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The effect of intensity on relative pitch

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In two experiments, we examined the effect of intensity and intensity change on judgements of pitch differences or interval size. In Experiment 1, 39 musically untrained participants rated the size of the interval spanned by two pitches within individual gliding tones. Tones were presented at high intensity, low intensity, looming intensity (up-ramp), and fading intensity (down-ramp) and glided between two pitches spanning either 6 or 7 semitones (a tritone or a perfect fifth interval). The pitch shift occurred in either ascending or descending directions. Experiment 2 repeated the conditions of Experiment 1 but the shifts in pitch and intensity occurred across two discrete tones (i.e., a melodic interval). Results indicated that participants were sensitive to the differences in interval size presented: Ratings were significantly higher when two pitches differed by 7 semitones than when they differed by 6 semitones. However, ratings were also dependent on whether the interval was high or low in intensity, whether it increased or decreased in intensity across the two pitches, and whether the interval was ascending or descending in pitch. Such influences illustrate that the perception of pitch relations does not always adhere to a logarithmic function as implied by their musical labels, but that identical intervals are perceived as substantially different in size depending on other attributes of the sound source.

Keywords: Relative pitch; Intensity; Looming; Music cognition; Interval size.

One of the most elementary processes in auditory perception is the extraction of pitch information from the acoustic environment. Pitch is a subjective sensation related to the fundamental frequency, or overall repetition rate, of periodic sound waves. Beyond the extraction of individual pitches from complex periodic sounds, humans are remarkably sensitive to changes in pitch, a skill called *relative pitch*. Relative changes in pitch are highly informative in both speech and music. Indeed, researchers have surmised that pitch changes in these two domains are processed by overlapping mechanisms (Juslin & Laukka, 2003; Patel, 2008; Ross, Choi, & Purves, 2007; Thompson, Schellenberg, & Husain, 2004).

In speech prosody, changes in pitch carry information about emotional intentions and linguistic accent, and they indicate whether a speaker is asking a question or making a statement. In music, pitch changes are the foundation of

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melody and harmony. Sequences of pitch intervals must be encoded in order to learn a melody, whereas encoding of absolute pitches is not required for recognition of familiar melodies. A melody retains its character when it is shifted up or down in pitch, as long as the relative distances between pitches are retained. A person who is familiar with "Ode to Joy" from Beethoven's Ninth Symphony will recognize the melody being hummed by a man, woman, or child, or played on a cello or flute, in spite of considerable differences in overall pitch height, tempo, and timbre. Relative pitch is also the basis of harmony. Pitch relations define the perceptual materials that make up harmony, such as consonance, dissonance, major and minor chords, and chord progressions. Notably, short-term memory for novel melodic materials does not always include a precise representation of pitch intervals (Dowling, 1978), and long-term memory for highly familiar music may include absolute pitch and tempo information (Levitin, 1994; Levitin & Cook, 1996; Schellenberg & Trehub, 2003). Nonetheless, sensitivity to relative pitch remains crucial for accurate recognition of music, and it is retained with high efficiency in long-term memory (Dowling & Bartlett, 1981).

Sensitivity to pitch relations also affects how we perceive music structure. Large melodic intervals are experienced as a point of accent (Boltz & Jones, 1986; Drake, Dowling, & Palmer, 1991; Jones, 1987). Conversely, melodies that consist of a sequence of small intervals sound more cohesive (Huron, 2001; Russo, 2002). The expectations that we form while listening to music—important for aesthetic enjoyment—are also influenced by the size and direction of pitch changes (Larson & McAdams, 2004; Margulis, 2005; Narmour, 1990). Finally, the size of pitch changes that occur in music are correlated with phrase boundaries and may be used for segmentation and grouping (Deliège, 1987; Lerdahl, 1989; Lerdahl & Jackendoff, 1983).

The perception of pitch relations is generally described by a logarithmic function: Intervals that span the same distance in log frequency are perceived to be equivalent regardless of the individual pitches involved. In music theory, intervals are assigned category labels such as perfect fourth, minor sixth, and octave, and musically trained individuals can recognize and classify intervals based on their category labels. Intervals with the same category label (octave, fifth, third) span the same log frequency, regardless of transposition. Categorical judgements of intervals by musicians are resistant to the influence of context (Siegel & Siegel, 1977a) and exhibit step-like functions suggestive of categorical perception (Siegel & Siegel, 1977b; see also Burns & Campbell, 1994; Burns & Ward, 1978). Musically untrained listeners, too, can recognize musical intervals, but they lack the vocabulary to label them (Attneave & Olson, 1971; Dowling & Fujitani, 1971; Schellenberg & Trehub, 1996).

The widespread use of categorical labels implies a form of perceptual constancy, whereby distances between pitches remain invariant over transformations in pitch height, timbre, direction of pitch movement, and intensity. This perceptual invariance is widely assumed in music theory and auditory perception and is reflected in the logarithmic model of pitch. However, a number of studies have suggested that a logarithmic model may not adequately capture the nature of relative pitch.

Stevens, Volkmann, and Newman (1937) examined whether the relation between pitch and frequency was strictly logarithmic and used psychophysical scaling strategies to derive a new scale, called the mel scale. They first defined a pure tone of 1,000 Hz at 40 dB above threshold as 1,000 mels. The pitch in mels of other frequencies was determined by asking subjects to adjust a comparison tone until it was perceived to be one half of the pitch height of a standard tone (method of fractionation). Their results indicated that the mel scale and the logarithmic scale are roughly equivalent below 500 Hz, but the mel scale increases at a slower rate above 500 Hz. In other words, perceptually equivalent pitch interval sizes (in mels) span progressively smaller frequency ratios with higher and higher transpositions (Stevens et al., 1937; see also, Beck & Shaw, 1961). These results suggest that the perception of interval size is dependent on pitch register.

Using a modified psychophysical scaling method, Stevens et al. (1937) also found that pitch direction exerts an influence on estimates of interval size (whether two consecutive tones ascend or descend in pitch).

The mel scale is not without its limitations. For example, it cannot be derived from other measures of pitch such as difference limens, critical bands, or equal cochlear distances (Greenwood, 1997). Some researchers have suggested that the mel scale is not a valid psychophysical scale because the tasks used to derive it are ambiguous (e.g., half as high), and responses are not always reliable (Burns, 1999; Krumhansl, 1990, 2000; Rasch & Plomp, 1999; Shepard, 1999). Nonetheless, it illustrates that judgements of pitch relations are not always logarithmic.

Recent findings suggest that acuity for judging pitch relations is not as high as previously thought given pitch discrimination thresholds (McDermott, Keebler, Micheyl, & Oxenham, 2010) and is highly susceptible to influences by sensory input other than pitch (Russo & Thompson, 2005a, 2005b; Thompson, Russo, & Livingstone, 2010). Russo and Thompson (2005b) asked musically trained and untrained listeners to estimate the size of 48 different intervals ranging between 50 cents (one-half semitone) to 2,400 cents (two octaves). Melodic intervals (i.e., two tones in sequence) were presented at a high or a low pitch register and in an ascending or a descending pitch direction. Judgements of interval size increased with increases in the number of semitones between the two tones. However, this association depended on the listener's level of musical training, the pitch register of the interval, the direction of melodic motion, and whether or not the interval was larger than an octave.

