©American Psychological Association, 2017. This paper is not the copy of record and may not exactly replicate the authoritative document published in the APA journal. Please do not copy or cite without author's permission. The final article is available, upon publication, at: http://dx.doi.org/10.1037/pmu0000172 Perceiving Changes of Sound-Source Size Within Musical Tone Pairs Joseph S. Plazak Illinois Wesleyan University Stephen McAdams McGill University

Author Note

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Abstract

Recent research suggests that the perception of sound-source size may be based in part on attributes of timbre, and further, that it may play a role in understanding emotional responses to music. Here, we report two perceptual studies in which the TANDEM-STRAIGHT vocoder was used to modify musical instrument tones in order to emulate equivalent instruments of different sizes. In each experiment, listeners heard sequential tone pairs in which tones from the same instrument were manipulated to sound as if they had originated from a larger or smaller source. Manipulations included modifications of both fundamental frequency (f0) and spectral envelope. Participants estimated the direction and magnitude of these size changes. We collected data both with and without RMS normalization of the output of the TANDEM-STRAIGHT vocoder in Experiments 1 and 2, respectively. In both cases, manipulations of 0 and spectral envelope were found to have significant effects on the perception of sound-source size change, although results varied across musical instruments and depended on whether the sounds were equalized in level. The results uncover several important considerations for understanding musical timbre and pitch, and are discussed in light of implications for the perception of musical affect.

Keywords: size perception, timbre, formant dispersion, spectral envelope, pitch register

Perceiving Changes of Sound-Source Size Within Musical Tone Pairs

Although the perception of sound-source size is among the many facets of pitch and timbre, the role of hearing size cues within the context of music perception is relatively unknown. Size information, primarily encoded within fundamental frequency and resonance patterns, is salient in many types of sounds, including animal communication (Morton, 1977; Fitch, 1994), speech (Smith, Patterson, Turner, Kawahara & Irino, 2005), and musical instrument sounds (Chiasson, Traube, Lagarrigue & McAdams, 2016). Chiasson et al., for example, found that sound "extensity" ratings by listeners using both ordinal and ratio scales could be related to the notion of "volume" (which may be roughly translated as "largeness" in French) as predicted by the French composer and orchestration treatise writer Charles Koechlin (1954). Similarly to Koechlin, but in the sphere of psychoacoustics, S. S. Stevens and colleagues have also proposed that "volume" be defined as "an apparent largeness and extensiveness." Stevens & Davis (1938) and Terrace & Stevens (1962) conducted studies on the perception of volume for pure tones and observed that volume increased when loudness increased and pitch decreased. Within speech, sound-source size ("source size" hereafter) is useful for both comprehending "what" a given message means and determining "who" is speaking (Patterson, Gaudrain, & Walters, 2010). However, within music perception, the implications of perceiving the size of a given sound source, and especially the ability to perceive changes in source size, have received little attention.

The literature on auditory size reports numerous examples of our capacity to hear size. Lakatos, McAdams, and Caussé (1997) found evidence that listeners can decode spatial dimensions of metal and wooden bars from sound cues alone. Kunkler-Peck and Turvey (2000) reported that listeners successfully infer size, shape, and material information from the sounds of plates being struck by a pendular hammer. Other research reports the capacity to infer the size of animals (Vestergaard et al., 2009), humans (Smith, Patterson, Turner, Kawahara, & Irino, 2005; Ives, Smith & Patterson, 2005), and musical instruments (van Dither & Patterson, 2006; Chiasson et al., 2016). Further, neurological evidence suggests that both adults and newborn infants can hear changes of musical instrument size, suggesting that this ability could possibly be innate (Vestergaard et al., 2009).

The psychophysical basis of auditory size perception involves two key acoustic features: fundamental frequency and acoustic scale/resonance (Cohen, 1993; Fitch, 1994; Smith et al., 2005). Relatively lower frequencies originate from larger, or more massive, sound sources, and therefore, fundamental frequency is often considered to be an important cue for perceiving affective size information (Huron, 2012). There are, however, a few exceptional cases in which sound sources can produce sounds that are much lower in frequency than would be expected from their size, as is the case with the low-pitched mating call of male koalas (Charlton et al, 2013). Resonance information, the reinforcement of certain frequencies above a fundamental frequency, also plays an important role in determining the size of many types of sounds. Within speech, vowels have distinctive resonance patterns (i.e., formant placements). For a given vowel, ratios between formants remain relatively constant from speaker to speaker, but the absolute placement of these formants differ depending on the given sound source. The absolute placement of formants is therefore thought to be useful for differentiating amongst multiple sound sources (Fitch, 1997; Patterson et al., 2010). Similar factors are at play when discriminating different musical instruments within a given instrument family. For example, one of the primary differences between a violin and a viola sounding the same fundamental frequency is the absolute placement of the resonances; the larger-sized viola typically exhibits resonant peaks at lower frequencies (van Dinther & Patterson, 2006)

The cues that are used to perceive timbral changes related to source size have been examined across a variety of modalities. Research indicates that our sensitivity to synthesized source-size change varies by stimulus; synthesized vocal consonants and spoken words have a just noticeable difference (JND) of about 5% (Ives et al., 2005; Irino, Aoki, Kawahara, & Patterson, 2010), whereas vowels have a size-change JND near 7% (Smith et al., 2005), and musical instruments have a JND around 10% (van Dinther & Patterson, 2006). Further, our ability to use spectral filter clues to infer the size of a sound source is generalizable beyond those sounds normally encountered in everyday life (Smith et al., 2005; Ives, et al., 2005; Irino et al.,

2010), and this finding also applies to musical sounds (van Dinther & Patterson, 2006). Despite this existing research, still relatively little is known about the way in which source size cues are perceived within a particular musical instrument. Musicians regularly alter the timbre/tone of their instruments, and the construct of source size may be useful towards understanding the perception of these timbral changes and, potentially, their role in orchestration practice and live electronic modification of acoustic instruments.

