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ILLUSORY TEMPO CHANGES DUE TO MUSICAL CHARACTERISTICS

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RECENT RESEARCH IN MUSIC COGNITION HAS investigated ways in which different structural dimensions interact to influence perception and cognition. In the present research, various musical characteristics were manipulated to observe their potential influence on perceived tempo. In Experiment 1, participants were given a paired comparison task in which music-like patterns differed in both the pitch octave (high vs. low) and timbre (bright vs. dull) in which they were played. The results indicated that relative to their standard referents, comparison melodies were judged faster when displaying a higher pitch and/or a brighter timbre—even when no actual tempo differences existed. Experiment 2 converged on these findings by demonstrating that the perceived tempo of a melody was judged faster when it increased in pitch and/or loudness over time. These results are suggested to stem from an overgeneralization of certain structural correlations within the natural environment that, in turn, has implications for both musical performance and the processing of tempo information.

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THERE ARE MANY QUALITIES THAT DISTINGUISH a mediocre from a masterful musician, but one is the expressiveness with which a composition is performed. Expressiveness refers to performance aspects beyond those specified by a musical score and contributes to the emotional meaning of the composition and what an audience feels as they listen. It includes dynamics (the relative intensity of different notes), articulation (the attack of notes and the way in which they transition), and the dimension of interest here, tempo or the overall rate at which a piece is performed. As noted by several researchers (e.g., Juslin, 1997; Scherer & Oshinsky, 1977), tempo is often the strongest determinant of emotional affect in the auditory modality. The question

addressed in the present research is whether the perceived tempo of musical sequences is influenced by factors other than the actual tempo produced by a performer. In particular, two experiments examine the potential impact of pitch, timbre, and loudness on the perceived rate at which musical sequences unfold.

Interactive Dimensions

This set of manipulations raises more general questions about the multidimensional nature of music. In studying how people perceive and apprehend music, the traditional methodological strategy has been to systematically manipulate one dimension while holding all others constant which, in turn, confers a high degree of experimental control and internal validity. However, more recent research has sought greater ecological validity by investigating how various combinations of musical dimensions may interact to influence perception and cognition (see Neuhoff, 2004; Prince, Thompson, & Schmuckler, 2009 for reviews). The strategy typically used with this goal in mind is to present stimuli that vary along two or more dimensions and ask participants to make judgments on one dimension while ignoring the other(s). The reasoning is that if the unattended dimension influences the attended one, the two are interactive. Conversely, null effects would suggest that the dimensions are perceptually independent of one another.

Several auditory dimensions have been found to reliably interact with one another. Perhaps the most well documented of these is the interaction between pitch and loudness as exemplified in a study by Neuhoff, McBeath, and Wanzie (1999). Within a dichotic listening paradigm, participants were presented with continuous tones that increased, decreased, or displayed a constant pitch frequency over time, and that also increased, decreased, or displayed a constant intensity over time. When participants were asked to track the magnitude of loudness changes while ignoring pitch, it was found that perceived intensity varied with pitch: high frequency tones were judged higher in intensity even though no such increase occurred. The reverse effect was observed when participants tracked pitch changes over time while ignoring intensity: as intensity increased, participants

reported a higher pitch. Similar results have been observed by others. Repp (1995) has found that in both music and speech, listeners expect melodic lines that rise in frequency to also rise in intensity. In the context of musical performance, rising and falling pitches enhance the impressions of crescendos and decrescendos, respectively (Nakamura, 1987). This interaction between pitch and loudness also contributes to the Doppler illusion: although a sound source traveling at a constant velocity will actually decrease in pitch as it approaches, an illusory *pitch increase* is heard due to increased intensity changes over time (Neuhoff & McBeath, 1996). As Neuhoff (2004) points out, many sounds in the auditory environment (i.e., speech, music, animal calls, mechanical sounds) display an inherent covariation in frequency and intensity that affords multiple opportunities in which to learn this relationship. Hence, when one dimension increases or decreases while the other is held constant, listeners will hear illusory increases or decreases in the second dimension that do not physically exist but are perceptually imposed to confirm one's learned expectations.

In addition to pitch and intensity, other acoustical dimensions have been found to interact, including ones involving temporal and non-temporal information. The relationship between pitch and rhythm has been well investigated and shown that pitch intervals are better recognized when they are rhythmically accented vs. unaccented (Jones, Boltz, & Kidd, 1982). Relatedly, a given melody is more difficult to recognize when it occurs in a different vs. the same rhythm (Jones, Summerell, & Marshburn, 1987). Tekman has conducted a number of studies on the acoustical correlates of musical accents and found that interonset intervals (IOI's) are misperceived as longer when they precede notes with a higher intensity and, conversely, notes are misperceived as louder when following longer IOI's (Tekman, 1997). As a set, then, the research on interactive dimensions indicates that music perception can be biased by certain natural covariations that occur in the auditory environment.

Tempo Perception

The dimension of interest here is tempo and its potential interaction with other musical qualities. Music, as well as other naturally occurring sounds, displays a recurrent sequence of beats arising from event markers (i.e., pitch frequencies) and the number of such beats per unit time (i.e., typically a minute) is referred to as "tempo." It is the underlying pulse rate of a tune. For a performer, tempo changes are a primary means through which to convey different moods and emotions within a composition (Gabrielsson, 1995; Juslin, 2001). It is also a dimension

that is well preserved in memory (Boltz, 2010; Clynes & Walker, 1986; Halpern, 1987; Levitin & Cook, 1996), enabling one to skillfully produce a melody and coordinate one's performance with that of others. From a listener's perspective, one must be able to effectively perceive tempo in order to fully appreciate the nuances of musical expression. A number of studies have shown that even nonmusicians have this ability and are able to tap in synchrony with a melody's sequence of beats at a high degree of accuracy and low variability (Brodsky, 2005; Dixon, Goebel, & Cambouropoulos, 2006; Repp, 2005). This skill persists in the presence of large tempo fluctuations (Drake, Penel, & Bigand, 2000; Large, Fink, & Kelso, 2002; Rankin, Large, & Fink, 2009; Repp & Keller, 2004) and, in fact, listeners are often able to predict tempo changes in advance on the basis of melodic phrase structure (Repp, 2002, 2005). Others have investigated how much of a change must occur (i.e., the just noticeable difference or jnd) for tempo discrimination. Participants are typically asked to make same/different judgments in a paired comparison task or, alternatively, to monitor the ongoing tempo changes of a melody through a sliding potentiometer. Across different studies, the results have shown that the jnd value ranges between 2% and 13% (e.g., Drake & Botte, 1993; Ellis, 1991; Friberg & Sundberg, 1995; Miller & McAuley, 2005; Povel, 1981) and depends on a number of contextual factors, including melody length (e.g., Drake & Botte, 1993; Miller & McAuley, 2005), base tempo (McAuley & Kidd, 1998; Vos, van Assen, & Franck, 1997), and the global temporal context of the experimental session (Jones & McAuley, 2005).

Of greater relevance to the present research are studies demonstrating that various types of melodic properties can enhance the perceived tempo of music and, indeed, lead to perceived accelerations and decelerations that are not physically present. One such factor is melodic complexity. Kuhn (1987) found that "ornamented" melodies (containing passing tones, upper and lower neighboring tones, and arpeggiated figures in addition to a basic melodic line) were judged as faster than "plain" melodies (with the basic melodic line alone), even though both tunes actually had the same tempo. Because relatively more melodic activity occurred per unit time, the former thereby seemed accelerated relative to the latter. Articulation style also exerts an influence in that staccato passages are judged faster than legato ones (Geringer & Madsen, 2006). A third set of factors involves changes in pitch intervals as they unfold over time (Boltz, 1998). This study relied on a paired comparison task in which melodies within a pair not only varied in tempo but number of contour changes (i.e., shifts in pitch direction) as well as the magnitude of pitch changes that

appeared at group boundaries. The main finding was that even in the same tempo condition in which no actual tempo differences occurred, those melodies containing larger pitch skips and/or more contour changes were judged significantly slower than their respective referents. A second study revealed that rhythm also exerts an influence on tempo perception. Melodies containing a temporal accent structure that conflicts with the arrangement of melodic accents are judged significantly slower than those displaying compatible accent structures. This latter effect has been reported by others (Drake & Botte, 1993; Wang, 1984) who have found that melodies with irregular rhythms are perceived as slower than those with regular rhythms.