For intervals up to an octave, differentiation of intervals was greater for musically trained than for untrained listeners, and only judgements by trained listeners aligned with predictions based on a logarithmic scale. For intervals larger than an octave, differentiation of intervals was similar for trained and untrained listeners and was substantially reduced compared with the differentiation observed for smaller intervals. Intervals presented at a high pitch register were also judged to be larger in size than were equivalent intervals presented at a low pitch register, consistent with predictions based on the mel scale (Siegel, 1964; Stevens & Volkmann, 1940; see also Stumpf, 1883). Finally, judgements of interval size depended on the direction of pitch motion. In the high pitch register, estimates of interval size were larger for ascending intervals than for descending intervals; the reverse was true for intervals presented in the low pitch register. One reason for this interaction is that pitch changes in music usually move toward the centre of the tessitura (regression to the mean), and such movement is expected (von Hippel & Huron, 2000). When one event follows another in an expected manner, the two events are perceived to be associated and psychologically proximal. Conversely, events that unfold in an unexpected manner are perceived to be psychologically distant.

Russo and Thompson (2005a) reported that the perceived size of intervals is also affected by the timbre of the component tones. Melodic intervals were presented to musically untrained (Experiment 1) and trained (Experiment 2) participants, who rated the pitch distance between them. Pitch changes were accompanied by a congruent timbre change (e.g., ascending interval involving a shift from a dull to a bright timbre), an incongruent timbre change (e.g., ascending interval involving a shift from a bright to a dull timbre), or no timbre change. Ratings of interval size were significantly influenced by timbre. The effect remained when participants directly compared the size of two intervals presented one after the other and could not be explained by poor resolution of the individual pitches involved.

The above results illustrate that relative pitch is not as stable as has previously been assumed (see also, McDermott et al., 2010). Indeed, sensitivity to relative pitch is even affected by the body movements of the musicians who are producing a melodic interval. Thompson et al. (2010; see also, Thompson & Russo, 2007) presented participants with silent video recordings of sung melodic intervals, who judged the size of the interval they imagined the performers to be singing. Participants discriminated interval sizes based on facial expressions and head movement alone, suggesting that facial and head movements carry reliable signals about interval size. Facial expressions influenced judgements of interval size even when the auditory signal was available.

In the present investigation, we tested the hypothesis that a change in the intensity of tones affects the perceived size of intervals. There were three motivations for the investigation. First, the study has the potential to contribute to the emerging understanding of relative pitch by revealing how it is affected by attributes of sound not previously considered. Russo and Thompson (2005b) reported that the spectral properties of tones influence the psychological distance between them. Revealing an influence by intensity on perceived pitch relations would clarify whether sensitivity to relative pitch is affected by nonspectral attributes of sound.

Second, frequency and intensity are fundamental physical attributes of sound, but there is little understanding of how *changes* in these two dimensions interact in perceptual judgements. Doppler (1842) arranged to have a locomotive pull an open car of trumpeters past a group of observers, who perceived a rise in pitch for the approaching sound source, even though there was no rise in frequency (see also, Neuhoff, Kramer, & Wayland, 2002; Neuhoff & McBeath, 1996). The observers also perceived a sharp drop in pitch as the sound source passed—a drop that greatly exceeds any physical changes in the frequency of approaching and receding sound waves (McBeath & Neuhoff, 2002). Equal loudness contours deduced from auditory psychophysics also reveal dimensional interaction for static intensity and frequency (e.g., Suzuki & Takeshima, 2004). Finally, evidence arising from experimental techniques referred to as *converging operations* (Garner, 1974) indicated that pitch and loudness are integral dimensions (Melara & Marks, 1990a, 1990b). However, in spite of these lines of evidence and the central role of relational information in human pitch processing, remarkably little is known about the influence of intensity on pitch relations.

Third, the study has the potential to contribute to a growing literature on the perceptual bias for continuous increases of acoustic intensity associated with *auditory looming* phenomena (e.g., Bach, Neuhoff, Perrig, & Seifritz, 2009; Neuhoff, 1998, 2001; Seifritz et al., 2002.). Changes in intensity, like changes in pitch, are common in music: Composers and performers systematically control such changes. Both types of change, in turn, affect perceptions and experiences of music. Huron (1991, 1992) argued that music composers consciously or unconsciously emphasize increases in intensity (a crescendo) over decreases in intensity (diminuendo) in order to facilitate the maintenance of attention by listeners. Increases in intensity capture attention whereas decreases in intensity may go unnoticed.

The importance of increasing over decreasing intensity in perceptual terms may be reflected in a "perceptual bias" to the increase of intensity associated with looming auditory motion. Several studies using nonmusical stimuli have reported overestimation of perceived loudness change in response to continuous linear increases of intensity (up-ramp), relative to decreases (down-ramp). For example, 1.8 s vowel and pure tone up-ramps are perceived to change significantly more in loudness than down-ramps matched on spectral content, stimulus duration, and range of intensity sweep (Neuhoff, 1998, 2001). Neuhoff argued that the overestimation of loudness change for tonal up-ramp stimuli is an evolved, adaptive perceptual bias to looming (or approaching) auditory motion in the environment. Such an adaptive response may provide a selective advantage for organisms that underestimate the time-to-contact of a looming object, effectively expecting contact earlier than actual contact and allowing time for an appropriate response. Other models of this perceptual bias have also been proposed (Olsen & Stevens, 2010; Pastore & Flint, 2011; Susini, McAdams, & Smith, 2007; Teghtsoonian, Teghtsoonian, & Canévet, 2005), including models that consider sensitivity to increases of intensity in musical stimuli (Olsen, Stevens, & Tardieu, 2010). The present investigation considered whether such perceptual biases related to intensity change permeate processes that underlie pitch perception.

Two experiments were designed to evaluate the impact of intensity on the perception of pitch distance. In Experiment 1, we examined the effect of continuous changes in intensity on the perception of pitch change within individual tones that glided from one pitch to another. Continuous changes were used to mimic continuous movement of sound sources in the natural environment. In Experiment 2, we examined the effect of discrete changes in intensity on the perception of pitch change within two separate tones that differed in pitch. This approach was adopted to determine whether the effects for continuous stimuli are also observed for discrete stimuli that mimic the properties of music. All pitch changes presented to participants were well above pitch discrimination thresholds. Convergence of results for continuous and discrete stimuli would suggest that the many discrete shifts in intensity and pitch that occur in sequences of musical events (crescendo, diminuendo) are processed in the same way as continuous changes in these attributes. Both experiments were realized as 2 × 2 × 4 designs. Interval (6 or 7 semitones), pitch direction (ascending, descending), and intensity (looming, fading, high static, low static) were manipulated within subjects. Ratings of perceived interval size between the two pitch events in a trial served as the dependent variable.