This study is interested in changes of source size. This interest is unique from other research that has examined the ability of listeners to discriminate between different instruments from within and beyond a given instrument family (e.g., van Dinther & Patterson, 2006). We believe the concept of "changing source size" may be useful within music perception in that musical agents (i.e., instruments) are typically constant within a given musical work, and yet, musical textures can expand and contract to sound larger or smaller. Further, we believe that the perception of changing source size may have important implications for understanding emotional responses to music. As an example, an EEG study conducted by Vestergaard et al. (2009) found that size increases of musical tones elicited a relatively larger mismatch negativity response in adult listeners compared to size decreases, suggesting a possible asymmetric sensitivity to changes of source size. Asymmetrical responses have been reported for other psychoacoustic features, such as the estimation of global loudness levels for tones with increasing and decreasing intensity envelopes (Susini, McAdams, & Smith, 2007). Therefore, one motivation behind the design of the current study was to investigate the role of source size asymmetry across a large number of musical size changes.

Despite our current understanding of the physical basis by which source size is transmitted, a number of perceptual questions remain. The primary aim of this research was to extend the literature on auditory size by investigating the perceived magnitude of changing source size within singular musical sound sources. Such changes might lead to new insights on the topic of musical orchestration and emotional communication via music. We also sought to further investigate the possibility of an asymmetrical perception to changing source size by using a larger number of paired size changes than has been previously reported in the literature. In particular, we hypothesized that musical sounds with cues indicating an increased source size

would be perceived as having a larger change magnitude relative to comparable decreasing source-size cues. Finally, we also sought to explore the interaction of source and filter manipulations on the perception of source-size change by examining the perception of both independent and concurrent modifications of fundamental frequency and spectral envelope ratios. These hypotheses were tested using an initial binary judgment of direction of size change (larger or smaller) followed by a rating to quantify the perceived sizechange magnitude heard by participants. Below, we report two perceptual studies in which the TANDEM-STRAIGHT vocoder was used to modify musical instrument tones in order to emulate equivalent instruments of different sizes. We collected data both with and without RMS normalization of the output of the TANDEM-STRAIGHT vocoder in Experiments 1 and 2, respectively. To foreshadow our results, both studies found that manipulations of f0 and spectral envelope had significant effects on the perception of source-size change, although results varied across musical instruments and depended on level equalization.

Experiment 1

We synthesized perceptual stimuli using the TANDEM-STRAIGHT vocoder to emulate equivalent instruments of different sizes. We presented these synthesized tones (as pairs) to listeners who estimated the direction and magnitude of these size changes. We used the direct output of the TANDEM-STRAIGHT vocoder without any further signal processing.

Methods

Participants. Twenty participants (16 females, mean age=26 years, SD=11.9, range = 18–67) were recruited via a McGill University classified ad. Participants were compensated for their participation. The experiment lasted approximately one hour. Eight of these participants indicated in a post-experiment survey that they self-identified as being amateur or professional musicians. Before the experiment, participants passed a pure-tone audiometric test using a MAICO MA 39 (MAICO Diagnostic GmbH, Berlin, Germany) audiometer at octave-spaced frequencies from 125 Hz to 8 kHz and were required to have thresholds at or below 20 dB HL to proceed to the experiment (ISO 389–8, 2004; Martin & Champlin, 2000). All participants provided informed consent, and this research was certified for compliance with ethical standards by the McGill University Research Ethics Board II.

Stimuli. The experimental stimuli consisted of melodic intervals constructed from five sounds with different musical timbres. In order to avoid issues that might arise from tessitura on a given instrument, notes were chosen from the approximate middle of the instrument's fundamental frequency range. The samples, along with the pitch of each sample, included: alto saxophone (F4), oboe (E4), French horn (C4), cello (F3) and male voice (F3), where C4 has a fundamental frequency of 261.6 Hz. The instruments were chosen to

include a representative instrument from the single-reed, double-reed, brass, and string-instrument families. Instrument samples were collected from the Iowa University Musical Instrument Samples collection, and the voice sample was collected from an online database of open-source sound files (freesound.org). All instrument samples were classified at a mezzo-forte marking. Throughout this experiment, stimulus pairs always consisted of two tones from the same instrument. Individual tones varied in duration from 1 to 3 s and pairs from 3 to 7 s.