These overall results can be attributed to correlated structural dimensions that involve the type of melodic/temporal accent structure typically found within Western music. In most cases, melodic accents, which can arise from contour changes or large pitch skips, are temporally accented through both ritards (i.e., decelerations in tempo) and prolonged durations (Benjamin, 1984; Berry, 1976; Jones, 1987; Lerdahl & Jackendoff, 1983; Todd, 1985). Given that compatible accent structures characterize much of Western music, people eventually learn this relationship and expect it to occur in future encounters with music. Hence, if temporal accents are physically absent at melodic accent points, listeners may nonetheless perceptually impose their presence—meaning that melodies with larger pitch skips and/or more contour changes will seem slower. Similarly, melodies with incompatible rhythms should seem slower than those with compatible accent structures if listeners impose temporal accents on melodic accent points that are temporally unaccented. Both of these effects were in fact observed.

Experiment 1

The purpose of the present research is to extend this previous work by examining some additional musical qualities that may influence perceived tempo. They too involve structural correlations frequently found in the auditory environment but ones unrelated to accent structures. The first is pitch level and whether melodies are heard in a low vs. high octave. Several researchers have noted that pitch, loudness, and tempo are often reliably correlated with one another in both speech and music (e.g., Eitan & Granot, 2006; Eitan & Timmers, 2010; Friberg, Bresin, & Sundberg, 2006; Granot & Eitan, 2011; Tamir, 2008). Black (1961), for example, instructed participants to articulate various speech phrases at a loud vs. soft vocal level. When these utterances were later acoustically analyzed, it was found that louder utterances were accompa-

nied by a higher fundamental frequency and faster tempo while softer utterances were slower and lower in pitch. Similarly, in the realm of music, ratings of individual tonal sequences reveal that those that are higher and/or ascending in pitch are characterized as happy, bright, and fast. Conversely, sequences that are lower and/or descending in pitch are judged to have the opposite set of characteristics (Collier & Hubbard, 2001).

These types of findings are typically attributed to differential amounts of energy expended in sound production. Decreased energy accompanying lower states of arousal will result in decreased amplitude, pitch, and tempo; as energy and arousal increase, so do values along these acoustical dimensions. Given this inherent covariation, perceived tempo differences may emerge in auditory events that differ in pitch and/or loudness but actually have the same tempo.

One goal of Experiment 1 was to investigate this hypothesis in the context of a paired comparison task. Music-like sequences, each containing 24 notes, were generated from a set of mathematical rules to achieve rigorous experimental control. The number of contour changes varied across melodies for purposes of generality but within a given pair, the standard and comparison always contained an identical number of contour changes. Given that there were negligible pitch skips and a control for contour changes, any apparent melodic accents were minimalized. Temporal accents were absent in that all melodies contained an isochronous rhythm.

The main manipulation was the relative pitch level of standard and comparison melodies. Melodies within a pair were either played in the same (low-low; high-high) or different (low-high; high-low) octaves. The actual tempo of melodies was also varied. In half of the melodic pairs, the comparison displayed a tempo that was identical to the standard while in the remainder, a tempo that was 8% faster or slower than the standard. The prediction was that across all tempo conditions, including the same one, comparison melodies with a higher pitch should seem faster than those with a lower pitch.

The final manipulation was timbre. Timbre can be characterized by a number of acoustical characteristics (Grey, 1977; McAdams, Winsberg, Donnadieu, DeSoete, & Krimphoff, 1995) but, in general, it refers to the sound quality that distinguishes one musical instrument from another (e.g., a trumpet vs. clarinet). Timbre and pitch differ from one another in that the latter refers to the periodicity of sound production as assessed by its fundamental frequency, while timbre is often characterized by the distribution of amplitude across the frequency spectrum for a given sound. Some instruments (e.g., trumpet) display a greater amplitude that's weighted toward the high frequency

partials within the spectrum and therefore sound “bright.” In other instruments (e.g., French horn), higher amplitudes are weighted toward the low frequency partials within the spectrum and therefore sound “dull.”

Several studies have demonstrated that pitch and timbre are interactive dimensions in that variations in timbre influence pitch judgments and vice versa. Brighter timbres are correlated with higher pitches and duller timbres with lower pitches that, in turn, facilitate performance on speeded classification tasks (Krumhansl & Iverson, 1992; Melara & Marks, 1990; Pitt, 1994). In musical performance, wind instrumentalists play higher notes when matching bright timbres but lower notes when matching dull timbres (Worthy, 2000). Given the correlation between pitch and timbre and that between pitch and tempo, melodies produced by brighter instruments may be perceived as faster than the same melodies produced by duller instruments. Collier and Hubbard (2001) found some support for this idea in that faster tonal sequences were rated as brighter. Experiment 1 assesses this issue more directly by examining the effects of timbre variations on perceived tempo within a paired comparison task. In addition to the pitch level and tempo, standard and comparison melodies within a pair either displayed the same (bright-bright; dull-dull) or different (bright-dull; dull-bright) timbres.

Method

Participants

Thirty-six students from an Introductory Psychology course at Haverford College participated in the experiment for course credit. The majority of these were nonmusicians: although a small percentage (8%) were members of the campus choir, none were currently playing or had played a musical instrument within the past three years.

Stimulus Materials

A total of six tonal sequences, each containing 24 tones, were constructed with two goals in mind. First, given that most participants were nonmusicians, all sequences were designed to be simplistic ones in which the pattern of pitch movement over time was highly predictable. Second, the magnitude of pitch skips within a tune has been found to influence tempo judgments (Boltz, 1998) and so this factor was held constant by minimizing the interval size distance between successive notes. With these constraints in mind, consider the set of tunes depicted in Figure 1. The first two sequences eliminated pitch interval differences entirely in that they were monotonic and displayed a single repetitive note (C and G, respectively).

Figure 1 displays six musical patterns in 3/4 time, each consisting of 24 notes arranged in eight groups of three notes. The patterns are categorized by the number of contour changes:

- Zero Contour Changes (Monotonic C notes)
- Zero Contour Changes (Monotonic G notes)
- One Contour Change (C, D, E, F, G, A, B, C, D, E, F, G, A, B, C, D, E, F, G, A, B, C)
- Three Contour Changes (C, D, E, F, G, A, B, C, D, E, F, G, A, B, C, D, E, F, G, A, B, C)
- Five Contour Changes (C, D, E, F, G, A, B, C, D, E, F, G, A, B, C, D, E, F, G, A, B, C)
- Seven Contour Changes (C, D, E, F, G, A, B, C, D, E, F, G, A, B, C, D, E, F, G, A, B, C)

FIGURE 1. The set of musical patterns used in Experiment 1. All melodies are generated from the *next* rule within the dihedral symmetry group, D₇, and contain 24 notes arranged into eight sets of three-tone groups. Notes within a group (demarcated by bar lines) are related by adjacent scale steps (N⁺¹) while those between groups display a relatively small pitch skip (N⁺¹ or N⁺²).

The remaining four sequences were adopted from the “small pitch skip condition” of Boltz (1998) and each displayed eight three-tone groups (demarcated by bar lines) based on the C major diatonic scale. They had been generated from a recursive rule system often found in Western music; namely, the *next* (N) rule within the dihedral symmetry group of Order 7 (D_7) (Budden, 1972; Hahn & Jones, 1981; Jones, 1981). As seen in Figure 1, notes within a group were always related by adjacent scale steps (N^{+1} rule). However, notes between groups were separated by 1 or 2 scale steps (N^{+1} or N^{+2} rules) that resulted in a negligible pitch skip. For purposes of generality, the four melodies varied in their respective number of contour changes (i.e., one, three, five, or seven changes in pitch direction). This method of tune generation is advantageous in that it yields a hierarchical sequence in which both adjacent and nonadjacent notes are interrelated. Moreover, the second half of the melody is the inverse of the first half, resulting in an overall melodic contour that’s symmetrical in nature. The unfolding sequence of pitch movement is therefore a highly predictable one that, on a behavioral level, has been found to facilitate attentional tracking, learning, and memory (e.g., Boltz & Jones, 1986).

