

Psychophysiological responses to auditory change

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Abstract

A comprehensive characterization of autonomic and somatic responding within the auditory domain is currently lacking. We studied whether simple types of auditory change that occur frequently during music listening could elicit measurable changes in heart rate, skin conductance, respiration rate, and facial motor activity. Participants heard a rhythmically isochronous sequence consisting of a repeated standard tone, followed by a repeated target tone that changed in pitch, timbre, duration, intensity, or tempo, or that deviated momentarily from rhythmic isochrony. Changes in all parameters produced increases in heart rate. Skin conductance response magnitude was affected by changes in timbre, intensity, and tempo. Respiratory rate was sensitive to deviations from isochrony. Our findings suggest that music researchers interpreting physiological responses as emotional indices should consider acoustic factors that may influence physiology in the absence of induced emotions.

Descriptors: Auditory change, Facial EMG, Heart rate, Skin conductance, Respiration rate

The ability to detect changes in our auditory environment is an essential component of auditory scene analysis. Research on the orienting response—a complex of physiological and behavioral responses elicited by novel sensory stimulation—indicates that humans are highly sensitive to even small, seemingly innocuous auditory changes (Sokolov, 1963). Functionally, studies have suggested that this reaction to novel stimuli in our environment reflects the reallocation of attention (Siddle, 1991), as well as an increase in stimulus sensitivity (Stekelenburg & van Boxtel, 2002). Much attention has been devoted to how this response is displayed physiologically, where markers of orienting typically include the skin conductance response (Barry & Sokolov, 1993) and heart rate deceleration (Graham & Clifton, 1966), as well as inhibition of respiration and electromyography (EMG) activity in the lower facial muscles (Stekelenburg & van Boxtel, 2002).

Despite advances made in our understanding of the physiological components of the orienting reflex, only a small body of research has focused on the effects of acoustic parameters on autonomic and somatic responding. This research indicates that the orienting response can be elicited by changes in tone frequency (Siddle & Heron, 1976) and acoustic intensity (Siddle & Heron,

1977), with the magnitude of the skin conductance response reflecting the magnitude of the frequency or intensity change. Changes in frequency, intensity, and rise time of the temporal envelope at the onset of a sound also elicit heart rate responses: An early deceleration in heart rate follows the onset of frequency and intensity change (Lyytinen, Blomberg, & Näätänen, 1992; Siddle & Heron, 1976, 1977), and a later heart rate acceleration follows changes in rise time (Lyytinen et al., 1992). Research also indicates that high-intensity auditory stimuli cause increases in corrugator activity (Dimberg, 1990), although to the best of our knowledge no work has focused on how changes in intensity or other parameters affect somatic activity.

The majority of research on auditory change processing focuses instead on the mismatch negativity (MMN), a component of the auditory ERP that is elicited by violations of acoustic regularities (Näätänen & Winkler, 1999). This research indicates that the MMN amplitude is directly related to the perceptual dissimilarity between the standard and change stimulus (Tiitinen, May, Reinikainen, & Näätänen, 1994; Toivianen et al., 1998). Importantly, there are few analogous studies investigating the degree of the auditory change's effect on the magnitude of autonomic and somatic responses. Given that stimulus changes that cause the MMN do not necessarily elicit comparable responses in the autonomic nervous system (Lyytinen et al., 1992), the current study investigates how changes on various acoustic parameters affect autonomic and somatic physiology.

Additionally, little research on the orienting response has been conducted on musically relevant parameters, such as rhythmic regularity, tempo, and timbre—the unique quality of a sound that allows us to distinguish between instruments. A greater understanding of how changes in these musically relevant parameters relate to autonomic and somatic physiology is particularly important given

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the growing popularity of measuring physiological responses to complex musical stimuli (e.g., Coutinho & Cangelosi, 2011; Gomez & Danuser, 2007). To be sure, music presents a challenging stimulus domain in experimental research as a consequence of the numerous individual acoustic features that vary constantly during music listening. The current study's investigation of the effects of acoustic change in specific sound parameters on physiological response will allow music researchers to better contextualize research on the relationship between acoustic features and physiology during music listening.