The spectral envelope for each of the five musical tone samples was scaled to 10 different "sizes" using the TANDEM-STRAIGHT vocoder (Kawahara, 2006; Kawahara, Takahasi, Morise, & Banno, 2009). TANDEM-STRAIGHT analyzes and extracts independently the fundamental frequency (f0) and spectral envelope shape (referred to by van Dinther & Patterson, 2006, as pulse rate and resonance scale, respectively), and then allows these two components to be independently manipulated. Specifically, the vocoder calculates the ratio of spectral peaks relative to the current fundamental frequency (Kawahara et al., 2009), and then allows the intensity of these spectral peaks to be scaled, so that the "content" (i.e., vowel / instrument family) remains the same, yet the impression of the sound source is changed (i.e., the "size" of the source can be altered). To obtain the different auditory sizes, we scaled the spectral filters of each audio sample in 10 different steps ranging from 0.5 to 1.5 times the scale of the original filter (see example in Figure 1). "Change of size was labeled based on the difference between the spectral envelope ratios (SER) of the two tones contained within a given tone pair (referred to hereafter as SER change). For example, if a tone modified to sound 25% smaller was followed by the same original tone modified to sound 25% larger, the change of size was referred to as a change of 1.67 (i.e., 1.25 / 0.75). In this same example, if the larger tone was presented and then followed by the smaller tone, the change was referred to as a size change of 0.6 (i.e., 0.75 / 1.25). In total, the five instrument samples (described above) were subjected to 10 different spectral filter modifications before being matched to create 10 SER change ratios: 0.33, 0.60, 0.74, 0.82, 0.90, 1.11, 1.22, 1.35, 1.67, 3.00. Note that increasing (e.g., a pair consisting of modified tones A & B) and decreasing (e.g., a tone consisting of modified tones B & A) size pairs were made from the same stimuli, only the temporal order of tones was reversed. Matching the stimuli within tone pairs allowed us to test the possibility of an asymmetrical perception in response to increasing and decreasing size changes. Within our initial experiment, the intensity levels produced by TANDEM-STRAIGHT manipulations were not modified or renormalized. The tone pair audio files used in Experiments 1 and 2 are available within the supplementary materials section.

<INSERT FIGURE 1 HERE>

Scaled instrument samples were also subjected to manipulations of the fundamental frequency (f0), which were again performed using the TANDEM-STRAIGHT vocoder. Each of the five musical tone samples was synthesized to sound at the same pitch level ($f_0 x 1$), a major 2nd higher ($f_0 x 1.125$), or a perfect 5th higher ($f_0 x 1.5$). These three different tones were then assembled to form five unique melodic pitch intervals: Perfect Unison, Ascending Major 2nd, Descending Major 2nd, Ascending Perfect 5th, and Descending Perfect 5th. We chose these five intervals to examine the influence of common musical pitch intervals on perceived changes of sound source size. Our pitch manipulations made no attempt to cover the entire pitch range of our chosen musical instruments. Further, although we aimed to use source files that were characteristic of each musical instrument, source and filter cues are known to interact differently across

an instrument's pitch range, and therefore, our choice of a single reference source file for each instrument

will limit the generalizability of our results. In this experiment, we were specifically interested in within-

instrument musical pitch manipulations that could be commonly observed within a typical melody.

In total, a corpus of 250 melodic dyads was created. The corpus consisted of five different instrument samples, ten SER change manipulations, and five different pitch intervals. Over the course of the one-hour experiment, participants heard and provided ratings on the complete corpus.

The experiment took place in an IAC model 120 act-3 double-walled audiometric booth (IAC Acoustics, Bronx, NY). Audio signals were sampled at 44.1 kHz with 16-bit amplitude resolution and stored on a Mac Mini computer running OS 10.6.8 (Apple Computer, Inc., Cupertino, CA). Stimuli were amplified through a Grace Design m904 monitor (Grace Digital Audio, San Diego, CA) and presented via Sennheiser HD280 Pro earphones (Sennheiser Electronic GmbH, Wedemark, Germany). Sounds were presented at an average level of 57 dB as measured with a Brüel & Kjær Type 2205 sound-level meter (A-weighting) and a Bruel & Kjær Type 4153 artificial ear (Bruel & Kjær, Nærum, Denmark) coupled to the HD280 Pro headphones.

Procedure. Participants were told that the goal of the experiment was to test which acoustic factors result in making some instruments sound larger or smaller than other instruments. After obtaining consent and completing audiometric testing, participants were asked to estimate the perceived size-change magnitude that occurred across various musical tone pairs. Specifically, they were instructed to judge the size of the second tone relative to the size of the first. Participants were given the following example: "You may hear the sound of a small flute followed by the sound of the large flute. Your task is to determine the size of the second source relative to the first." Participants were also told that each block would consist of sounds from only one of the following instruments: cello, oboe, voice, alto saxophone, and French horn.

Before the experiment began, the experimenter allowed participants to hear up to four example stimuli that were randomly selected from the full stimulus set. No feedback was provided regarding the direction or magnitude of the size changes contained in these stimuli. Data from these practice trials were not recorded. Five experimental blocks, each of which consisted of 50 melodic musical intervals from a single instrument, were presented in random order. The 50 trials within each block (five pitch intervals combined with ten SER changes) were also randomized. The experimental session was run with the PsiExp computer environment (Smith, 1995). Participants listened to each musical dyad as many times as they wished (via an on-screen repeat button), and then provided subjective ratings of the dyad using a two-step process. First, they reported whether the second sound was relatively "larger" or "smaller" than the first by clicking on-screen virtual buttons. After making this binary judgment, they then rated the magnitude of the size change (i.e., "how much [larger or smaller] was the second sound") on a continuous scale with equally spaced indicators from 1 ("a little" on the far left of the scale) to 7 ("a lot" on the far right) using an on-screen virtual slider. They were encouraged to use the entire scale. Participants were free to change their initial binary response (i.e., "larger" or "smaller") at any time within a trial.