For the paired comparison task, tonal sequences were paired and arranged into two randomized orders of 192 trials. Melodies within a pair always contained the same number of contour changes but varied from one another in terms of their pitch level and timbre. For the pitch manipulation, the standard and comparison were either played in the same pitch octave (low-low; high-high) or a different pitch octave (low-high; high-low). Those sequences displaying a low pitch always began on C in the third octave while those displaying a high pitch always began on C in the fifth octave. The timbre manipulation consisted of standard and comparison melodies that displayed either the same (dull-dull; bright-bright) or different (bright-dull; dull-bright) timbres. The instruments used in this experiment were ones that have previously been observed to display a bright (trumpet, oboe, alto sax) vs. dull (French horn, bass clarinet, tenor sax) timbre and are relatively easy to discriminate from one another (Grey, 1977, 1978; McAdams et al, 1995). All were from the same instrument class (i.e., winds) and displayed relatively rapid attack and decay times, as determined from the parameter functions of the FM tone synthesizer used to generate the stimuli. In order to validate the brightness manipulation, a digitally synthesized note (middle C) from each instrument was acoustically analyzed via PsySound (Cabrera, 1999). A frequency spectra analysis confirmed that the spectral centroid (f_c or the amplitude-weighted mean of the frequency spectrum) was higher for the brighter instruments than the

duller ones such that energy in the former was weighted toward the higher partials and toward the lower partials for the latter. On average, f_c was approximately a perfect fifth higher for the brighter instruments than the duller ones. In the paired comparison task, melodic pairs displaying a different timbre were of three types; namely, the trumpet paired with the French horn, the oboe paired with the bass clarinet, and the alto sax paired with the tenor sax. In pairs displaying the same timbre, the standard and comparison melodies were both played with the same instrument.

Lastly, melodies within a pair always displayed an isochronous rhythm and one of two base rates. In one, the stimulus onset asynchrony (SOA) value for all notes was 375 ms (250 ms on-time and 125 ms off-time), which yielded a total melody duration of 9 s. In the second, the SOA value was 450 ms (300 ms on-time and 150 ms off-time) to yield a total duration of 10.8 s. Within a pair, the comparison melody contained either the same base tempo as the standard or a tempo that was 8% faster or slower than the SOA of the base value. This transformation preserved the original ratio of on- to off-times and is based on past literature (Drake & Botte, 1993) that suggests that an 8% change should be sufficient for discriminability.

Two randomized orders of 192 trials were constructed. Within each order, 50% ($n = 96$) of the trials consisted of melodic pairs with the same tempo, 25% ($n = 48$) with comparison melodies faster than their standards, and 25% ($n = 48$) with comparisons slower than their standards. Within the same tempo condition, each of the 16 experimental manipulations (4 pitch pairs \times 4 timbre pairs) occurred on six occasions, once with each of the six melodies that was heard in the context of a given instrument pair and one of the two base rates. On the different tempo trials, 3 of the 6 melodies reflecting the 16 pitch \times timbre pairs were assigned to the slower tempo condition and the remaining three to the faster tempo condition. Within each order, the two base rates and various instrument pairs appeared an equal number of times and were evenly distributed across all melodies and experimental conditions. Across the two randomized orders, all melodies were presented in the context of a different instrument pair and base rate, and the three melodies assigned to the faster condition in order one were now assigned to the slower condition in order two, and vice versa.

Apparatus

The Midilab software system, developed by Todd, Boltz, and Jones (1989), was used to construct the set of tonal sequences and arrange them within a given randomized

order for the paired comparison task. The set of instruments used to instantiate the timbre manipulation was obtained from a pre-stored menu of instrument options on a Yamaha TX81Z FM tone generator.

During an experimental session, melodies were played online by the Yamaha tone generator controlled by an IBM AT computer with a Roland MPU-401 MIDI interface unit. Sequences of tones were amplified by a Kenwood KR-A4010 receiver and binaurally presented over Koss Pro 4AAA Plus headphones. All tunes were played at 65 dB SPL which, despite variations in pitch octave and timbre, should appear equivalent in amplitude according to published norms for equal-loudness contours (e.g., Suzuki & Takeshima, 2004). This, in fact, was confirmed through a pretest on eight individual participants.

Procedure

Eighteen participants were randomly assigned to one of the two randomized orders and were tested over a two-day period in small groups of two to four individuals. On the first day, recorded instructions related the presentation details and task requirements. On each trial, a 1 s warning tone (C in the seventh octave) preceded the standard melody of a pair by 2 s. Three seconds after the offset of the standard, the comparison melody was played. During the 5 s response period that followed, the participants were asked to judge the apparent tempo of the comparison melody relative to that of the standard on a 7 point scale (i.e., -3 = much slower; 0 = same tempo; and $+3$ = much faster). They were told that melodies within a pair could vary in their pitch characteristics and the instruments in which they were played but to ignore these differences and focus on tempo alone. These judgments were made on a response console and were automatically recorded by the computer. The procedure for the second day was identical to that of the first except instead of receiving the full set of instructions,

participants were simply reminded of their rating task. On each day, participants received four practice trials followed by a set of 96 experimental trials, with a brief rest break after the first 48 trials.

Results

An initial analysis of variance (ANOVA) indicated there were no significant effects of counterbalance order, melodic instance, instrument pair, or base tempo; the data were therefore collapsed over these variables. The resulting statistical design was a $3 \times 4 \times 4$ repeated measures factorial with three independent variables: tempo (same, faster, slower); pitch pairs (low-low; high-high; low-high; high-low); and timbre pairs (dull-dull; bright-bright; dull-bright; bright-dull). When significant differences emerged, pairwise comparisons were examined through a set of Tukey HSD tests in which p was set to .05.

The overall ANOVA revealed several significant effects. First, there was a main effect of pitch pairs, $F(3, 105) = 15.05$, $p < .001$, shown in the column means of Table 1. Across all conditions of the experiment, comparison melodies containing a higher pitch than the standard were judged significantly faster ($M = 0.64$) than pairings containing a comparable level of pitch ($M = -0.02$ for low-low; $M = -0.06$ for high-high). Conversely, comparisons with a relatively lower pitch than the standard were judged significantly slower ($M = -0.55$) than same pitch pairs.

Second, tempo ratings varied due to a significant main effect of timbre pairs, $F(3, 105) = 8.01$, $p < .01$, shown in the row means of Table 1. Relative to melodic pairs containing the same timbre ($M = 0.01$ for dull-dull; $M = 0.03$ for bright-bright), comparison melodies with a brighter timbre than the standard were judged significantly faster ($M = 0.35$). In contrast, comparison melodies played with a duller timbre than the standard were judged significantly slower ($M = -0.38$).

TABLE 1. Mean Tempo Ratings in Experiment 1 as a Function of the Timbre and Pitch Level Within Standard and Comparison Melodies.

Timbre Pairs	Pitch Pairs				Means
	Low-Low	High-High	High-Low	Low-High	
Dull-Dull	-0.02	-0.03	-0.47	0.54	0.01
Bright-Bright	0	0.01	-0.55	0.68	0.03
Bright-Dull	-0.36	-0.47	-0.97	0.28	-0.38
Dull-Bright	0.29	0.26	-0.21	1.05	0.35
Means	-0.02	-0.06	-0.55	0.64	

Note: Relative to a value of 0 indicating a same tempo judgment, positive values indicate that the comparison was judged faster than the standard while negative values indicate that the comparison was judged slower.

Pitch and timbre also interacted with one another, $F(9, 315) = 11.75, p < .001$, an effect that occurred in each of the three tempo conditions. In the first two rows of Table 1, which depicts melodic pairs containing the same timbre, the main effect of pitch pairs is observed. Relative to pairs with the same pitch, low pitch sequences seem slower in contrast to high pitch ones, and vice versa. Similarly, as seen in the first two columns of Table 1, the main effect of timbre is observed within same pitch pairs. Relative to pairs with the same timbre, duller instruments seem slower in contrast to brighter ones, and vice versa. The source of the interaction lies within the remaining four conditions; namely, those in which *both* pitch and timbre vary within a pair. There are two findings of note. First, congruent pairs (i.e., high/bright—low/dull, and the reverse) produced additive effects in that these pairs were perceived significantly slower ($M = -0.97$) and faster ($M = 1.05$), respectively, than pairs in which one dimension alone (pitch or timbre) varied while the other was held constant.

The second finding, involving incongruent pairs, suggested that pitch had a greater impact on perceptual ratings than timbre. For example, one might expect low/bright—high/dull pairs to yield effects that cancel one another out (i.e., yield same tempo ratings). Nonetheless, the overall rating is positive (i.e., “faster”) and significantly above zero ($M = 0.28$), indicating that participants were more influenced by a comparison melody’s pitch than timbre. A similar phenomenon occurred with high/dull—low/bright pairs. Here, the overall rating is negative (i.e., “slower”) and significantly below zero ($M = -0.21$), once again illustrating that a comparison’s pitch had a greater impact than timbre.