The central aim of the current study was to characterize physiological responding to changes in acoustic parameters that are also commonly manipulated in music. These parameters were pitch, timbre, intensity, interonset interval (or tempo), tone duration, and rhythmic isochrony. We chose to employ a repetition-change paradigm to measure the orienting reflex, allowing for the controlled study of the effect of these acoustic parameters on physiology. We introduced a standard stimulus, and after a period of repetition, presented a novel stimulus representing varying degrees of auditory change, which was then repeated. Autonomic physiological measures (heart rate, respiration rate, and skin conductance response) and somatic measures (zygomaticus and corrugator muscle activity) that are often employed in music research were collected. Experiment 1 evaluated whether changes in pitch, timbre, and rhythmic isochrony could elicit changes in autonomic nervous system activity and facial motor activity. Experiment 2 examined responses to changes in pitch, timbre, loudness, tempo, and tone duration.

Consistent with previous research, we expected to observe evidence of orienting responses to auditory change, which consist of skin conductance responses, decelerations in heart rate, decreases in respiration rate, and a decrease in zygomaticus activity. We also considered the possibility that some auditory changes (e.g., intensity increases) would induce defensive responses, which would be characterized by the presence of skin conductance responses (SCRs) and accelerations in heart rate (Cook & Turpin, 1997; Graham & Clifton, 1966), although there is some controversy concerning the ability of the directionality of heart rate change to differentiate orienting and defensive responses (Barry & Maltzman, 1985).

Overall, we predicted that the degree of deviation between the standard and comparison tones would influence the magnitude of the physiological response. This prediction is in line with Sokolov's (1963) concept of a neuronal model of orienting and Gati and Ben-Shakhar's (1990) feature-matching model of orienting, both of which suggest that the degree of stimulus novelty—and thus, the magnitude of orienting—is inversely proportional to the closeness of the match between the incoming stimulus and the established short-term memory representation (neuronal model) of the past stimulus. This prediction would also agree with evidence from the auditory change detection literature, which indicates that the MMN amplitude is directly related to the perceptual dissimilarity between the standard and change stimuli (Tiitinen et al., 1994; Toivainen et al., 1998).

In the current experiments, we defined the degree of change in pitch as a difference in log fundamental frequency (pitch height in log Hz) between two notes, loudness as a difference in intensity (decibels or dB), tempo as a difference in interonset interval (IOI in ms), and duration as a difference in tone duration (ms). Timbre change was operationalized as a combination of three dimensions: spectral flux, which represents the degree of variation of the spectral envelope over time (Krimphoff, McAdams, & Winsberg,

1994); spectral centroid, which corresponds to our experience of auditory "brightness" (Krimphoff et al., 1994); and log rise time, which corresponds to the duration of the attack portion of a tone's amplitude envelope (McAdams, Winsberg, Donnadieu, De Soete, & Krimphoff, 1995). We also predicted that temporal expectations might shape the listener's physiological response. Listeners are sensitive to the temporal regularities of auditory events, and perturbations from regularity have a number of effects, from influencing our ability to detect tempo deviations (McAuley & Kidd, 1998) to altering tapping production behavior (Madison & Merker, 2004). To assess the role of a departure from isochrony on physiological activity, we therefore included an isochrony manipulation in Experiment 1, in which the target tone could fall earlier or later than the established IOI.

Experiment 1

Method

Participants. Forty participants (20 male; $M = 23$ years, $SD = 4$ years) took part in the experiment. Participants were recruited in Montreal, Canada. All participants underwent a brief hearing exam to ensure that their pure-tone hearing thresholds were within 20 dB of standard hearing levels at octave-spaced frequencies from 250 Hz to 8000 Hz (ISO, 2004; Martin & Champin, 2000). All participants gave informed consent. The study was certified by the McGill University Review Ethics Board.

Stimuli. Each sequence faded in from silence to 65 dB SPL across the first four tones and faded out to silence across the last four tones. For all sequences, the reference tone was a synthetic tone with a bassoonlike timbre and a pitch of Eb4 (311 Hz fundamental frequency). The auditory stimuli consisted of 144 trials of isochronous sequences of 24 events presented at a tempo of 100 beats per minute (IOI of 600 ms). Each sequence was approximately 15 s in duration. On the target tone (event 10, 11, 12, 13, 14, 15), the sequence would contain either a change in pitch, a change in timbre, or no change. Tones were drawn from the set used by McAdams et al. (1995) and had a sampling rate of 44.1 kHz and 16-bit amplitude resolution. In the pitch block, all tones were 499 ms in duration. In the timbre block, the durations of tones were 499 ms (standard tone; bassoon), 512 ms (trumpet), 574 ms (French horn), and 546 ms (obochord—the obochord was conceived as a digital hybrid between an oboe and a harpsichord; Wessel, Bristow, & Settel, 1987). The sounds had been equalized for loudness and perceived duration by McAdams et al. (1995).