Results and Discussion

By combining the participants' binary judgments ("larger" or "smaller") and magnitude judgments ("how much"), perceived size-change scores were formulated. If a participant indicated that the second sound originated from a smaller source, the associated magnitude rating was assigned a negative value (and vice-versa). In this regard, the actual scale used for data analysis ranged from -7 to -1 (for dyads of decreasing size), and 1 to 7 (for dyads of increasing size). In order to normalize the data so that the midpoint of our scale was centered near zero, we subtracted .99 from all positive size-change ratings, and added .99 to all negative size-change ratings. The result was a measure of perceived size-change magnitude that ranged from -6.01 (a lot smaller) to -0.01 (a little smaller) and 0.01 (a little bigger) to 6.01 (a lot larger). Consistent with the initial binary judgment, ratings of zero (i.e., no change) were not possible. In general, our participants responded to manipulations of both pitch and SER (i.e., spectral filter) as predicted. Specifically,

decreasing pitch manipulations and increasing SER changes were both generally associated with increasing sound source size.

In order to examine the relationship between perceived size-change magnitude scores and the manipulations of SER change and f0 on the sounds for each instrument, we performed a linear mixed-effects analysis using R (R Core Team, 2014) and lme4 (Bates, Maechler & Bolker, 2014). The advantage of the LMM approach over traditional omnibus analyses of variance is that it takes into account variability due to participants and stimulus items. SER change, fundamental frequency change, and instrument were entered into the model as fixed effects. We also included the interactions between SER change, fundamental frequency change, and musical instrument as potential variables of interest. Following Barr et al. (2013), we included a random-effects structure with random intercepts for each participant and each stimulus, as well as by-participant slopes for the three within-subject fixed factors. Our mixed-effects model accounted for approximately 46% of the variance, adjusted R^2 (4998)=.46, p < .001. In order to calculate significance of main fixed effects and interactions, we employed the Anova function from the car package (Fox & Weisberg, 2011) to perform post-hoc Type II Wald chi-squared tests. On average, size-change ratings increased with SER change and pitch interval, and reflected the direction of change. However, both factors interacted with instrument and with each other. All three two-way interactions were significant: between SER change and pitch interval, SER change and instrument, and pitch and instrument. The three-way interaction between instrument, pitch interval, and SER change was not statistically significant. The results are listed in Table 1.

<INSERT TABLE 1 NEAR HERE>

Given that instrument interacted significantly with both other factors, separate linear mixed-effects analyses were performed for each instrument to further explore these interactions, again using R and lme4. Each model contained fixed effects of SER change ratio and pitch interval (with interaction), as well as a random-effects structure that consisted of random intercepts for each participant and stimulus, and random slopes (by-participant) for the fixed factors (SER change and pitch interval). Models for the cello and the French horn failed to converge. Therefore, for these two models only, and in order to keep interactions with instrument, which was a factor of primary interest in this study, we omitted the interaction of SER change ratio and pitch interval within the random effect structure, while leaving all other factors the same. The results for these models are provided in Table 2 and plotted in Figure 2. Given that five analyses were performed, the experiment-wise significance criterion was set to p = .01.

<INSERT TABLE 2 NEAR HERE> <INSERT FIGURE 2 NEAR HERE>

Several unique perceptual patterns can be observed in Figure 2. SER change had a significant effect on perceived size-change magnitude for the voice (see Table 2). SER changes resulted in perceived size changes in the corresponding direction (note the positive regression lines in the corresponding panels in Fig. 2). For the cello and alto saxophone samples, increases in fundamental frequency, but not increases in SER

change ratio, had a significant negative effect on perceived size-change magnitude. These results are indicated by the different heights of the lines in Figure 2 for these instruments. Lastly, a significant interaction was found between the factors of SER change ratio and fundamental frequency for the oboe. This latter result indicates a greater effect of SER change for small intervals (unison, major 2nd). Note that the slopes are steeper for these intervals than for the perfect 5ths, and that the ascending perfect 5th slope is steeper than the descending perfect 5th slope.

Due to the matched presentation of our stimuli, we compared differences between tone pair increases and decreases for a given pitch interval and instrument. For a hypothetical musical dyad, AB, tone pair decreases occurred whenever tone B has been synthesized with a smaller SER than tone A. If these same two tones were presented in the opposite order (BA), the result might be considered a SER "distance" of comparable size to AB. One might expect that for any given matched tone pair, the perceived size-change magnitudes for an "AB" presentation would be opposite but equal to a matched "BA" presentation. In order to test for possible asymmetrical responses to increasing and decreasing source-size tone pairs, participant responses were averaged across all pitch intervals and instruments for each of the 10 different SER changes. We then took the absolute value of this average response and performed paired Wilcoxon signed-rank tests between ratings of comparable tone pair increases and decreases (SER change pairs of 0.95/1.05, 0.9/1.1, . 85/1.15, 0.75/1.25, and 0.5/1.5). These results are depicted in Figure 3.