Lastly, there was a main effect of tempo, $F(2, 70) = 28.65, p < .01$, in which, relative to the same tempo condition, comparison melodies that were actually faster or slower than the standard were, in fact, perceived as such.

In order to assess the generality of these overall findings, a secondary analysis examined the number of participants whose tempo judgments were influenced by the experimental manipulations. Here, the percentage of participants responding “same,” “slower,” and “faster” was determined for each pitch x timbre condition within those melodic pairs containing equivalent tempi. These are shown in Table 2. The same tempo condition was selected for this analysis because any differences in perceived tempo can be attributed to the effects of pitch and timbre alone.

These data were evaluated through a variant of the chi-square analysis; namely, a multidimensional McNemar test that assesses categorical responses for a set of repeated measures variables. As before, the effects of pitch, timbre, and their interaction were all significant

TABLE 2. Percentage of Participants Responding “Same,” “Faster,” and “Slower” Within the Same Tempo Condition of Experiment 1 as a Function of Variations in the Octave Pitch Level and Timbre Between Standard and Comparison Melodies.

Pitch Level	Participants’ Responses		
	“Same”	“Faster”	“Slower”
LOW-LOW			
Dull-Dull Timbre	100	0	0
Bright-Bright Timbre	97	3	0
Dull-Bright Timbre	53	41	6
Bright-Dull Timbre	56	3	41
HIGH-HIGH			
Dull-Dull Timbre	94	3	3
Bright-Bright Timbre	100	0	0
Dull-Bright Timbre	50	44	6
Bright-Dull Timbre	56	6	38
LOW-HIGH			
Dull-Dull Timbre	42	55	3
Bright-Bright Timbre	39	55	6
Dull-Bright Timbre	25	75	0
Bright-Dull Timbre	53	36	11
HIGH-LOW			
Dull-Dull Timbre	50	8	42
Bright-Bright Timbre	42	6	52
Dull-Bright Timbre	58	11	31
Bright-Dull Timbre	39	0	61

($N = 36, p < .001$ for each) and, as revealed here, applied to a high percentage of participants. First, consider the top half of the table in which the pitch level of standard and comparison melodies is comparable (i.e., low-low; high-high). Between 94 to 100% of the participants correctly judged melodies as equivalent in tempo when their timbre was also equivalent. However, relative to these conditions, a significantly higher percentage of participants produced “slower” responses when comparisons displayed a relatively duller timbre than their standard ($M = 39.5\%$), and “faster” responses when the timbre of the comparison was brighter ($M = 42.5\%$).

The lower half of Table 1 indicates that responses were also influenced by variations in pitch level. Comparison melodies with a higher pitch than the standard yielded a high percentage of “faster” responses when timbre was comparable within a pair (55%), and an even greater percentage when timbre was also brighter than the standard (75%). Conversely, a high percentage of “slower” responses was produced when comparison melodies were relatively lower in pitch ($M = 47\%$), especially when timbre was also duller ($M = 61\%$). Lastly, the data once again reveal that pitch exerted a greater impact than timbre upon perceived tempo. Comparisons displaying a

duller timbre but a higher pitch were more apt to yield “faster” responses (36%) than “slower” ones (11%). In contrast, the reverse applied with comparisons that were relatively brighter in timbre but lower in pitch. Here, “slower” responses (31%) were more frequent than “faster” ones (11%).

Discussion

The primary finding from this first experiment is that changes in pitch level and timbre influenced the perceived tempo of a melody. Those melodies played in a higher octave or brighter timbre were perceived to unfold more quickly than those played in a lower octave or duller timbre. Conversely, the opposite pattern of results was observed when the temporal ordering of these pairs was reversed. Lastly, octave pitch and timbre exerted additive effects upon one another. Relative to the presence of one factor alone, tempo ratings were enhanced when both dimensions increased or decreased in tandem with one another.

These effects were relatively small but highly reliable ones that generalized across different base tempi, melodies with a varying number of contour changes including monophonic ones, instruments with different timbres, and melodies with both null and actual tempo differences. The same tempo condition of this experiment was the most compelling because even though no actual tempo differences existed, a high percentage of listeners nonetheless perceived such changes in the presence of pitch and timbre variations.

These results are also consistent with related research in the past literature. In the ratings of individual melodies, recall that Collier and Hubbard (2001) found that melodies higher and/or ascending in pitch were judged faster while those lower and/or descending in pitch were judged slower—an effect replicated here in the context of a paired comparison task. Another study in the realm of music assessed listeners’ ability to simultaneously detect changes in pitch and changes in tempo that appeared in excerpts from orchestral arrangements (Geringer & Madsen, 1984). The results showed that when pitch was unaltered, people were relatively poor in discriminating tempo changes. However, performance markedly improved when pitch increased or decreased, especially when detecting tempo accelerations and decelerations, respectively. Similarly, pitch changes were better detected when tempo changed in the same direction as pitch. Lastly, Feldstein and Bond (1981) conducted a study in which participants were asked to make tempo judgments of paired speech samples that were identical in rate but different in pitch and intensity. Illusory tempo

changes were observed such that increases in both pitch and loudness led to perceptions of faster tempi. Thus, the interactive relationship between pitch and tempo appears to generalize across different types of auditory events.

Here, it is argued that these effects stem from the inherent covariation between certain structural dimensions within the auditory environment. In both music and speech, decreased energy states are characterized by lower amplitudes, lower pitch frequencies, and slower tempi (e.g., Black, 1961). This is perhaps most obvious in the expression of different emotions across different stimulus domains. For example, Gabrielsson (1995) asked flutists and violinists to interpret the same piece of music with different emotional tones. Performances reflecting happiness were played with greater dynamics, faster tempi, and in higher octaves. Analogous findings have been observed when actors are asked to read the same speech passage with different emotional interpretations (e.g., Williams & Stevens, 1979). Given this lawful covariation across different types of auditory events, there are ample opportunities to learn the relationship between pitch and tempo and eventually come to expect their copresence in any future encounters. Hence, when one hears variations in pitch qualities alone, corresponding tempo changes are perceived, even when no such changes are physically present.

Unlike pitch height, timbre has not been reported as a dimension that covaries with tempo. Nonetheless, timbre interacts with pitch in that higher and lower pitches are associated with brighter and duller timbres, respectively, and variations in one dimension influence perceptual judgments of the other (Krumhansl & Iverson, 1992; Melara & Marks, 1990; Pitt, 1994). Moreover, from an acoustical perspective, brighter and duller timbres are characterized by a greater amplitude toward higher and lower partials, respectively, within the frequency spectrum. Through its strong relationship to pitch, variations in timbre appear to exert a similar effect on perceived tempo as do variations in pitch.

Although pitch level and timbre both influenced perceived tempo, octave differences exerted a greater effect than timbre: when the two dimensions conflicted with one another (i.e., lower octave but a brighter timbre, or vice versa), listeners’ ratings were more biased by octave differences. If the effect of timbre on perceived tempo primarily stems from its relationship with pitch, then one would, in fact, expect a greater effect of pitch vs. timbre on behavior. However, a second possibility is that the finding is a methodological artifact of the experimental manipulations. Given the multidimensional nature of timbre, it is difficult to equate the magnitude

of timbre differences with that of octave differences; the latter may have been acoustically more salient to listeners and thereby exerted a greater effect. A third possibility is that melodic pairs displaying pitch octave vs. timbre transformations appeared more similar to one another such that tempo changes were more obvious. Recall that melodies within a pair always displayed the same sequence of notes and were, in fact, the same melodies. This may be more apparent when melodies are played by the same instrument but in different octaves, than when performed in the same octave but by different instruments. Some support for this idea has been reported in the past literature (Beal, 1985; Crowder, 1989; Krumhansl & Iverson, 1992). Beal (1985), for example, found that participants can more quickly and accurately decide whether two chords are the same when both have the same vs. different timbres. With respect to the present experiment, melodic pairs with different timbres may appear to vary in multiple ways such that tempo differences are less obvious. Future research is needed to disentangle these various possibilities to determine which are responsible for the observed effects.