We predicted that the intensity of tones would influence perceived pitch relations. Specifically, perceptual biases for increasing intensity and high overall intensity should be reflected in judgements of perceived pitch interval size. First, compared with fading intervals, looming intervals should be perceived to involve a larger change in pitch, in the same way that they are perceived to involve a larger change in loudness. That is, the adaptive perceptual bias to looming stimuli reported by Neuhoff (1998, 2001) and others should be manifested in judgements of pitch change just as it is manifested in judgements of loudness change. Second, high-static-intensity intervals should be perceived as larger than low-static-intensity intervals because stimuli with greater intensity, like looming phenomena, should be prioritized perceptually. Third, based on the results of Russo and Thompson (2005b), we expected that the perceived size of intervals would depend on pitch direction.

EXPERIMENT 1: GLIDING PITCH INTERVALS AND INTENSITY CHANGE

Method

Subjects

Thirty-nine adults participated in the experiment (16 women, 23 men, age: 18–28 years, $M = 21.46$ years, $SD = 3.10$). Three participants had musical training for 1 year or less; the rest were untrained ($M = 0.77$ months, $SD = 2.81$ months). All reported normal hearing. Participants received partial course credit or monetary compensation for their participation. Participants provided informed consent, and methods were approved by the ethics committees of the University of Western Sydney and Macquarie University.

Stimuli and equipment

Stimuli were digitally synthesized using Audition 3.0 software (Adobe Inc) and incorporated 10-ms fade-in and fade-out ramps at the beginning and end of each stimulus to remove onset/offset click artefacts. Each stimulus consisted of 11 harmonically related partials. The amplitude of the partials varied as an inverse proportion to the partial number. All stimuli were 1 s in duration. Within the 1 s duration, the fundamental frequency of the stimulus increased or decreased in a continuous manner by six semitones (a tritone) or seven semitones (a perfect fifth) from the starting frequency, resulting in an ascending or descending tone glide. There were three starting fundamental frequencies in the rising condition: F3 (174.61 Hz), G3 (195.99 Hz), and A3 (220 Hz). The final fundamental frequencies in the ascending condition served as the initial fundamental frequencies for the descending condition. Hence, the initial fundamental frequencies in the descending tones were B3 (246.94 Hz), C4 (261.62 Hz), C#4 (277.18 Hz), D4 (293.66 Hz), D#4 (311.12 Hz), and E4 (329.62 Hz).

Each tone glide was presented in one of the four intensity conditions: (a) looming, (b) fading, (c) high static, or (d) low static. Looming and fading intensity manipulations denote the direction of intensity change. In the looming condition, intensity continuously increased from the start to the end of the stimuli (50 dB SPL to 80 dB SPL). This amount of intensity change (30 dB) was chosen to convey a strong impression of looming (Neuhoff, 2001), while remaining within a range of intensities that would not distort the perceived pitch of individual tones (Terhardt, 1974; Verschuure & van Meeteren, 1975). Hence, for looming ascending intervals, intensity and frequency both increased; for looming descending intervals intensity increased while frequency decreased. In the fading condition, the intensity decreased from the start to the end of the stimuli (80dB SPL to 50dB SPL). Hence for fading ascending intervals, intensity decreased while frequency increased; for fading descending intervals both frequency and intensity decreased. The intensity was kept constant at 80 dB SPL for the high-static condition and at 50 dB SPL for the low-static condition. The rate of change in intensity and frequency was defined by a linear logarithmic function.

Three blocks were presented per participant. Each block consisted of all 48 items, yielding 144 trials. There were 3 starting frequencies (for ascending intervals: F3, G3, or A3), 2 intervals (6 or 7 semitones), 2 directions (ascending or descending), and 4 intensity manipulations (looming, fading, high static, or low static). The presentation order of items in each block was randomized. Stimuli were presented binaurally through Sennheiser HD 515 headphones in a quiet room. Stimulus presentation and response collection were accomplished using *Presentation* software (Neurobehavioral Systems Inc.) running on a PC. Intensity levels were calibrated using a Brüel and Kjær Artificial Ear 4152 attached to a Brüel and Kjær Hand-Held Analyser 2250 using Sound Level Meter Software BZ-7222.

Procedure

The participants were provided with an explanation of interval size and were told that they would be rating the perceived size of pitch intervals using a discrete scale from 1–5, where 5 indicated a large perceived pitch interval, and 1 indicated a small perceived pitch interval. To make a response, participants pressed the relevant number on a computer keyboard number pad. They were told that the full range of the scale could be used. In order to monitor potential lapses in attention, participants were also asked to indicate the direction of the pitch change for each stimulus presentation (rising or falling). The concept of pitch direction was explained to each participant. Practice trials were administered to ensure that participants were comfortable with the task. In the experimental blocks, participants again rated the size and direction of each interval. They were instructed to respond only after the stimulus had ended and to make both responses within 3 s. If the responses were not made within 3 s, a “TIMED OUT” message appeared on the screen. Timed out trials were repeated later in the testing session. There was a 2-s intertrial interval.

Data analysis

Two classes of responses were analysed: percentage correct for direction judgement, and interval size rating.[1] The direction of frequency change was judged correctly in 93.14% ($SD = 8.88$) of trials. Trials eliciting an incorrect direction judgement were discarded, and analyses of ratings were restricted to the remaining valid trials. Ratings were collapsed across valid trials from the three

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[1] Although direction accuracy was assessed merely to monitor lapses in attention, it was affected by the intensity of stimuli. Post hoc analyses of direction accuracy data (inverse reflected to address ceiling effects; see Tabachnick & Fidell, 1996, p. 83) revealed that direction judgements were more accurate for looming ($M = 94.45\%$, $SE = 1.41$) than for fading ($M = 90.90\%$, $SE = 1.49$) stimuli. For ascending intervals, accuracy was also better for high-static-intensity ($M = 96.67\%$, $SE = 1.03$) than for low-static-intensity ($M = 92.5\%$, $SE = 2.57$) stimuli; for descending intervals, the reverse was true (high static intensity: $M = 89.03\%$, $SE = 3.32$; low static intensity: $M = 96.25\%$, $SE = 0.94$). The analysis of direction accuracy data is available by request from W.F.T.

Table 1. *Mean interval size ratings obtained in Experiment 1*

	Dynamic intensity		*Static intensity*	
Condition	*Looming*	*Fading*	*High*	*Low*
Tritone (6 semitones)				
Ascending	3.78 (0.50)	3.02 (0.52)	3.95 (0.69)	2.27 (0.57)
Descending	3.22 (0.56)	2.72 (0.70)	3.72 (0.63)	1.77 (0.51)
Perfect fifth (7 semitones)				
Ascending	3.81 (0.57)	3.18 (0.52)	4.06 (0.64)	2.40 (0.65)
Descending	3.19 (0.61)	2.79 (0.57)	3.87 (0.62)	1.91 (0.62)

Note: Standard deviations in parentheses.

starting frequencies and three repetitions (blocks), yielding a mean rating for each combination of interval, pitch direction, and intensity condition. Statistical comparisons were within subjects with alpha set at .05 unless stated otherwise. Partial eta squared (η_p^2) was calculated as a measure of effect size (Cohen, 1973).