Variations in pitch. On the target tone, 25% of the trials consisted of no change in pitch, 25% contained an upward shift of four semitones to G4 (392 Hz fundamental frequency, an interval of a major third, M3), 25% an upward shift of 6 semitones to B4 (494 Hz, an interval of a tritone, TT), and 25% an upward shift of 11 semitones to E5 (659 Hz, an interval of a major seventh, M7). Pitch shifting of the original Eb4 bassoonlike tone was performed using AudioSculpt (IRCAM-Centre Pompidou, Paris). The authors verified that the pitch shifts resulted in no audible artifacts or changes in loudness.

Variations in timbre. On the target tone, 25% of the sequences experienced no change in timbre, 25% contained a shift to a trumpetlike tone, 25% to a French hornlike tone, and 25% to an obochord tone. For these stimuli, variations in timbre result from changes along three dimensions: spectral flux, spectral centroid,

Table 1. Distances from the Reference Bassoonlike Tone and the Global Distance Including Specificities on Each Instrument

Instrument	Attack time	Spectral centroid	Spectral flux	Global distance
French horn	0.9	3.1	0.5	3.8
Trumpet	0.2	<u>0.1</u>	2.4	3.2
Obochord	<u>4.9</u>	0.5	<u>0.7</u>	5.2

Note. Distances (on a scale of 1–9) were measured along each dimension of the McAdams et al. (1995) space. Primary dimension of interest for each timbre is underlined.

and log rise time (McAdams et al., 1995). With respect to the (bassoonlike) reference tone, the trumpet timbre varied primarily along the spectral flux dimension, the French horn along the spectral centroid dimension, and the obochord along the log rise time dimension (see Table 1 for relative distances along primary dimensions; McAdams et al., 1995).

Variations in rhythmic isochrony. One third of the trials in the pitch and timbre blocks were completely isochronous (on condition), in one third the onset of the target tone was advanced by 80 ms (early condition), and in one third it was delayed by 80 ms (late condition). The IOI of the target tone and the following tone was the standard 600 ms, and all subsequent tones maintained this standard IOI. The nonisochronous tones did not fall on the beat established by the preceding tones and thus were presumed to violate a listener's temporal and rhythmic expectations.

Apparatus. The stimuli were reproduced using an M-Audio Audiophile 192 sound card (Avid, Irwindale, CA), converted to analog using a Grace Design m904 monitor system (Grace Design, Boulder, CO), and presented over a pair of Sennheiser HD 280 headphones (Sennheiser Electronics, GmbH, Wedemark, Germany). Stimuli were presented at a level of 65 dB SPL on average as measured with a Bruel & Kjaer (Holte, Denmark) Type 2250 sound level meter (A weighting, fast setting) and a Type 4157 artificial ear to which the headphone was coupled. The experimental program, subject interface, and data collection were programmed using the Pure Data signal processing software environment (Pd version 0.42.5, <http://puredata.info>) controlled by the PsiExp software environment (Smith, 1995).

All physiological measurements were recorded with a ProComp Infiniti Monitor (SA7500) with several biosensors (Thought Technology Ltd., Montreal, Canada). Respiration was measured using a respiration monitor (stretch transducer, SA9311M) attached around the chest of the participant just below the pectoral muscles. Blood volume pulse was measured using a photoplethysmograph (SA9308M) on the palmar side of the distal phalange of the middle finger of the nondominant hand. Skin conductance was measured using electrodes (SA9309M) on the distal phalange of the index and ring fingers of the nondominant hand. Activation of muscles during facial expression was measured using two MyoScan-Pro EMG electrodes (SA9401M-60) placed over and in line with the corrugator supercilii and zygomaticus major muscles, which are active during frowning and smiling, respectively. EMG electrodes were placed on the side of the face contralateral to the dominant hand.

The samples were sent to the computer via a USB interface optically coupled to the ProComp. The USB data were decoded and recorded by a monitor process running on the workstation. The synchronization of data recording by the USB monitor process and

signal generation by Pure Data was accomplished by OSC (Wright, 2005) messages sent by the PsiExp program. Synchronization latency was less than one sample period (4 ms).