Experiment 2

Experiment 2 was designed to both converge upon and extend the findings of Experiment 1. In the auditory environment, different melodic lines not only occur within different octaves but, just as commonly, pitch contours ascend or descend over the span of several octaves and are accompanied by changes in amplitude. In music and speech, rising contours are expected to increase in intensity, while descending ones are expected to decrease in intensity (Repp, 1995). This relationship has also been observed by Neuhoff et al. (1999), who found that pitch and loudness are interactive. Variations in one dimension influence perceptual judgments of the other and can lead to illusory perceptions of their copresence when one dimension varies and the other is held constant. This study also found that pitch and loudness yield “redundancy gains”: correlated increases or decreases along both dimensions exerted a greater impact on perceptual behavior than did changes in one dimension alone—a finding also reported by Nakamura (1987).

There is also evidence that pitch and loudness are associated with tempo. In the context of speech, Black (1961) found that the upper registers of pitch are correlated with a greater amplitude and faster tempo while lower pitch registers tend to be softer and slower. Feldstein and Bond (1981) argue that this set of structural correlations is responsible for the results of their study in which paired speech samples, equivalent in tempo, were perceived

to have different rates when pitch and loudness covaried in a correlated fashion. In analyses of musical performances, tempo increases or decreases are often accompanied by corresponding changes in loudness (Friberg, Bresin, & Sundberg, 2006). Lastly, in an experimental paradigm, Walker and Smith (1984) presented a single tone that varied in pitch frequency (i.e., 50, 2500, 3500, or 5500 Hz) and asked participants to rate this on a series of 7-point scales. Among other associations, higher tones were judged as “fast” and “loud” while lower tones were judged “slow” and “soft.” A second study provided converging evidence through a Stroop paradigm. Participants were required to press one of two keys for the classification of adjective pairs (e.g., slow/fast; loud/soft) while simultaneously listening to a high vs. low pitch tone. The results showed that response times were significantly faster when adjectives were congruent (vs. incongruent) with the tone’s pitch. In each of these studies, pitch height (i.e., high vs. low) varied across stimuli but remained constant within a given stimulus. In contrast, Collier and Hubbard (2001) presented ascending or descending scales and asked participants to rate them on overall speed, brightness, degree of arousal, and happiness. They found that ascending sequences were judged as happy, bright, and increasing in speed while descending ones were judged as sad, dark, and decreasing in speed. Similar findings have been reported by Eitan and Timmers (2010).

These findings, as a set, suggest that pitch, loudness, and tempo are all lawfully interrelated and should thereby influence perception in a systematic fashion. When judging the tempo of one melody relative to another, those that gradually increase in pitch and/or loudness over time should seem relatively faster than those that gradually decrease in one dimension or the other—even when no such tempo differences exist. Moreover, correlated changes in both dimensions at once should enhance the magnitude of perceived tempo differences relative to variations in one dimension alone. Conversely, negatively correlated changes (e.g., rising pitch but decreasing loudness) should attenuate any perceived tempo differences and perhaps eliminate them entirely.

These hypotheses were once again investigated through a paired comparison task. As in Experiment 1, melodies within a pair were highly simplistic ones in which notes were related by adjacent scale steps. Although the number of contour changes varied between melodic pairs for purposes of generality, melodies within a pair always displayed the same number of contour changes. The two main independent variables were direction of pitch movement and type of loudness change over time. Standard and comparison melodies either displayed the same

direction of movement (both ascended or descended) or a different direction in which one melody ascended while the other descended in pitch. The loudness variable also consisted of four levels. Standard and comparisons either displayed the same (louder-louder; softer-softer) or different (softer-louder; louder-softer) types of loudness change. Lastly, tempo was once again manipulated such that the comparison melody was either the same tempo, or 8% faster or slower than its referent.

Method

Participants

Thirty-six students from an Introductory Psychology course at Haverford College participated in the study for course credit. As in Experiment 1, the majority of these were nonmusicians: a small percentage (11%) were members of the campus choir but none were currently playing or had played a musical instrument within the past three years.

Stimulus Materials

A set of eight musical patterns was generated from the next rule within the dihedral symmetry group, each pattern containing 24 notes from the C major diatonic scale. Successive notes within each melody were always related by adjacent scale steps (N^{+1} rule) and ultimately resolved on the tonic note, C.

As seen in Figure 2, melodies varied in their number of contour changes such that there were two instances of melodies containing 0, 1, 2, and 3 contour changes, respectively. Across all melodies, there was an attempt to equate the range of pitch distances (i.e., the difference between the highest and lowest notes) as much as possible. In particular, melodies with 0, 1, 2, and 3 contour changes spanned 24, 22, 19, and 16 scale steps, respectively. Within a given level of contour change, the two melodic instances varied in their pitch direction: one ascended toward its final ending point while the other descended. When contour changes appeared, these always occurred at the beginning of a melody such that the melody could then rise or fall in an unimpeded fashion. This initial set of melodies was then transposed to the G major diatonic scale to yield a total set of 16 melodies.

The amplitude level of melodies was also manipulated by creating two different versions of each melody. In one version, amplitude gradually increased over the melody's total time span such that the first note began at 56 dB and incrementally increased by 1 dB for each successive note until the final one which occurred at 80 dB. In the second

version, the reverse was done such that amplitude began at 80 dB and then decreased to 56 dB for the final note.

Lastly, all melodies displayed an isochronous rhythm that derived from two different base tempi. One was relatively slower than the other in that the SOA was 300 ms (200 ms on-time, 100 ms off-time) while the other was relatively faster with an SOA of 225 ms (150 ms on-time, 75 ms off-time). The total duration of tunes was therefore 7.2 vs. 5.4 s, respectively. Comparison melodies either displayed the same base tempo as the standard or one that was 8% faster or slower.

For the paired comparison task, melodies were paired and arranged into two randomized orders of 256 trials. Melodies within a pair always shared the same key and number of contour changes but varied in their overall tempo, pitch direction, and type of loudness change. Within a given order, 50% of the trials consisted of melodic pairs with the same tempo ($n = 128$), 25% ($n = 64$) with comparison melodies faster than the standard, and 25% ($n = 64$) with comparison melodies slower than the standard. Within the same tempo condition, melodic pairs either displayed the same (ascending-ascending; descending-descending) or different (ascending-descending; descending-ascending) pitch directions in conjunction with either the same (increasing-increasing; decreasing-decreasing) or different (increasing-decreasing; decreasing-increasing) types of loudness change to yield a total of 16 types of melodic pairs. Each occurred on eight occasions such that there were two instances of melodies displaying a given number of contour changes. On the faster and slower tempo trials, the 16 types of melodic pairs occurred on four occasions for each tempo condition such that there was one instance of a melody displaying a given number of contour changes. Within each order, the two base rates and two melodic keys appeared an equal number of times and were evenly distributed across all melodies and pitch change \times loudness change conditions. Across the two randomized orders, a melody presented within a given key and base rate in order one was presented in the other key and base rate in order two.

Apparatus and Procedure

These were identical to those of Experiment 1. The Midilab software system was used to instantiate the loudness changes on notes within a melody, and the instrument used to generate all melodies was the grand piano.

The study was run over a two-day period. On each day, participants received four practice trials followed by a set of 128 experimental trials, with a brief rest break after the first 64 trials.