Results

Table 1 illustrates mean interval size ratings for each condition. The results of Experiment 1 supported the three hypotheses for gliding stimuli. First, looming interval glides were perceived as larger than fading interval glides. Second, high-static-intensity intervals were perceived as larger than low-static-intensity intervals. Third, the direction of pitch movement significantly influenced perceived interval size. We also observed slight but statistically reliable interactions among variables, suggesting that the strength of the predicted effects varies depending on the stimulus attributes.

Looming and fading intensity

Interval ratings for correctly judged trials were subjected to a three-way analysis of variance (ANOVA) with repeated measures on interval (6 or 7 semitones), intensity (looming, fading), and pitch direction (ascending, descending). There were significant main effects of intensity, $F(1, 38) = 33.29$, $p < .001$, $\eta_p^2 = .47$, and pitch direction, $F(1, 38) = 62.40$, $p < .001$, $\eta_p^2 = .62$. As shown in Figure 1 (left panel), intervals presented with looming intensity ($M = 3.50$, $SE = 0.08$) were rated as significantly larger than the same intervals presented with fading intensity ($M = 2.93$, $SE = 0.07$). Moreover, intervals presented with ascending pitch ($M = 3.45$, $SE = 0.06$) were rated as significantly larger than the same intervals presented with descending pitch ($M = 2.98$, $SE = 0.07$).

There was also a significant interaction between intensity and pitch direction $F(1, 38) = 5.75$, $p < .05$, $\eta_p^2 = .13$. The effect of intensity (looming or fading) was slightly greater for ascending than for descending intervals, and the effect of pitch direction on ratings of interval size was slightly greater for looming than for fading intervals. However, post hoc analyses with Bonferroni adjusted alpha of .0125 confirmed that the effect of intensity was significant for both ascending intervals, $F(1, 38) = 45.41$, $p < .001$, $\eta_p^2 = .54$, and descending intervals, $F(1, 38) = 14.16$, $p < .01$, $\eta_p^2 = .27$. Among ascending intervals, looming intervals ($M = 3.79$, $SE = 0.08$) were rated as significantly larger than fading intervals ($M = 3.10$, $SE = 0.08$). Among descending intervals, looming intervals ($M = 3.20$, $SE = 0.09$) were also rated as significantly larger than fading intervals ($M = 2.75$, $SE = 0.09$). Post hoc analyses also confirmed that the effect of pitch direction was significant for both looming intervals, $F(1, 38) = 76.35$, $p < .001$, $\eta_p^2 = .67$, and fading intervals, $F(1, 38) = 15.59$, $p < .001$, $\eta_p^2 = .29$.

High and low static intensity

Interval ratings for correctly judged trials from high- and low-static-intensity conditions were

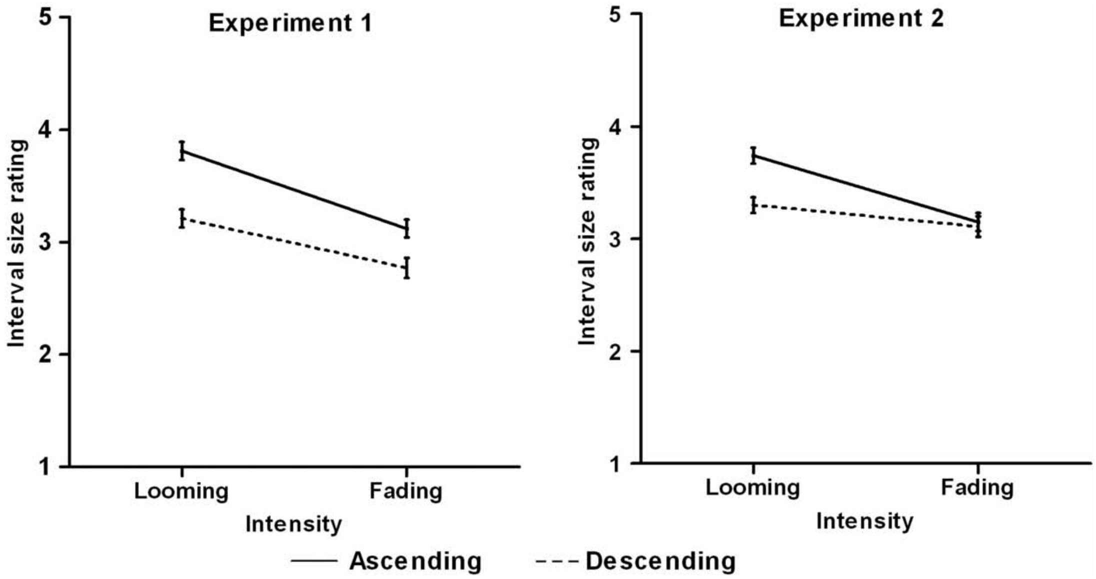

Figure 1. *Mean ratings of interval size as a function of intensity change and pitch direction. Error bars represent standard error of the mean.*

subjected to a separate three-way ANOVA with repeated measures on interval (6 or 7 semitones), intensity (high static, low static), and pitch direction (ascending, descending).[2] There was a significant main effect of interval, $F(1, 38) = 7.73$, $p < .01$, $\eta_p^2 = .17$. Ratings of interval size were significantly larger for 7-semitone intervals ($M = 3.06$, $SE = 0.06$) than for 6-semitone intervals ($M = 2.93$, $SE = 0.06$) when intensity was static. There were also significant main effects of intensity, $F(1, 38) = 192.86$, $p < .001$, $\eta_p^2 = .84$, and pitch direction, $F(1, 38) = 35.84$, $p < .001$, $\eta_p^2 = .46$. Intervals presented at a high static intensity level ($M = 3.90$, $SE = 0.09$) were rated as significantly larger than the same intervals presented at low static intensity ($M = 2.09$, $SE = 0.08$). Furthermore, intervals with ascending pitch ($M = 3.17$, $SE = 0.06$) were rated as significantly larger than the same intervals with descending pitch ($M = 2.82$, $SE = 0.06$).

We also observed a significant intensity × pitch direction interaction, $F(1, 38) = 15.27$, $p < .001$, $\eta_p^2 = .29$, which was explored using post hoc analyses with a Bonferroni adjusted alpha of .0125. As shown in Figure 2 (left panel), the effect of intensity on ratings was slightly smaller for ascending than for descending intervals. For ascending intervals, high-static-intensity stimuli ($M = 4.00$, $SE = 0.10$) were assigned higher ratings than low-static-intensity stimuli ($M = 2.34$, $SE = 0.09$), $F(1, 38) = 135.76$, $p < .001$, $\eta_p^2 = .78$. For descending intervals, high-static-intensity stimuli ($M = 3.80$, $SE = 0.09$) were also assigned higher ratings than low-static-intensity stimuli ($M = 1.84$, $SE = 0.09$), $F(1, 38) = 236.00$, $p < .001$, $\eta_p^2 = .86$. Figure 2 also suggests that the effect of pitch direction on ratings of interval size was slightly smaller for high-intensity than low-intensity stimuli. For high-intensity stimuli, ratings of ascending intervals were significantly higher than ratings of descending stimuli, $F(1, 38) = 7.15$, $p = .011$, $\eta_p^2 = .16$. For low-intensity stimuli, ratings were significantly higher for ascending intervals than for descending intervals, $F(1, 38) = 70.90$, $p < .001$, $\eta_p^2 = .65$.

