average dynamic level and the degree of dynamic variability in the different tempi are compared.

- A keyboardist is asked to perform the same piece several times, in each of which the keyboard is tuned to a different pitch level. Average tempo, tempo variability, average dynamics, and dynamic variability in the different tunings are compared.

- A keyboardist is asked to perform the same piece several times on an electronic keyboard. Available dynamic range is set differently in each performance condition, ranging from normal range of a concert Steinway to disabling loudness variability completely, such that key velocity would not affect loudness. Tempo, tempo variability and ornamentation in the different loudness conditions are compared.

The piece performed in the experiments suggested above will not have been known by the performer prior to the experiments. Performances in each condition will be recorded and analyzed twice: first on sight reading, and then after several hours of practice.

The effect of relationships between parametric levels on listeners' evaluation of performance. In this line of experiments, listeners' ratings of performances, rather than the performance characteristics themselves, are the dependent variables. Listeners are presented with different manipulations of a given recording, each exhibiting a different interaction of two parameters (e.g., tempo and dynamics), and are asked to rate each recording (see Table 1). For instance, with dynamics and tempo as the manipulated musical variables, the compared recordings could be:

1. The original performance (tempo and dynamics freely selected by the performer).

2. A recording based on the same performance, with electronically increased dynamic level.

3. A recording based on the same performance, with electronically decreased dynamic level.

4. A recording based on the same performance, with electronically accelerated tempo.

5. A recording based on the same performance, with electronically accelerated tempo and increased dynamic level.

6. A recording based on the same performance, with electronically accelerated tempo and decreased dynamic level.

7. A recording based on the same performance, with electronically decelerated tempo.

8. A recording based on the same performance, with electronically decelerated tempo and increased dynamic level.

9. A recording based on the same performance, with electronically decelerated tempo and decreased dynamic level.

Table 1 summarizes these options, which could be similarly applied to other parameter pairs.

Parameter A	Parameter B
0	0
0	+
0	-
+	0
+	+
+	-
-	0
-	+
-	-

Table 1. Combinations of a parameter pair in performance rating experiments.
0: parameter unaltered (i.e., as set in original recording).
+: Parameter increased in comparison to original performance.
-: Parameter decreased in comparison to original performance.

Conclusions

Shaping musical intensity (or energy) in time is what performers do. Controlled empirical methods will enable us to understand better how performers associate different musical dimensions in their search of an appropriate intensity levels and shapes. This article surveyed what such empirical investigations have yielded so far, and sketched several experimental paradigms enabling further investigation. In particular, we proposed an empirical approach into a basic issue which has not been sufficiently explored:

how the overall level of one musical parameter affects those of others. We suggest that interrelationships among dimensions such as mean tempo, loudness, and pitch register may play a significant role in performers' decisions and in the evaluation of music performances by listeners. The experimental paradigms outlined here may help investigating this suggesting, and provide insights into the ways the elusive dimension of intensity or musical "energy" is created and recreated in music performance.

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[1] . Increase in discharge rates may not be the only mechanism for representing changes in intensity (e.g., Polley et al., 2004).

[2] . Boltz (manuscript in preparation) reports a related recent experiment. Using a paired comparison task, she found that when two melodies having the same tempo differ in pitch level or timbre, the one higher in pitch or timbre would be judged faster.

[3] . Models explaining aspects of musical structure in terms of overall processes of intensification and abatement integrating different musical parameters were suggested by several music theorists, including Kurth (see 1991), Berry (1976), Meyer (1989) and Rink (1999), as well as by neuropsychologist Neil Todd (1992, 1999). For surveys of such approaches, see Eitan & Granot (2006, in press), and Shove & Repp (1995).

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[4] . Comparing measurements of dynamics in different sound recording raises complex methodological and technical issues. For examples and discussions of relevant methodologies see, e.g., Repp (1999) and Timmers (2005).