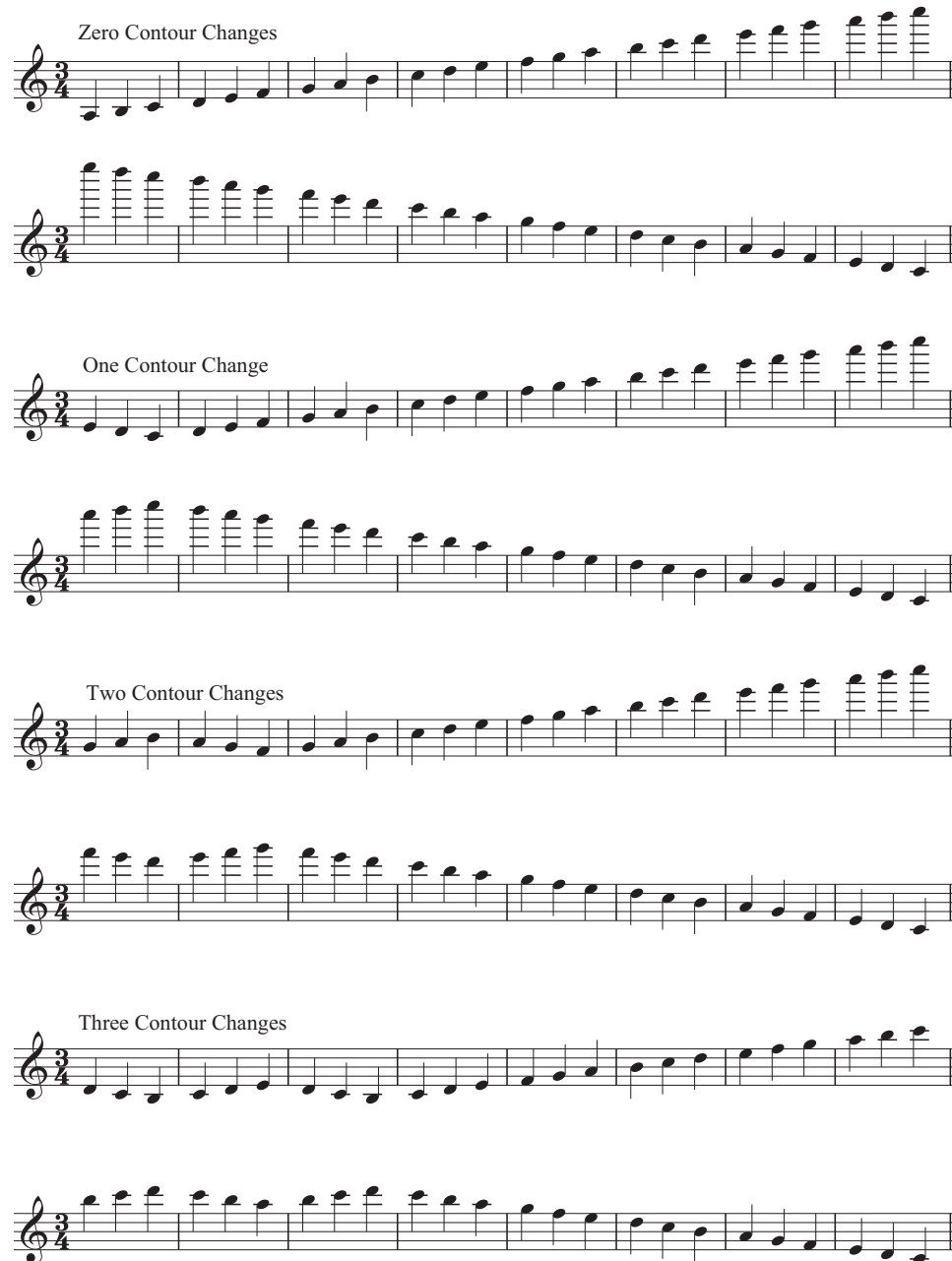


FIGURE 2. The set of musical patterns used in Experiment 2 that each contain 24 notes related by adjacent scale steps (i.e., $N^{\pm 1}$ rule). Within each level of contour change, the first melody ascends in pitch direction and the second descends.

Results

A preliminary ANOVA of all manipulations was conducted and revealed null effects for order, base tempi, and key. The data were therefore collapsed over these variables. The resulting statistical design was a 3 (tempo) \times 4 (pitch direction of standard and comparison melodies) \times 4 (type of loudness change in standard and comparison

melodies) repeated-measures factorial. When significant differences emerged, they were further analyzed through a set of Tukey HSD posthoc comparisons in which p was set to .05.

The overall ANOVA revealed several significant effects. First, there was a main effect for pitch direction, $F(3, 105) = 13.54, p < .001$, as shown in the row means of Table 3. Relative to pairs containing the same direction

TABLE 3. Mean Tempo Ratings in Experiment 2 as a Function of the Relative Pitch Direction and Type of Loudness Change Within Standard (S) and Comparison (C) Melodies.

Pitch Direction	Type of Loudness Change				Means
	S louder C louder	S softer C softer	S louder C softer	S softer C louder	
S increases	0	0.01	-0.50	0.72	0.06
C increases					
S decreases	0.03	0.01	-0.65	0.56	-0.02
C decreases					
S increases	-0.54	-0.61	-1.87	0.03	-0.75
C decreases					
S decreases	0.67	0.52	0.01	1.75	0.74
C increases					
Means	0.04	-0.02	-0.75	0.77	

Note: Relative to a value of 0 indicating a same tempo judgment, positive values indicate that the comparison was judged faster than the standard while negative values indicate that the comparison was judged slower.

of pitch movement (i.e., both increasing, $M = 0.06$, or both decreasing, $M = -0.02$), comparison melodies that increased in pitch were judged significantly faster than standards that decreased in pitch ($M = 0.74$). Conversely, comparisons were judged significantly slower when they decreased in pitch relative to standards that increased in pitch ($M = -0.75$).

Type of loudness change also produced a significant main effect, $F(3, 105) = 14.01, p < .001$, as shown in the column means of Table 3. Relative to pairs displaying the same type of loudness change, (i.e., $M = 0.04$ and $M = -0.02$), comparison melodies that became louder over time were judged significantly faster than standards that became softer ($M = 0.77$). The opposite effect occurred when the temporal order of loudness changes was reversed ($M = -0.75$).

The more interesting finding was a significant interaction between pitch direction and loudness change, $F(9, 315) = 16.08, p < .001$, which generalized to all tempo conditions. In the simple main effect of loudness change as a function of melodies sharing the same pitch direction (i.e., top two rows of Table 3), notice that the main effect of loudness is observed. Relative to standard melodies that become increasingly louder, comparison melodies that become softer seem slower, whereas the opposite occurs when the temporal order of melodies is reversed. Similarly, the main effect of pitch direction applies to the simple main effect of this variable as a function of melodies sharing the same type of loudness change (i.e., the first two columns of Table 3). Relative to standard melodies that ascend in pitch, comparison melodies that descend appear slower, but faster when the temporal ordering of melodies is reversed. However, a different

pattern of results emerges in the remaining conditions; namely, those in which standard and comparison melodies differ in both pitch direction and type of loudness change. Congruent pairs (ascending pitch/louder—descending pitch/softer and the reverse) produce additive effects by enhancing the magnitude of perceived tempo differences, while incongruent pairs (ascending pitch/softer—descending pitch/louder and the reverse) eliminate any (mis)perceptions of tempo differences—the latter pairs are correctly judged as having the same tempo.

Lastly, there was a main effect of tempo, $F(2, 105) = 18.5, p < .001$, in which comparison melodies that were actually slower or faster than their standards were, in fact, perceived as such.

A second ANOVA was conducted that included melodic instance, reflecting a differential number of contour changes across melodic pairs, within the statistical design. The main finding was a three-way interaction between melodic instance, pitch direction, and type of loudness change, $F(18, 105) = 7.97, p < .01$. Overall, the pitch \times loudness interaction described earlier generalized across all melodic instances but the magnitude of perceived tempo differences observed for congruent pairs varied with the number of contour changes. As the number of contour changes decreased, the magnitude of perceived tempo differences increased: although melodies with 0 and 1 contour change yielded comparable mean values, these means were significantly higher than those for two contour changes, which in turn were higher than those for three contour changes.

To determine the generality of these overall results, the percentage of participants responding “same,” “faster,” and “slower” was determined as a function of the pitch direction and loudness change manipulations within the same tempo condition alone. They are shown in Table 4. The results of a McNemar test were consistent with those from the overall ANOVA and revealed significant effects for pitch, loudness, and their interaction ($N = 36, p < .001$ for each).

The top half of Table 4 depicts standard and comparison melodies that share the same direction of pitch movement (i.e., both increasing or decreasing). When these pairs also display the same type of loudness change, they are correctly judged as equivalent in tempo by 94–100% of all participants. However, loudness differences between standard and comparison melodies lead to systematic errors in 35 to 50% of the participants. A similar finding (shown in the bottom half of Table 4) occurs when standard and comparison melodies share the same type of loudness change but differ in pitch direction: here, tempo differences are (mis)perceived by 30–50% of all participants. The most notable finding is

TABLE 4. Percentage of Participants Responding “Same,” “Faster,” and “Slower” Within the Same Tempo Condition of Experiment 2 as a Function of the Relative Pitch Direction and Type of Loudness Change Between Standard and Comparison Melodies.

Pitch Level	Participants' Responses		
	“Same”	“Faster”	“Slower”
INCREASE-INCREASE			
Louder-Louder	100	0	0
Softer-Softer	97	3	0
Louder-Softer	62	3	35
Softer-Louder	50	50	0
DECREASE-DECREASE			
Louder-Louder	94	3	3
Softer-Softer	97	0	3
Louder-Softer	63	0	47
Softer-Louder	53	47	0
INCREASE-DECREASE			
Louder-Louder	57	0	43
Softer-Softer	50	0	50
Louder-Softer	33	0	67
Softer-Louder	94	3	3
DECREASE-INCREASE			
Louder-Louder	53	47	0
Softer-Softer	67	30	3
Louder-Softer	97	3	0
Softer-Louder	25	75	0

that illusory tempo differences are reported by a majority of participants when pitch and loudness changes are congruent within melodic pairs ($M = 67\%$ and 75% , respectively). Conversely, incongruent pairs lead to few errors and accurate judgments of “same” tempo by 94 and 97% of all participants.