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[2] We conducted a second analysis using rating data that were first normalized for each participant. All significant effects reported for the analysis of raw data were observed when data were normalized. These analyses are available by request from W.F.T.

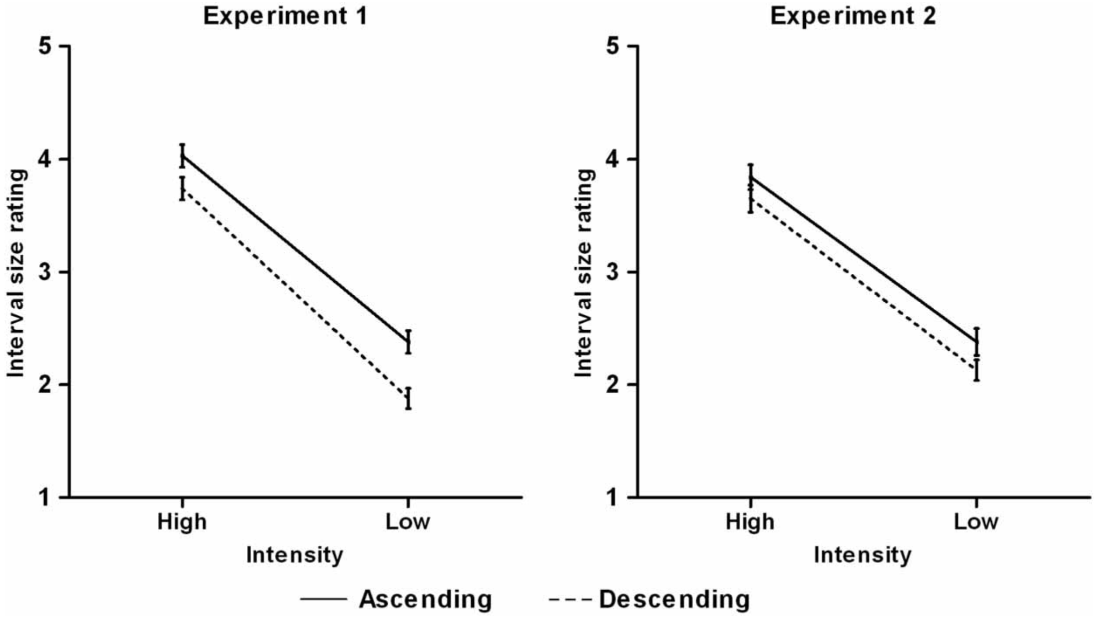

Figure 2. *Mean ratings of interval size as a function of static intensity level and pitch direction. Error bars represent standard error of the mean.*

CONTROL EXPERIMENT

The effects reported in Experiment 1 indicate that the perception of interval size is influenced by stimulus intensity, consistent with other evidence illustrating perceptual interactions between intensity and pitch (Doppler, 1842; McBeath & Neuhoff, 2002; Melara & Marks, 1990a, 1990b; Neuhoff et al., 2002; Neuhoff & McBeath, 1996; Suzuki & Takeshima, 2004). It should be acknowledged, however, that only two interval sizes were presented to participants (6 and 7 semitones), and they were similar in size. Faced with small trial-to-trial differences in interval size, participants may have drawn upon other attributes of the stimuli in a conscious attempt to use the full range of the rating scale. To check this possibility, we conducted a control experiment using intervals that were much more distinct: 6- and 10-semitone intervals. If the effect of intensity were an artefact of small trial-to-trial differences in interval size, then the effects should disappear when greater differences in interval size are introduced from trial to trial. Conversely, if interactions between intensity and interval size occur at a perceptual level regardless of trial-to-trial differences in interval size, then the influence of intensity observed in Experiment 1 should also be observed in the control experiment.

Method

Thirty adults participated in the experiment (24 women, 6 men, age: 18–40 years, $M = 21.10$ years, $SD = 4.60$), 10 of whom had received some musical training ($M = 1.4$ years, range = 0.5–1.5 years). Each 1-s stimulus was presented with 30 dB (50 dB SPL to 80 dB SPL) looming or fading intensity, and pitch change was continuous and rising over 6 or 10 semitones. Four frequency ranges were presented as 6 semitones (A3–D#4, B3–F4, F3–B3, G3–C#4) and 10 semitones (C#3–B3, D#3–C#4, F3–D#4, G3–F4). The experiment was realized as a 2 × 2 within-subjects design with intensity (looming, fading) and interval (6 semitones, 10 semitones) as independent variables. Stimulus generation, equipment, and procedure followed those of Experiment 1.

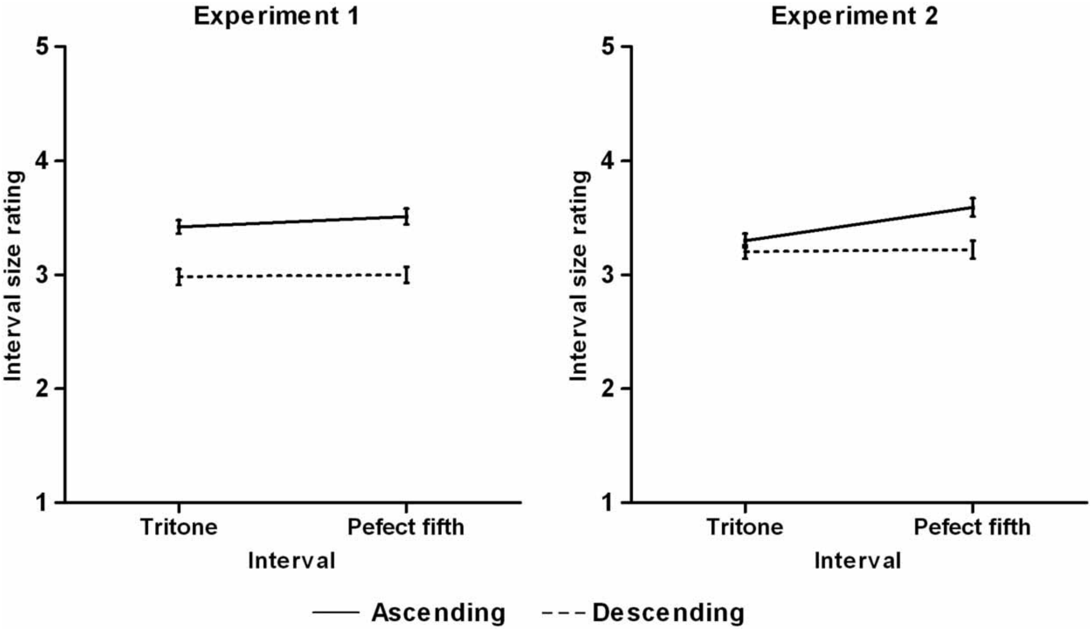

Figure 3. *Mean ratings of interval size as a function of actual interval size and pitch direction averaged across looming and fading stimuli. Error bars represent standard error of the mean.*

Results

There was a significant main effect of intensity, $F(1, 29) = 43.12, p < .001, \eta_p^2 = .60$, with perceived interval size for looming stimuli ($M = 3.56$, $SE = 0.10$) significantly greater than that for fading stimuli ($M = 2.78$, $SE = 0.06$). This finding corroborates the findings reported in Experiment 1. There were no other significant effects.