<INSERT FIGURE 3 NEAR HERE>

Globally across instruments, increases of size were perceived to be of greater magnitude than corresponding decreases, and this absolute average-value difference was significant for three of the five sizechange pairs after Bonferroni-Holm correction. Specifically, tone pairs consisting of the SER values 0.95 and 1.05 were perceived as having significantly larger perceived change magnitude when the smaller SER (0.95) was presented first, W=1, Z=-2.91, p=.004. Similar results were found for tone pairs consisting of the SER values .85 and 1.15, W=1, Z=-2.61, p=.009, as well as tone pairs consisting of SER values of 0.75 and 1.25, W=1, Z=-2.43, p=.015. Curiously, the largest size change did not produce a significant asymmetry in response, perhaps due to the greater variability in ratings for these stimuli. Given the significant interaction

between SER change and instrument, we performed this same asymmetry analysis separately for each

instrument. However, no systematic asymmetries were found after Bonferroni-Holm correction, suggesting

that this effect is not reliable.

Finally, we also investigated the possibility that intensity changes introduced by the TANDEM-STRAIGHT vocoder may have influenced the participant's subjective ratings of perceived size change. We first computed the average RMS values for each source file using Praat (Boersma & Weenink, 2016), and then calculated the average RMS difference between the first and second tones of each stimulus pair. We found that SER change was significantly and positively correlated with change in RMS amplitude for all instruments, r(48) = .87, p < .001. Maximum RMS change between samples was between 4.4 dB (for saxophone stimuli) and 7.3 dB (for horn stimuli). Next, we ran a correlation analysis to determine how much of the variance in subjective ratings of size change could be explained by the average RMS difference between the two tones. We found that for both voice and oboe samples, mean responses were significantly correlated with RMS change, r(48)= .848 and .527, respectively, p < .001 in both cases, thus leaving the possibility that small differences in loudness influenced judgments of size-change magnitude for these instruments. Therefore, in order to ensure that our results resulted from manipulations of SER and pitch changes, we repeated our experimental paradigm using RMS-normalized samples.

Experiment 2

In our second experiment, we used the stimuli from Experiment 1, but we normalized the RMS

amplitude of TANDEM-STRAIGHT's output for each tone to control for potential intensity differences

between tones within a tone pair.

Methods

Participants. An additional 20 participants (16 females, mean age=21.8 years, SD=3.0, range=18-31) were recruited via a McGill University classified ad. Participants were compensated for their participation. The experiment lasted approximately one hour. Eight of these participants self-identified as amateur or professional musicians in a post-experiment survey. Participants followed the same pre-test assessment described in the previous experiment.

Stimuli. The experimental stimuli were nearly identical to those used in Experiment 1, except that the levels of the source stimuli were normalized before forming stimulus pairs. RMS values of each sound file were determined with Praat, and normalization was accomplished via SoX (sox.sourceforge.net), which ensured that all stimuli had identical RMS values.

Procedure. The procedure was identical to that of Experiment 1.

Results and Discussion

Our process for formulating perceived size-change scores was identical to the procedure used in our initial experiment. Once again, decreasing pitch manipulations and increasing SER changes were both generally associated with increasing source size. We examined the relationship between perceived size-change magnitude scores and the manipulations of SER change and f0 via a linear mixed-effects model. We

again included a random-effects structure with random intercepts for each participant and each RMSnormalized stimulus, as well as by-participant slopes for the three within-subject fixed factors. Our mixedeffects model again accounted for approximately 46% of the variance, adjusted $R^2(4998)$ = .46, p < .001. The analysis is summarized in Table 3. Although the results of this model were similar, they were not identical. When utilizing RMS-normalized stimuli, the main effect of instrument was no longer significant, nor was the interaction between SER change and pitch change. This may suggest that intensity differences influenced subjective ratings of perceived source-size change in Experiment 1, and further, that the differences in that experiment may have varied across instruments.

<INSERT TABLE 3 NEAR HERE>

As in Experiment 1, we observed unique patterns amongst the five instruments used in the present experiment as indicated by significant interactions between instrument and SER change, as well as between instrument and f0. Therefore, we again proceeded to calculate a post-hoc linear mixed-effects model for each instrument. Each model contained fixed effects of SER change ratio and pitch interval (with interaction), as well as a random-effects structure that consisted of random intercepts for each participant and stimulus, and random slopes (by-participant) for the fixed factors (SER change and pitch interval). The results for each model are provided in Table 4 and the data are plotted Figure 4.

<INSERT TABLE 4 NEAR HERE> <INSERT FIGURE 4 NEAR HERE>

A few unsystematic differences can be observed between Figures 2 and 4. The main effect of SER change was maintained under RMS equalization for voice (increasing ratings with larger size changes in the appropriate direction), and the effect became significant for the oboe and marginally significant for the cello, which is in direct opposition to the hypothesis that the main effects in Experiment 1 may have been driven by RMS differences. It should also be noted that for the oboe and horn samples, the interaction of SER change with pitch interval disappeared with equalization. The main effect of pitch interval remained the same under RMS equalization, with significant pitch interval effects observed for both the alto saxophone and cello samples. Based on these findings, results from Experiment 2 might be considered a clearer assessment of SER manipulations on perceived changes of source size.

Again, we compared differences between matched tone pairs for a given pitch interval and instrument. Using the same procedure as in Experiment 1, we performed paired Wilcoxon signed-rank tests between ratings of comparable tone pair increases and decreases. Unlike Experiment 1, in which asymmetrical responses were found between three of the SER change groups, in Experiment 2 with RMS-normalized stimuli, no significant asymmetry was found after Bonferroni-Holm correction. These results are depicted in Figure 5.