Discussion

These overall results converge with those of Experiment 1 by showing that, relative to their standards, melodies that increase or decrease in pitch over time are perceived as relatively faster and slower, respectively—a result that’s consistent with the work of Collier and Hubbard (2001). The novel finding is that increases or decreases in loudness also influenced perceived tempo, as did pitch and loudness together. In congruent pairs in which pitch and loudness were positively correlated with one another, the magnitude of tempo differences was significantly greater than that observed for variations in one dimension alone. In contrast, incongruent pairs in which pitch and loudness were negatively correlated with one another (e.g., ascending pitch that became

softer) yielded null effects. The presence of one dimension served to negate the effects of the other such that in the same tempo condition, standard and comparison melodies were correctly judged as equivalent in tempo. Given that perceptual judgments in these conditions were not differentially biased toward one dimension or the other, this suggests that pitch and loudness exerted a comparable influence on tempo perception. This overall pattern of results not only generalized across different melodic instances, musical keys, and base tempi but to sequences with both actual and null tempo differences. In the latter case, a high percentage of participants were susceptible to these illusory perceptions of tempo differences.

Covariations in pitch, loudness, and tempo are commonly experienced in the auditory environment across different stimulus domains. Most typically, they occur during changing states of energy such as that of emotional expression. Emotional states often increase (e.g., anger into rage; pleasure into excitement) or abate in their intensity (fear into relief; agitation into calm) and these, in turn, are expressed through qualities of the voice or musical performance. Decreases in pitch, loudness, and tempo also occur during movements toward closure such as the end of syntactic boundaries and the final end of a musical composition or speech utterance itself (Todd, 1985). The present results suggest that through repeated experience, we come to expect this covariation in any future encounters with relevant stimuli, and if one dimension varies while another does not, we nonetheless “hear” its presence. Others have observed illusory pitch changes with loudness variations and illusory loudness changes with pitch variations. Here, illusory tempo perceptions emerged due to variations in pitch and/or loudness.

Lastly, it’s noteworthy that variations in pitch and loudness exerted a differential effect on melodies with a varying number of contour changes. The magnitude of perceived tempo increases became progressively higher as the number of contour changes within a melodic pair progressively decreased. Given that contour changes occurred at the beginning of tunes, those melodies with no or only one contour change therefore had more subsequent notes that increased or decreased in pitch in an unimpeded fashion. A greater momentum of pitch movement was thereby established to render any perceived tempo changes from a melody’s beginning to end much more salient. A momentum of unimpeded pitch movement is less evident, of course, in melodic pairs containing relatively more (2 or 3) contour changes and this in turn rendered perceived tempo changes less pronounced.

General Discussion

The results from the two studies reported here demonstrate that the perception of musical tempo was influenced by variations in octave differences, timbre, pitch direction, and intensity changes—effects that occurred in both the presence of actual tempo differences between standard and comparison melodies and, more interestingly, null differences (i.e., equivalent tempi). As a set, these findings are argued to stem from lawful structural covariations that are acquired from repeated experience with different types of auditory events.

Illusory changes in perception are not a new phenomenon and have been observed in numerous studies within the past literature. This research is typically conducted by asking participants to perform a perceptual judgment or classification task on one stimulus dimension while simultaneously ignoring the presence of another (e.g., a Stroop paradigm). With this sort of methodology, Garner (1974) has noted that structural dimensions can display different types of interrelationships that, in turn, influence cognitive processing. Some relationships are separable and perceptually independent of one another in that unattended dimensions either exert no or an interfering influence on attended ones. Other dimensions, however, are integral and display a number of characteristics, including: an incidental learning of one dimension when selectively attending to another, a facilitation of performance when both dimensions covary in a correlated fashion, and reciprocal effects upon one another. Several studies have demonstrated this type of relationship for many auditory dimensions, including pitch and loudness (e.g., Grau & Kemler-Nelson, 1988; Neuhoff et al., 1999), pitch and timbre (Krumhansl & Iverson, 1992; Melara & Marks, 1999; Pitt, 1994), and the duration and intensity of musical accents (Tekman, 2002). From a processing stance, Garner (1974) would argue that these types of integral dimensions are perceived in a holistic and unitary fashion.

The design of the present research does not allow one to determine whether the relationship between musical tempo and pitch, timbre, or loudness are integral. This would demand a different set of studies that examine the effects of pitch, timbre, and loudness variations on perceived tempo *and* the reverse; namely, effects of tempo variations on perceived pitch, timbre, and loudness. Although Geringer and Madsen (1984) have investigated musicians' ability to detect pitch vs. tempo changes, the experimental design of this study was also such that it did not allow one to assess the integral vs. separable issue. Hence, the nature of the relationship between tempo and these other musical qualities remains an issue

for future research. Nonetheless, the present research suggests that tempo and pitch, timbre, or loudness are interactive variables in the sense that variations of the latter can influence and alter behavioral responses to the former.

From the perspective adopted here, illusory tempo changes stem from lawful covariations among structural dimensions that are learned through repeated experience such that, eventually, their copresence becomes expected in future interactions. Hence, if one dimension remains constant while the others vary, perception becomes distorted to confirm one's expectations. This process is consistent with the "unity assumption" (Welch, 1999) that claims that humans are motivated to maintain congruence in their perceptual world such that any physical discrepancies (of a reasonable magnitude) are reduced in order to attain an integrated and unitary percept. This, in turn, ensures a more efficient use of cognitive resources. In lieu of dividing attention among separate sources of information, perceptual unification allows one to direct attention toward a single event that requires less effort. Although Welch (1999) has primarily discussed the unity assumption relative to intersensory conflict between stimuli, it can also be argued to apply to dimensions within a given event.

Others, however, have argued that illusory perceptual changes do not stem from expectancy confirmations but, instead, from expectancy violations. The basic idea is that deviations from expectancies should lead to distortions that are opposite of the expected direction. Repp (1992, 1995, 1998), for example, has found that an interonset interval (IOI) lengthened relative to its preceding context is more difficult to detect at expected locations such as phrase boundaries. On the other hand, shortened IOI's at these same locations are well detected, presumably because they violate listeners' expectancies and thereby capture one's attention. Tekman (2001) has observed similar results for timing variations that precede musical accents.

Within the present research, standard and comparison melodies displaying equivalent tempo are of greatest interest in that they are ambiguous relative to the surrounding context. According to the expectancy violation view, melodic lines that increase in pitch and/or loudness—thereby creating an expectancy for a faster tempo—should seem slower in contrast because they aren't as fast as expected. On the other hand, these same melodies should seem faster when melodic lines create expectancies for a slower tempo; namely, in the presence of decreasing pitch and/or loudness. These effects, however, did not emerge. Instead, tempo perception was distorted toward expectancy confirmation.

One possibility is that illusory perceptual changes can arise from either expectancy confirmations or violations, depending on event context. Distortions opposite of the expected direction primarily seem to arise when there are local deviations within an unfolding event. In the studies by Repp (1992, 1995, 1998) and Tekman (2001), for example, expectancies were violated by variations of a *single* IOI relative to a melody's preceding context. Due to their uniqueness, these violations will be highly salient and stand out as being different. They are therefore unlikely to be unified with the surrounding context and so perception is distorted away from the expected and toward the value of the violation itself. In contrast, distortions reflecting expectancy confirmations primarily seem to arise when a given dimension, though contrary to what might be expected, remains *constant* throughout an event's total time span. For example, the melodies used in the present research all displayed a constant tempo from a melody's onset to its end. Although this overall rate may have been slightly faster or slower than expected from the accompanying melodic line, it nonetheless remained the same throughout, with no deviations from the unfolding context. In these instances, the motivation for perceptual unification may be such that the perceived tempo of the entire melody is distorted in the expected direction of those covariations learned in the past. A similar process can be argued to apply to the illusory pitch and loudness changes observed by Neuhoff et al. (1999) that were also biased toward expectancy confirmation. These ideas represent another avenue for future research and underscore the need to determine what types of distortions are likely to occur in different contexts.