It is notable that interval size is difficult to judge for pitch glides that involve salient changes in intensity, and not all participants assigned higher ratings to 10-semitone intervals than to 6-semitone intervals. This difficulty in judging the size of intervals that involve a change in intensity was also apparent in Experiment 1. In that experiment, the two intervals were assigned significantly different ratings when the intensity remained static, but not when stimuli involved changes in intensity (see Figure 3, left panel). To evaluate whether the effects of intensity were associated with difficulty in discriminating the two interval sizes, two types of difference scores were calculated. First, interval discrimination ability was calculated for each participant by subtracting ratings of 6-semitone intervals from ratings of 10-semitone intervals. The larger the score, the better the discrimination between the two intervals. Second, the tendency of participants to be influenced by intensity was estimated by subtracting ratings of fading stimuli from ratings of looming stimuli. The larger the score, the greater the influence of intensity on interval size ratings. The correlation between the two sets of scores was nonsignificant, ($r = -.16$, $p > .05$), indicating that the effects of intensity on perceived interval size are unrelated to poor interval discrimination.

To ensure that the effect of intensity remains when interval sizes are distinguished, we ran an additional 2 × 2 within-subjects ANOVA on those participants who rated 10-semitone intervals ($M = 3.38$, $SE = 0.07$) as larger than 6-semitone intervals ($M = 3.02$, $SE = 0.12$). For this sample of participants, there was a significant main effect of interval, $F(1, 14) = 19.85$, $p = .01$, $\eta_p^2 = .59$, and again a significant main effect of intensity,

$F(1, 14) = 15.08, p < .01, \eta_p^2 = .52$. That is, intensity significantly influenced interval size ratings even for participants with good interval-size discrimination. In short, continuous intensity change significantly influenced perceived interval size when there were large trial-to-trial differences in interval size and when those intervals were judged to be significantly different from one another.

EXPERIMENT 2: DISCRETE PITCH INTERVALS AND INTENSITY CHANGE

The results of Experiment 1 indicate that intensity significantly influenced judgements of perceived interval size within individual gliding tones. Ratings of interval size increased with the number of semitones traversed within individual gliding tones. However, across the two intervals (6 or 7 semitones), ratings were higher for looming (up-ramp) stimuli than for fading (down-ramp) stimuli and higher for high-intensity stimuli than for low-intensity stimuli. We also observed effects of pitch direction: Ratings of interval size were higher for ascending pitch glides than for descending pitch glides, especially for low-intensity stimuli.

Experiment 2 was conducted to determine whether these effects would be observed in discrete tones, which is characteristic of music. Thus, instead of presenting listeners with an individual tone that changed continuously in intensity and pitch, we presented listeners with pairs of tones that involved a discrete change in pitch.

Method

Subjects

Forty adults with normal hearing participated in Experiment 2 (23 women, 17 men, age: 18–29 years, $M = 21.10$ years, $SD = 2.71$) and received monetary compensation for their participation. Four participants had musical training for 1 year or less; the rest were untrained (M = 1.2 months, SD = 3.65 months). Two additional participants were tested but their data were excluded, as they did not follow the instructions during testing. Informed consent was obtained from all participants.

Stimuli and equipment

Stimulus generation and equipment followed those reported in Experiment 1. The exception was that in Experiment 2, each trial presented pairs of discrete tones separated by either six (tritone) or seven (perfect fifth) semitones, instead of a continuous glide between six or seven semitones used in Experiment 1.

Procedure and data analysis

The procedure and data analysis were identical to those used in Experiment 1. The direction of frequency change (ascending versus descending) was judged correctly in 85.40% ($SD = 12.93$) of trials.[3] As in Experiment 1, trials eliciting an incorrect direction judgement were discarded, and analyses of ratings were restricted to the remaining valid trials.

Results

Table 2 provides mean interval size ratings for each condition. The results of Experiment 2 supported the three hypotheses for discrete pitch intervals. First, intervals that increased in intensity from the first to second tone (looming) were perceived as larger than intervals that decreased in intensity (fading). Second, high-static-intensity intervals were perceived as larger than low-static-intensity intervals. Third, the direction of pitch movement significantly influenced perceived interval size. As in Experiment 1, we observed significant

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[3] Post hoc analyses of direction accuracy data (inverse reflected to address ceiling effects) revealed that for ascending intervals, direction accuracy was reliably better for looming ($M = 87.22\%$, $SE = 2.54$) than for fading ($M = 77.78\%$, $SE = 2.89$) stimuli; for descending intervals, the reverse was true (looming stimuli: $M = 83.47\%$, $SE = 2.83$; fading stimuli: $M = 90.00\%$, $SE = 2.12$). For static-intensity stimuli, accuracy was also better for high-intensity ($M = 87.85\%$, $SE = 2.00$) than for low-intensity ($M = 84.52\%$, $SE = 2.11$) stimuli and for descending ($M = 89.31\%$, $SE = 2.00$) than for ascending ($M = 83.06\%$, $SE = 2.46$) intervals. The analysis of direction accuracy data is available by request from W.F.T.

Table 2. *Mean interval size ratings obtained in Experiment 2*

	Dynamic intensity		*Static intensity*	
Condition	*Looming*	*Fading*	*High*	*Low*
Tritone (6 semitones)				
Ascending	3.63 (0.50)	2.98 (0.51)	3.74 (0.84)	2.27 (0.69)
Descending	3.31 (0.53)	3.08 (0.53)	3.58 (0.88)	2.00 (0.52)
Perfect fifth (7 semitones)				
Ascending	3.86 (0.56)	3.32 (0.67)	3.94 (0.64)	2.49 (0.97)
Descending	3.19 (0.50)	3.15 (0.73)	3.72 (0.81)	2.26 (0.72)

Note: Standard deviations in parentheses.

interactions among variables, suggesting that the predicted effects are dependent on stimulus attributes.

Looming and fading intensity

Interval ratings for correctly judged trials from looming and fading intensity conditions were subjected to a three-way ANOVA with repeated measures on interval (6 or 7 semitones), intensity (looming, fading), and pitch direction (ascending, descending). There was a significant main effect of interval, $F(1, 39) = 6.80$, $p < .05$, $\eta_p^2 = .15$. The 7-semitone interval ($M = 3.40$, $SE = 0.07$) was rated as significantly larger than the 6-semitone ($M = 3.25$, $SE = 0.05$). There were also significant main effects of intensity, $F(1, 39) = 18.16$, $p < .001$, $\eta_p^2 = .32$, and pitch direction, $F(1, 39) = 12.42$, $p < .01$, $\eta_p^2 = .24$. Intervals presented with looming intensity ($M = 3.52$, $SE = 0.06$) were rated as significantly larger than the same intervals presented with fading intensity ($M = 3.13$, $SE = 0.08$). Moreover, intervals presented with ascending pitch direction ($M = 3.45$, $SE = 0.06$) were rated as significantly larger than the same intervals presented with descending pitch direction ($M = 3.21$, $SE = 0.06$).