Procedure. Biosensors were attached to the face, hands, and around the chest. Participants read the instructions and could ask any questions of the experimenter. Each trial consisted of a 5-s countdown shown with numbers on the screen to prepare the participant to remain still during stimulus presentation. The auditory sequence was then played. As an attentional control task, following each auditory sequence participants were required to indicate whether they heard a change during the sequence by typing *Y* for yes or *N* for no on the computer keyboard and then pressing Enter. Upon pressing the Enter key, the countdown for the next trial began. The intertrial interval therefore consisted of the 5-s countdown, the duration of the 24-tone stimulus sequence, and the participant's response time (roughly 7 s on average between stimuli).

The main experiment consisted of a total of 144 trials divided into two blocks of 72 auditory sequences each. Each block was approximately 30 min in duration and consisted entirely of either pitch variations or timbre variations within the auditory sequence. Block order was counterbalanced, and trial order within each block was randomized. Participants were given a 2-min break between blocks. To familiarize the participants with the procedure and control task, the experimental session began with two practice trials.

Data Preprocessing. Blood volume pulse, respiration, and electrodermal activity were collected at a sampling rate of 256 Hz and were then processed offline in MATLAB (The MathWorks, Inc., Natick, MA) to extract relevant features: respiration rate (breaths per minute or BrPM), heart rate (beats per minute or BPM), and skin conductance response magnitude (microSiemens or μ S). Before sampling the analog signal at 256 Hz, the MyoScan-Pro EMG electrodes performed analog rectification and band-pass filtering (20–500 Hz), and this signal was then converted to an equivalent of RMS (root mean square) using a first-order IIR low-pass filter with a time constant of 20 ms. No further processing steps were performed for the corrugator and zygomaticus EMG signals. To remove artifacts and extraneous noise, all other signals were low-pass filtered with a fourth-order, Butterworth zero-phase filter, which avoids phase shifting the signal by convolving the filter impulse response with itself in reverse time. Skin conductance level (SCL) was filtered with a cutoff frequency of 0.3 Hz, blood volume pulse with a cutoff frequency of 2.2 Hz, and respiration with a cutoff frequency of 2 Hz. All filtered signals were visually inspected for remaining artifacts, and trials with abnormal signals within the time window of interest (–1 to 4 s after auditory change) were removed from the analysis.

To extract heart rate from the blood volume pulse signal, inter-beat intervals were calculated by locating local maxima and translating the resulting beat period to a beats-per-minute measure at that time point (Berntson, Quigley, & Lozano, 2007). Samples that were less than half or more than two times the median were replaced by the median. In order to create a continuous time series, the resulting times series were then upsampled back to 256 Hz using linear interpolation. Like the other physiological signals, the continuous heart-rate time series was then binned into 1-s epochs as described below.

A technique involving cross-correlation of the filtered respiratory signal with sinusoidal signals of different frequencies was used to estimate the time-varying frequency of the respiration. To extract instantaneous respiration rate in BrPM from the respiration

belt signal over fairly small time periods, for which average interinhalation interval would be difficult to assess, we adapted a spectral analysis technique from Müller (2007), originally designed for pitch analysis and beat detection on audio signals (Upham, 2014). It identifies the principal frequency of oscillation by the peak correlation between 10-s frames of the signal and a bank of sinusoidal signals of appropriate frequency. The procedure first downsamples the filtered respiration signal to a 10-Hz sampling rate and calculates the first-order difference, thus representing the rate of change in the expansion and contraction of the thorax. It then computes the cross-correlations between the resulting time series and a bank of 101 sinusoids with frequencies of 5–30 BrPM at 0.25 BrPM increments, using 10-s frames and a hop size of 1 sample (0.1 s). To account for anomalous respiratory behaviors such as yawning, one component of the set of sinusoids was generated at 1 BrPM, resulting in a monotonic set of samples over the 10-s window. Within this window, this component would cross-correlate well with breathing rates of 3 BrPM or less. Frames with absolute correlation coefficients greater than 0.5 were sampled for peak values that fit the short segment of the respiration cycle in phase and frequency. From the resulting series, maxima were extracted, interpolated, and smoothed with a 0.1 Hz 4th-order Butterworth low-pass filter. This technique thereby provides a measure of the time-varying breathing rate. This breathing-rate signal was then upsampled to 256 Hz for comparison with other series in the data set. This technique provides a more robust estimate of time-varying respiration rate on fairly short signals by making use of more signal information than the onset of each breath.