<INSERT FIGURE 5 NEAR HERE>

General Discussion

In both experiments, spectral envelope ratio (SER) change and fundamental frequency (f0) change affected the perception of the magnitude of perceived changes in source size. The relative roles of these two cues were different for the five instruments tested. Furthermore, in some cases across instruments, asymmetries in the perception of size change were found depending on the direction of change of SER, but these asymmetries disappeared when using RMS-normalized stimuli. The implications of these findings are discussed below.

Consistent with other studies that have utilized the TANDEM-STRAIGHT vocoder to investigate auditory size perception (see Patterson & Irino, 2014, for an overview), results from the present study on perceiving changes of source size found that SER and fundamental frequency modifications had significant

effects on perceived size-change magnitude, with the results varying by instrument. The process of normalizing the levels of our tone pairs also resulted in some changes in the pattern of results. In general, SER changes had a significant effect on perceived size change for the voice stimuli, which became significant for the oboe and marginally significant for the cello when the stimuli were RMS-normalized. Fundamental frequency changes resulted in significant effects for alto saxophone and cello stimuli in both experiments and were thus unaffected by level normalization. SER change and f0 had an interactive effect for the oboe stimuli and a marginally significant effect for the French horn stimuli, in which smaller intervals showed stronger changes in perceived size with changes in SER, but this interaction effect disappeared when the stimuli were equalized in RMS amplitude.

Our results are mostly consistent with the work of van Dither & Patterson (2006), who found that listeners reliably discriminate SER change in musical instrument samples. Our data reveal that for two RMS-normalized sources, namely the voice and oboe tone pairs, SER changes were rated with predictable increases and decreases of size-change magnitude; results for the cello tone pairs were marginally significant (p < .012). Similar to van Dither & Patterson (2006), our SER manipulations were associated with more pronounced perceived change for vocal timbres. SER manipulations did not have a significant effect on the perceived size-change magnitude of RMS-normalized alto saxophone or French horn tone pairs. In listening to the stimuli again, we noted that SER changes for the alto saxophone were quite subtle, and may have potentially been perceived by participants as a change of timbral brightness rather than size. This caveat notwithstanding, SER change, which has been shown to be useful for directly comparing different sound sources in the musical domain (Patterson et al., 2010), was a predictor of perceived size-change magnitude for two of the five instruments used in these experiments.

With regards to manipulations of fundamental frequency, our results for the RMS-normalized alto saxophone and cello sounds found that fundamental frequency change was a predictor of size-change magnitude. For these sounds, tone pairs with increasing fundamental frequencies (i.e., low-to-high pitch pairs) were associated with decreasing size changes, whereas tone pairs with decreasing frequencies (i.e., high-to-low pitch pairs) were associated with increasing size changes. These findings are consistent with the general notion that lower fundamental frequencies tend to be associated with larger physical sound sources (Fitch, 1997; Bonner, 2011), but in our case they were limited to only two of the five sound sources. Pitch manipulations did not have a significant effect on the perceived size-change magnitude of voice, oboe or French horn tone pairs. Despite the lack of statistical significance, the data across pitch manipulations for these tone pairs followed a similar trend: increases of frequency were associated with decreasing size, and vice versa, with the exception of the voice where this trend is not evident. Further, larger pitch manipulations (i.e., perfect 5ths) tended to have a more pronounced effect on ratings of perceived size-change magnitude than smaller pitch manipulations (i.e., major 2nds). Regarding this discussion of pitch, it bears reminding that our manipulations of f0 were synthesized via the TANDEM-STAIGHT vocoder, which could potentially be perceived differently than pitch changes performed on an actual musical instrument. That is, one should not expect pitch changes across many musical instruments to exhibit uniform spectral envelops (like those produced by the TANDEM-STRAIGHT vocoder), as would certainly be the case when pitch changes move between distinct instrument registers (such as a clarinet moving between the Chalumeau and Clarino registers).

When looking at data for the five individual instruments used in Experiment 1, the oboe exhibited

significant source/filter interactions, and this interaction was marginally significant for the French horn stimuli. Specifically, for the oboe, smaller pitch intervals showed a more pronounced SER effect. Similar interactions among pitch and spectral envelope cues, in which the data suggest a perceptual trade-off between cues, have been reported in other studies on source-size perception (Fitch, 1994; Smith & Patterson, 2005; van Dither & Patterson, 2006). It seems plausible that large pitch intervals may be more relevant to the listener than timbral changes induced by the spectral manipulations within the perception of musical instrument size changes, an idea worthy of further investigation, taking into account that it is only the case for one particular instrument. Taken as a whole, the interaction between fundamental frequency and spectral filter manipulations may be of interest in musical textures that consist of relatively conjunct musical melodies. One other potential source of variability regarding SER and pitch interaction might pertain to the strategies used by listeners to estimate size-change magnitude. In unison tone pairs with no pitch change, listeners may have utilized a unique strategy to infer source size, such as focusing on shifts of the most intense frequency component from one sound to the other. For example, the oboe sample spectral slices shown in Figure 1 reveal that the most intense frequency component changed across manipulations of SER (when f0 stayed constant). As summarized in Chiasson et al.'s (2015) model, a lower-frequency resonance is associated with larger (more extensive) sources. A deeper understanding of the strategies used by participants to infer size might therefore provide further insight into systematic interactions between SER and pitch change manipulations. In our second experiment during which all stimuli were RMS-normalized, none of the instruments exhibited a significant interaction between SER and pitch changes. When considering the results from both experiments, this provides some evidence that intensity cues may play a role in the perception of changing sound source size.