As in Experiment 1, there was a significant Intensity × Pitch Direction interaction, $F(1, 39) = 20.10$, $p < .001$, $\eta_p^2 = .35$. Figure 1 (right panel) illustrates that the effect of intensity was only evident for ascending intervals. Among ascending intervals, looming stimuli ($M = 3.75$, $SE = 0.07$) were assigned higher ratings than fading stimuli ($M = 3.15$, $SE = 0.08$), $F(1, 39) = 41.05$, $p < .05$, $\eta_p^2 = .51$. Among descending intervals, however, looming stimuli ($M = 3.30$, $SE = 0.07$) and fading stimuli ($M = 3.11$, $SE = 0.09$) were assigned similar ratings, $F(1, 39) = 2.87$, $p > .05$, $\eta_p^2 = .07$. The figure also suggests that the effect of pitch direction was only evident for looming intervals. Post hoc analyses revealed that for looming stimuli, ascending intervals were assigned higher ratings than descending intervals, $F(1, 39) = 30.82$, $p < .001$, $\eta_p^2 = .44$. For fading stimuli, however, similar ratings were assigned to ascending intervals and descending intervals, $F(1, 39) = 0.20$, $p > .05$, $\eta_p^2 = .01$.

We also observed a significant Interval × Pitch Direction interaction, $F(1, 39) = 12.72$, $p < .01$, $\eta_p^2 = .25$. As illustrated in Figure 3 (right panel), when stimuli involved changing intensity, there was a reliable effect of interval size on ratings for ascending but not for descending intervals. Post hoc analyses with a Bonferroni adjusted alpha of .0125 revealed that for ascending intervals, the 7-semitone interval ($M = 3.59$, $SE = 0.08$) was assigned higher ratings than the 6-semitone interval ($M = 3.30$, $SE = 0.06$), $F(1, 39) = 14.39$, $p < .01$, $\eta_p^2 = .27$. For descending intervals, however, the 7-semitone interval ($M = 3.22$, $SE = 0.08$) and 6-semitone interval ($M = 3.20$, $SE = 0.06$) were assigned similar ratings. This contrasts with static intensity stimuli, in which the two intervals were assigned significantly different ratings of interval size. Figure 3 (right panel) also illustrates that there was an effect of pitch direction for the 7-semitone interval interval but not for the 6-semitone interval interval. For the 7-semitone interval, ascending intervals were assigned higher ratings than descending intervals, $F(1,\ 39) = 22.96$, $p < .001$, $\eta_p^2 = .37$. For the 6-semitone interval, ratings for ascending and descending intervals were similar.

High and low static intensity

Interval ratings for correctly judged trials from high- and low-static-intensity conditions were subjected to a separate three-way ANOVA with repeated measures on interval (6 or 7 semitones), pitch direction (ascending, descending), and intensity (high static, low static). A significant main effect of interval was observed, $F(1,\ 39) = 11.87$, $p < .01$, $\eta_p^2 = .23$. When intensity remained static across the two pitches, ratings of interval size were significantly larger for 7-semitone intervals ($M = 3.10$, $SE = 0.09$) than for 6-semitone intervals ($M = 2.90$, $SE = 0.07$). There were also significant main effects of intensity, $F(1,\ 39) = 97.12$, $p < .001$, $\eta_p^2 = .71$, and pitch direction, $F(1,\ 39) = 11.40$, $p < .01$, $\eta_p^2 = .23$. Intervals presented at a high static intensity level ($M = 3.75$, $SE = 0.11$) were rated as significantly larger than intervals presented at low static intensity ($M = 2.26$, $SE = .09$). Furthermore, intervals presented with ascending pitch direction ($M = 3.11$, $SE = 0.08$) were rated as significantly larger than the same intervals presented with descending pitch direction ($M = 2.89$, $SE = 0.08$). There were no significant interactions between interval, pitch direction, or intensity.[4]

DISCUSSION

The results of the investigation confirm that musically untrained listeners were sensitive to small differences in interval size when intensity was static: Ratings of perceived interval size were significantly higher when intervals differed by 7 semitones than when they differed by 6 semitones. However, this association was dependent on the overall intensity of the stimuli, the changes in intensity from one pitch to the next, and whether the interval was ascending or descending. Such influences on the perception of pitch relations by acoustic attributes other than fundamental frequency have been reported in other investigations (Russo & Thompson, 2005a, 2005b; Thompson et al., 2010) and illustrate contexts in which identical intervals are perceived as different in size on a phenomenological level. Such differences occur even for musically trained participants who can classify the intervals in question (Russo & Thompson, 2005b) and cannot be explained by errors in the extraction of the individual pitches involved (Russo & Thompson, 2005a). Rather, the effects may reflect a nonanalytic mode of processing musical intervals that is susceptible to influences by acoustic attributes other than pitch (Makeig, 1982).

Across the two intervals, ratings of interval size were higher for high-intensity stimuli than for low-intensity stimuli, regardless of whether those stimuli were individual gliding tones (Experiment 1) or pairs of discrete tones (Experiment 2). One explanation of this finding is that high-intensity acoustic information is processed in magnified detail because it is salient and hence prioritized perceptually. When stimuli are prioritized for processing, changes occurring in those stimuli may be more noticeable. More noticeable changes, in turn, may seem larger than less noticeable changes. A related explanation is that high-intensity stimuli elicit higher levels of physiological arousal (Krumhansl, 1997) and have greater emotional connotations (Schubert, 2004) than low-intensity stimuli. Higher ratings of interval size may reflect the heightened arousal and emotion associated with high-intensity stimuli. Such explanations assume that estimations of change are influenced by the overall impact of stimuli, which is influenced not only by the extent of pitch change but also by other salient attributes of stimuli such as intensity.

Ratings were also higher for looming (up-ramp) stimuli than for fading (down-ramp) stimuli. This

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[4] We conducted a second analysis using rating data that were normalized for each participant. All significant effects reported for the analysis of raw data were observed when data were normalized. These analyses are available by request from W.F.T.

finding indicates that the well-known tendency to overestimate changes in looming auditory stimuli applies not just to judgements of intensity (e.g., Neuhoff, 1998, 2001; Olsen et al., 2010; Susini et al., 2007), but also when participants are engaged in a pitch-judgement task. That is, auditory stimuli that imply approaching motion of the sound source affect perceptual judgements even when they relate to another perceptual dimension or quality other than loudness.

Neuhoff (1998) argued that overestimation of intensity change in looming stimuli reflects an adaptive tendency to underestimate the time of arrival of "approaching" stimuli, which prepares organisms to respond effectively to these biologically significant events. Our results suggest that the tendency to overestimate stimulus changes in looming stimuli is not restricted to an assessment of the time of arrival of stimuli, in that pitch changes as presented here are not reliable indicators of approaching stimuli. As proposed by McDermott, Lehr, and Oxenham (2008), the extraction of stimulus change may be a general feature of the auditory system that can be engaged to represent not only pitch but also dynamic patterns of intensity and timbre (brightness). The effects reported in the present investigation may reflect the presence of such general mechanisms that operate on multiple sensory attributes.