At a more general level, expected covariations of certain structural dimensions are assumed to be acquired from past perceptual experiences that eventually become internalized into the cognitive system. Some recent research suggests that these learning experiences may extend beyond the auditory environment to the broader domains of human motion and language. Some music theorists, for example, have argued that various musical parameters are isomorphic with particular bodily gestures and forms of human motion that, in turn, contribute to music's meaning and its ability to evoke visual imagery and emotions within listeners (e.g., Spitzer, 2003; Zbikowsky, 2002). Eitan and Granot (2006) have investigated this idea by presenting participants with simple melodies that vary in their acoustical qualities (e.g., ascending or descending pitch contours; fast vs. slow tempi; soft vs. loud intensities), and for each, they are asked to visualize an animated human figure. The motion of this figure is then rated on a variety of dimensions

that include its level of energy, speed, vertical direction, distance from the self, and type of motion (e.g., walking, running). They find that most musical parameters influence visualized motion in very lawful ways that are highly consistent across different individuals. Of relevance here, faster and slower speeds of visual motion are associated with increases and decreases in musical intensity and changes in pitch contour—results that converge with the present findings.

Boltz (1998) has argued that these types of effects stem from certain common invariants between human and auditory motion. Humans are locomotive beings who are able to see and hear as they move around and, with learning, will eventually internalize basic principles of motion along with their concomitant sounds and visual images. Given these crossmodal associations, one would expect certain parallels between the perception of visual and auditory motion. For example, it's been found that melodies appear relatively slower when displaying more (vs. fewer) changes in pitch direction, an irregular (vs. regular) rhythm, and large (vs. small) pitch skips (i.e., distances). Similarly, animals who shift their direction of movement must necessarily decelerate to maintain motor control, individuals who walk in an arrhythmic and uncoordinated fashion move more slowly, and greater distances take more time to traverse, which often results in decreased velocity. In sum, then, the perception of musical motion and any perceived tempo changes may stem from more global principles of motion that have learned from the movement of objects in the world around us.

In addition to human motion, crossmodal equivalences between acoustical parameters and visual imagery are also manifested in language. For example, the literature on phonetic symbolism indicates that high-pitched vowels are commonly used to represent brightness, quickness, and smallness while lower-pitched vowels typically denote the opposite set of characteristics (e.g., Marks, 1978; Taylor & Taylor, 1962). Others have investigated "synesthetic metaphors" (Marks, 1982, 1987) that include references to two or more modalities (e.g., bright sneezes or dark coughs) and found that certain types of auditory sounds are strongly correlated with certain visual qualities: for example, greater loudness and a higher pitch are metaphorically expressed in terms of greater brightness, and vice versa. Lastly, a number of studies have shown that certain adjectives are reliably used (e.g., fast, loud vs. slow, soft) when referring to parameters such high vs. low pitch (e.g., Eitan & Timmers, 2010; Walker & Smith, 1984). Taken together, these types of equivalences between music, human motion, and language serve to reinforce those structural covariations

heard in the auditory environment, which form the basis for the interactive nature of perception.

The argument advanced here is that learned structural covariations serve to distort the perception of musical tempo so that one's expectancies are confirmed to achieve structural unification. It is important, however, to acknowledge at least two alternative processes that may be at play. These have been offered by Martino and Marks (1999, 2001) in their investigation of synesthesia that, in its strong form, is manifested by a small population of individuals who experience cross-sensory associations (e.g., seeing colors while listening to music) but more commonly is manifested by most adults who show similar associations in their language behavior and perceptual judgments (e.g., pairing low vs. high pitch tones with the colors of black vs. white). They note that such correspondences may arise at a sensory level in which neural mechanisms are activated by certain common properties across different modalities (i.e., the sensory hypothesis). Alternatively, cross-sensory associations may be learned from perceptual experiences and the language used to describe these experiences that eventually become represented in an abstract semantic network in long-term memory (i.e., semantic coding hypothesis). Martino and Marks (1999, 2001) have conducted a number of studies to contrast these two hypotheses and, overall, find more support for the semantic coding hypothesis. The most compelling evidence comes from research showing that verbal labels, such as "black" and "white," are classified more quickly when they are congruently (vs. incongruently) paired with low and high pitch tones, respectively—which is difficult to explain in terms of sensory processing.

The semantic-coding hypothesis is very similar to the view offered here except that, in the former, distortions are assumed to arise from long-term memory representations vs. online perceptual processing to achieve structural unification and expectancy confirmation. These views are not necessarily incompatible with one another in that perception can certainly be biased by long-term memory associations acquired from past experience. Nonetheless, it would be useful to evaluate the effects of pitch, timbre, and loudness on tempo judgments through tasks other than that used here (e.g., production tasks such as stimulus matching or tapping) to assess if any observed effects are due to perceptual processing vs. retrospective assessments based on memory representations. The present research is also unable to assess the validity of the sensory hypothesis and the mediation of common neural responses to the loudness, pitch, timbre, and tempo dimensions. The related work by Walker and Smith (1984, 1986) showing that participants can more

quickly classify verbal pairs such as "loud" vs. "soft" and "fast" vs. "slow" when these are congruently paired with the pitch height (high vs. low) of tones is difficult to explain from this perspective. However, this doesn't necessarily invalidate the sensory hypothesis. As noted by Martino and Marks (1999, 2001), the mediation of sensory mechanisms vs. semantic coding may be more relevant in infants and young children who have not yet acquired interdimensional associations from language and perceptual experience. Although not mentioned by Martino and Marks, it's also possible that, in adults, both neural and cognitive mechanisms operate in tandem but are differentially weighted depending on the surrounding context. Future research, especially in the field of neuroscience, is needed to better elucidate this possibility.

Lastly, it is worthwhile to consider the implications of the present research to at least two areas of interest. One involves research and theoretical models within the study of tempo behavior. The psychophysical approach to tempo discrimination has focused on Weber's law and the ability to detect jnd's, which, overall, has been found to be quite impressive with an error rate as low as 2% (Povel, 1981). The typical strategy, however, has been to manipulate tempo alone while holding all other stimulus dimensions constant. While this is useful for methodological rigor, a multivariate approach is likely to reveal that tempo sensitivity is context dependent, and influenced by the particular relationship among stimulus dimensions. A second and more general avenue for future research is to consider the effects of interrelated perceptual dimensions on other types of temporal judgments beyond those of tempo. For example, do covariations among pitch, loudness, and tempo exert an influence on the experienced rhythm or duration of a tune? Subjective time estimates, in particular, are likely to be influenced in that perceived increases and decreases in tempo should result in perceptually shorter and longer time spans, respectively. On a theoretical level, the present research indicates a need to address the impact of pitch and other musical dimensions on those cognitive mechanisms assumed to mediate the processing of tempo information. One influential model, offered by Large and Jones (1999), envisions a set of neural oscillators that resonate and entrain to the ongoing beat (pulse) of an environmental event (e.g., a melody) and can flexibly shift their phase and periodicity to accommodate any temporal fluctuations that may occur. The results observed here suggest that this neural system is not only responsive to the actual tempo of an event but also to correlated non-temporal dimensions (e.g., pitch and loudness) to render perceived tempo changes that are not physically present. In this way, then, additional investigations may grant

some validity to the sensory hypothesis noted by Martino and Marks (1999, 2001) by illustrating a neural level that operates in parallel to the semantic one.

A second area to which the present set of findings has relevance is that of musical performance. Although the set of stimuli used here are music-like in their simplicity, they nonetheless represent certain types of structural arrangements found in musical events. This, in turn, suggests that composers may rely on certain musical qualities, such as pitch, loudness, or timbre, to enhance or retard the flow of musical tempo that's important for musical expressiveness and the communication of moods and emotions within listeners. As the work of Eitan and Granot (2006) suggests, these same musical qualities may also be effective in evoking certain visual images that may be useful, for example, in musical soundtracks accompanying film. In an illusion related to one reported here, Madison (2009) constructed an isochronous tonal sequence in which every other note was louder than adjacent ones. The perceptual consequence is two interleaved melodies in which one seems twice

as fast as the other. This, in turn, provides an interesting means of creating a type of counterpoint to enhance musical complexity and its potential aesthetic appeal.

In closing, the study of auditory and music perception can benefit from a multivariate analysis of event structure. This type of methodological strategy may reveal the presence of more general environmental invariants that can help to explain why we perceive events the way we do, as well as a lawful set of stimulus dimensions that will influence the nature of their cognitive processing.

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