One unique feature of this study was the use of tone pairs presented sequentially in order of both increasing and decreasing acoustic scale in order to investigate a potential asymmetry in perceiving changes of source size. This asymmetry, in which larger sounds might be more salient than smaller sounds, was reported in the work of Vestergaard et al. (2009). Results from Experiment 1, when averaged across all timbres and all pitch intervals, found that three of the five tone pair categories were perceived asymmetrically in this same manner. Namely, for SER differences of .95 vs. 1.05, .85 vs. 1.15, and .75 vs. 1.25, tone pairs with increasing SERs (e.g., pair A-B) were judged as having a significantly greater change magnitude relative to the same tone pair played in the opposite direction (e.g., pair B-A). These effects disappeared when tone pairs were normalized for RMS amplitude. This finding not only highlights the importance of multiple cues for perceiving changes of source size, but also that the asymmetrical responses observed in Experiment 1 may have been the result of intensity differences between tone pairs.

Conclusion and Implications

The interaction between manipulations of fundamental frequency and spectral envelope (SER change in our case) is a complex topic with several important implications. As an example, our ability to normalize the pitch level of an unknown sound source is believed, in some situations, to benefit from the interaction of source and filter cues (Bishop & Keating, 2012). In this way, it becomes possible for the listener to

determine whether a given tone is relatively low or high in pitch for a specific sound source (i.e., "that is a pretty low tone for a flute"). Although it is straightforward to think about the absolute difference in size between a cello and a violin, the complex nature of auditory size dictates that a given instrument will be capable of producing sounds of both relatively large and relatively small sizes. This "relative" dimension of size may parallel the musical concepts of register and/or tessitura, and may be useful towards understanding how certain aspects of Sound-Size Symbolism (Morton, 1977) apply to music perception. For example, the relative "lowness" or "highness" of sound is believed to have important implications for the perception of musical affect, and therefore, the interaction between pitch and instrument (i.e., register) is worthy of further perceptual investigation. Within source-filter models of speech production (Fant, 1960), if fundamental frequency is held constant, formant dispersion should result in the perception of a changing register. With the ability to independently manipulate source and filter cues, researchers are now more capable of exploring affective associations for relatively high or low sounds. A standard quantitative measurement of source size may have practical applications within the study of communication, including music, speech, animal signals, and computer-human interactions. Specifically, the ability to quantify the size of a sound source might lead to a better understanding of how we normalize affective cues from different types of sound sources.

The primary focus of our study pertained to pitch and timbre cues that signal changes in source size, but it is important to note that there are other auditory cues of size as well. Most obviously, intensity is also an established predictor of source size, and by repeating our experimental paradigm twice, both with and without amplitude-normalized stimuli, several interesting potential effects of intensity were noted. After amplitude normalization, but with all other factors being held constant, the observed significant asymmetrical responses between matched tone pairs disappeared. Thus, while manipulating intensity did not systematically change the main effects of interest, it did seem to influence some participant's ratings of perceived size change. In order to generate a more complete model of source-size perception, future studies will need to continue to address the role of intensity cues, as well as the ways in which intensity interacts with size cues derived from f0 and SER change information. As theorized by Gussenhoven (2001), such intensity cues are particularly complex and dynamic, and serve multiple functions within speech.

Of additional value to the music community, particularly those interested in orchestration, is the notion of "combined size" within instrumental pairings. Currently, there are a number of ways in which one might quantify source size, and it seems reasonable that such measurements might lead to breakthroughs for describing or defining concepts such as instrumental blend, as suggested by Koechlin's (1954) link between *volume* (size or extensity) and *fondu* (blend). Relations between the spectral envelopes of concurrent sounds have been shown to affect the degree to which they blend together perceptually (Sandell, 1995; Lembke & McAdams, 2015). A deeper understanding of the extent to which pitch and spectral envelope interact within textures involving multiple instrument families could lead to new insights regarding the manner in which musical timbres blend together.

This research highlighted details about our capacity to perceive changes of size information from sound cues alone. Both f0 and acoustic-scale or resonance-scale cues (manipulated as SER change) were found to be important for the perception of auditory source size, although our results vary across different musical instruments. Thus, these results might serve as evidence that size-related sound cues could play an important role in understanding our perceptual and affective responses to music, especially with regards to various aspects of musical orchestration.

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	df	χ^2	p
	(1	$R^2 = .46$)	
SER Change	1	9.42	.002
Pitch Interval	4	13.45	.009
Instrument	4	13.39	.010
$SER \times Pitch$	4	15.96	.003
SER × Instrument	4	254.94	<.001
Pitch × Instrument	16	38.97	.001
SER \times Pitch \times Instrument	16	9.53	.89

Table 1. Experiment 1 (non-RMS-normalized stimuli) linear mixed-effects model Type II Wald chi-squared tests for perceived size-change magnitude ratings.