It should be noted that the effect of looming was most clearly evident for ascending intervals. For descending intervals, the effect was reduced in Experiment 1 and was unreliable in Experiment 2. One explanation for this asymmetry derives from the observation by McBeath and Neuhoff (2002) that there is a natural correlation between changes in intensity and frequency. When sound sources such as accelerating engines or human vocalizations increase in intensity, their rate of vibration or frequency also tends to increase, and vice versa. As such, descending intervals may have implied a corresponding decrease in intensity, reducing any potential effect of looming intensity on perceived interval size. McBeath and Neuhoff proposed that a neural structure incorporates a processing bias to take advantage of this natural correlation between changes in intensity and frequency, giving rise to perceptual interactions such as those observed in our investigation.

An alternative to the above accounts that warrants consideration is that the effects of intensity on ratings of interval size merely reflect a response bias that arose in the absence of salient differences along the relevant perceptual dimension. That is, participants may have had difficulty distinguishing the two interval sizes presented and may have resorted to using differences in irrelevant acoustic attributes as the basis of their ratings. This account implies that the effects observed did not reflect a genuine perceptual interaction between acoustic attributes but a conscious or inadvertent misuse of the rating scale.

Four factors cast doubt on this explanation. First, when gliding (Experiment 1) or discrete (Experiment 2) intervals were presented at a static intensity, ratings of interval size were significantly larger for 7-semitone intervals than for 6-semitone, confirming that the relevant dimension of pitch distance influenced ratings. Second, we observed the same effects of intensity on perceived interval size in a control experiment that involved intervals of 6 and 10 semitones, and there was no correlation between the capacity to discriminate the two intervals and the tendency for interval size ratings to be influenced by intensity. Third, on each trial, participants were presented with a pitch interval spanning a minimum of 6 semitones and were specifically asked to rate the distance between the two pitches. Participants were never asked to judge differences that were near or below discrimination thresholds, nor were they asked to discriminate pairs of intervals. Finally, the effects of intensity on ratings of interval size were not restricted to conditions in which there was a change in intensity. In both Experiments 1 and 2, ratings of interval size were higher for intervals presented at a high static intensity than for those at a low static intensity. If participants had based their ratings on *changes* in irrelevant attributes because they were unable to detect changes in the relevant dimension from trial to trial, the latter findings would not be expected. In view of these considerations, we conclude that the effect of stimulus intensity on judgements of interval size occurs at a perceptual level, consistent with other findings of perceptual interactions between intensity and pitch (Doppler, 1842; McBeath & Neuhoff, 2002; Melara & Marks, 1990a, 1990b; Neuhoff et al., 2002; Neuhoff & McBeath, 1996; Suzuki & Takeshima, 2004).

We also observed effects of pitch direction. As seen in Figures 1–3, ratings of interval size were generally higher for ascending intervals than for descending intervals. Russo and Thompson (2005b) also observed an effect of direction on interval size ratings. They examined judgements of interval size at two pitch registers: one centred at F3 (174.6 Hz) and one centred at F4 (349.2 Hz). The effect of pitch direction was dependent on the pitch register of the interval. Those centred at F4 were rated as larger if they were ascending than if they were descending; those centred at F3 were rated as larger if they were descending than if they were ascending. One explanation for this interaction is that listeners expect movement towards the middle of an established pitch register (Huron, 2006; Von Hippel & Huron, 2000). Movement away from the middle of the pitch register is unexpected. When one event is followed by an unexpected event, the two events are perceived to be psychologically distant. The psychological distance between pitches, in turn, may be reflected in judgements of interval size.

The latter explanation cannot account for the effect of pitch direction observed in this investigation, however, because only one pitch register was examined. As such, ascending and descending intervals were always centred at the same pitch register, which was in between the high and low pitch registers examined by Russo and Thompson (2005b). We now consider two alternative explanations for this asymmetry.

The first explanation draws on findings that musically trained and untrained listeners can infer tonal structure and musical scales from short fragments of music, including isolated intervals (Cohen, 1991; Thompson & Parncutt, 1997). Across trials, listeners may have inferred tonal structure from the intervals, with the lower tone functioning as a prototype for the set of tones in the scale (i.e., the tonic, or "doh" in the scale do-re-mi-fa-sol-la-ti-do). This possibility applies to either experiment because pitch changes in music can be continuous (e.g., as produced by a voice or violin) or discrete (e.g., as produced by a piano or recorder). Consistent with asymmetries reported for other prototypes (Bartlett & Dowling, 1988; Bharucha & Krumhansl, 1983; Iverson & Kuhl, 2000; Schellenberg & Trehub, 1994), estimates of the distance between two tones should be greater when a more stable tone (the lower pitch tone) is the first tone or referent than when a less stable tone (higher pitch tone) is the referent.

Research by Krumhansl (1979) supports this hypothesis. She presented listeners with two tones and asked them to judge the similarity between them. When the first tone was more stable than the second tone (e.g., the tonic of an established musical scale), ratings of the similarity between tones were lower (i.e., a larger psychological distance) than when the first tone was less stable than the second tone (see Krumhansl, 1979, Table 3, p. 358). In the current study, the first tone of ascending intervals may have been perceived as more stable than the second tone, whereas the first tone of descending intervals may have been perceived as less stable than the second tone.

A second explanation draws from observations of a ubiquitous tendency in human vocalizations for vocal pitch to decline as an utterance progresses (Lieberman, 1967; Pike, 1945; 't Hart, Collier, & Cohen, 1990). As the air supply in the lungs is depleted, the subglottal air pressure drops, leading to a tendency for vocal pitch to decline. As such, any localized rises and falls in pitch that carry linguistic meaning are superimposed on a baseline contour that gradually drifts downward. Stimuli that are counter to this general tendency, such as rising intonation characteristic of questions, may conflict with expectations based on the physiological constraints of vocalization. The psychological distance between the initial and final tones of an interval should be larger when the pitch changes in an unexpected direction than when it changes in an expected direction. That is, when one pitch follows another in an unexpected manner, those pitches may be judged to be psychologically distant from each other, giving rise to higher ratings of interval size.

To conclude, the current findings contribute to a growing body of evidence that the perception of interval size is not always consistent with predictions based on a logarithmic scale, but is influenced by other acoustic attributes. By revealing an influence by a nonspectral property of sound on judged interval size, our findings extend previous evidence showing that relative pitch is dependent on spectral attributes such as tonal context, timbre, and overall pitch height (Krumhansl, 1979; Russo & Thompson, 2005a, 2005b). Our findings also inform hypotheses outlined by Neuhoff (1998, 2001) and Huron (1992, 2001). High-intensity and looming auditory stimuli may be prioritized for processing because of their potential biological significance. Changes that occur within prioritized stimuli, in turn, may be perceptually magnified as an adaptive response to such stimuli. The expressive use of dynamic intensity in music may exploit such perceptual effects, illustrating an aesthetic manifestation of a biological adaptation.

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