Notes. Results of Type II Wald chi-squared tests with the following random effects: a) random intercepts for each participant and stimulus, b) random slopes (by participant) for SER change, pitch intervals, and instrument.

	df	Chi Sq.	р	df	Chi Sq.	р
	Voice $(R^2 = 0.72)$			Alto Saxophone ($R^2 = 0.59$)		
SER Change	1	23.22	<.001***	1	0.003	.96
Pitch Interval	4	1.15	.88	4	17.99	.001**
SER * Pitch	4	0.85	.93	4	3.46	.48
	Oboe $(R^2 = 0.58)$			Cello ($R^2 = 0.49$)		
SER Change	1	7.73	.05	1	0.89	.34
Pitch Interval	4	6.21	.18	4	26.91	<.001***
SER * Pitch	4	15.5	.003*	4	5.06	.28
French Horn $(R^2 = 0.52)$						
SER Change	1	2.97	.08			
Pitch Interval	4	8.57	.07			
SER * Pitch	4	12.51	.013			

Table 2. Experiment 1 (non-RMS-normalized stimuli) linear mixed-effects model Type II Wald Chisquared tests of perceived size-change magnitude for each of the five instruments.

Notes. The criterion p-value is .01 due to multiple tests. p < .01 *p < .002 **p < .001.

	df	$\chi^2 p$	
	$(R^2 = .46)$		
SER Change	1	10.91 <.001	
Pitch Interval	4	18.72 <.001	
Instrument	4	6.21 .18	
SER \times Pitch	4	5.48 .24	
SER \times Instrument	4	310.01 <.001	
Pitch × Instrument	16	39.98 <.001	
SER \times Pitch \times Instrument	16	7.69 .95	

Table 3. Experiment 2 linear mixed-effects model Type II Wald chi-squared tests for perceived size-change magnitude ratings using RMS-equalized stimuli.

Notes. Results of Type II Wald chi-squared tests with the following random effects: a) random intercepts for each participant and stimulus, b) random slopes (by participant) for SER change, pitch intervals, and instrument.

magintade using KWB equalized stillar for each of the five instruments.						
	df	Chi Sq.	р	df	Chi Sq.	р
Voice $(R^2 = 0.73)$			Alto Saxophone ($R^2 = 0.45$)			
SER Change	1	32.80	<.001***	1	0.11	.73
Pitch Interval	4	0.85	.93	4	23.07	<.001***
SER * Pitch	4	0.52	.97	4	9.13	.06
	Oboe $(R^2 = 0.57)$			Cello ($R^2 = 0.57$)		
SER Change	1	12.37	<.001***	1	6.35	.012
Pitch Interval	4	3.14	.53	4	21.51	<.001***
SER * Pitch	4	2.89	.57	4	8.05	.09
	French Horn ($R^2 = 0.51$)					
SER Change	1	0.30	.58			
Pitch Interval	4	10.70	.03			
SER * Pitch	4	4.29	.36			

Table 4. Experiment 2 linear mixed-effects model Type II Wald Chi-squared tests of perceived size-change magnitude using RMS-equalized stimuli for each of the five instruments.

Notes. The criterion p-value is .01 due to multiple tests. p < .01 *p < .002 **p < .001.

Figure Captions

Figure 1. Spectral slices and waveforms for select sounds used in the experiment. The solid lines represent source files that have been reduced in size, whereas the dashed lines represent source files that have been increased in size. Note that the periodicity for both sound files in each plot is the same. Sound Pressure Level (dB/Hz) is abbreviated as SPL, and amplitude (linear) is abbreviated as Amp. In general, sounds processed to sound larger by TANDEM-STRAIGHT have more energy in the lower portion of the spectrogram and more gradual waveform decay patterns relative to sounds processed to sound smaller.

Figure 2. (Color online) Perceived size-change magnitude (y-axis) as a function of SER change (x-axis) and pitch interval (plotted as five lines) for each of the five instruments used in Experiment 1. The red (dark grey) lines represent tone pairs with descending pitch intervals, whereas the blue (light grey) lines represent tone pairs with ascending pitch intervals. Dotted lines are used to indicate the pitch interval of a Major 2nd, whereas dashed lines are used to indicate the pitch interval of a Perfect 5th. The solid black line represents tone pairs with no pitch change (i.e. perfect unisons).

Figure 3. Experiment 1 comparisons of paired increasing and decreasing SER changes averaged across all instruments and pitch intervals. For a given SER change, such as 0.95:1.05, if the smaller-scale sample (0.95) was played before the larger-scale sample (1.05), the pair was classified as becoming "larger" (black bars) and vice-versa (grey bars). ** = Significant difference at the Bonferroni-Holm-corrected alpha level.

Figure 4. (Color online) Perceived size-change magnitude (y-axis) as a function of SER change (x-axis) and pitch interval (plotted as five lines) using RMS-equalized stimuli for each of the five instruments in Experiment 2. The red (dark grey) lines represent tone pairs with descending pitch intervals, whereas the blue (light grey) lines represent tone pairs with ascending pitch intervals. Dotted lines are used to indicate the pitch interval of a Major 2nd, whereas dashed lines are used to indicate the pitch interval of a Perfect 5th. The solid black line represents tone pairs with no pitch change (i.e., perfect unisons).

Figure 5. Experiment 2 comparisons of paired increasing and decreasing SER changes averaged across all instruments and pitch intervals using RMS-equalized stimuli.











Figure 1 (con't.)





Figure 2



Figure 2 (con't.)



Oboe

Figure 2 (con't.)



Horn

Figure 2 (con't.)



Cello



Alto Sax





Figure 4



Voice (RMS Equalized)



Oboe (RMS Equalized)



Horn (RMS Equalized)



Cello (RMS Equalized)



Alto Sax (RMS Equalized)

Figure 5