Heart rate, respiration rate, and zygomaticus and corrugator signals were averaged offline into 1-s epochs ranging from 1 s before to 4 s following the auditory change. Epochs were calculated by taking the mean of all values falling between 0.5 s before and after the time point of interest. Using a method similar to that described by Bradley and Lang (2000a), the magnitude of the physiological response was measured by deviating epoch means from the participant's baseline physiological activity in that trial, which was taken as the average signal level 1 s immediately preceding the onset of the change. Epoch values per participant and per condition were averaged across the six repetitions for subsequent analyses.

To quantify SCR magnitude, the first peak and trough occurring after the onset of auditory change were located in the skin conductance signal, and the response amplitude was taken as the difference between the trough and peak values. Signals without a peak were assigned a value of zero. To calculate SCR magnitude, which includes trials with amplitude values of zero, the amplitude data were normalized using a $\log(\text{amplitude} + 1)$ transformation, where 1 is added to all SCR amplitudes before calculating the log, as the log of 0 is undefined (Boucsein, 2012). SCR magnitude per condition and per participant was then averaged across all six repetitions of the condition for subsequent statistical analyses.

Given the short duration of stimulus sequences prior to auditory change, the square root of the mean squared differences (RMSSD) between successive interbeat intervals was used as an index of heart rate variability. RMSSD was treated as a between-subjects covariate in the analyses that follow, so the RMSSD was calculated for the prechange portion of each trial and then averaged across all trials in the experimental session for each participant. Finally, to consider the effect of the respiratory sinus arrhythmia (RSA) on heart rate, the proportion of inhalations versus exhalations during the target event for each condition (across six repetitions) was calculated per participant.

Analyses. For SCR and proportion of inhalations, a repeated measures analysis of variance (ANOVA) was conducted with auditory change along a given dimension (timbre, pitch, rhythmic isochrony) as a within-subject factor.

For all other processed physiological signals (heart rate, respiration rate, zygomaticus and corrugator EMG activity), a mixed-design, repeated measures ANOVA was conducted to determine the effect of auditory change on the physiological response over time. For each block, epoch and auditory change were treated as within-subject factors. In instances in which sphericity was violated (indicated by Mauchly's test), we report the original degrees of freedom, the value of the Greenhouse-Geisser ϵ , and adjusted p values. Effect size is reported as generalized η^2 (notated η_G^2 ; Bakeman, 2005; Olejnik & Algina, 2003), because η_G^2 allows for comparison of effect sizes across both between-subjects and within-subject designs. When post hoc tests are used, Bonferroni-Holm-corrected p values are reported.

We interpreted Epoch \times Auditory Change interactions as an indicator that the auditory change elicited a measurable effect on the physiological signal over time (i.e., the effect of change condition was not due to baseline differences between conditions existing before the target tone). If an interaction existed, we conducted a separate polynomial trend analysis on epoch to determine the nature of the interaction; a different trend analysis was done at each level of the auditory change factor, and additional pairwise trend comparisons were conducted to determine whether the change condition trends differed significantly from the no-change condition trend. The trend analysis was conducted with a generalized least squares approach in R by specifying an orthogonal cubic polynomial for epoch and using a first-order autoregressive specification for correlations among repeated measures. For trend analyses, we report the coefficient estimate, B , and the ratio between the estimate and the standard error, t . Main effects of epoch were not reported in the analyses that follow; however, as physiological signals generally change over time, only the Epoch \times Auditory Change interaction was of interest.

Post hoc analyses were conducted on significant main effects to determine significant differences between conditions. For significant Epoch \times Auditory Change interactions, pairwise comparisons were conducted to determine change-condition differences within particular epochs. Similarly, for significant effects of Auditory Change on SCR magnitude, pairwise, one-tailed t tests were conducted to determine which change conditions elicited a significantly greater SCR magnitude than the no-change condition. All p values were adjusted using the Bonferroni-Holm method for all pairwise comparisons. Marginally significant effects are only reported for pairwise comparisons and Parameter \times Epoch interactions (our primary effects of interest).

One participant was excluded from the heart rate analysis due to consistent artifacts present in the blood volume pulse signal. After excluding this participant, on average 3.9% ($SD = 0.77$) of the remaining heart rate trials were removed from each block. One participant was excluded from the respiratory rate analysis, as the stretch monitor sensor stopped working during the experiment. After excluding this participant, on average, 3.69% ($SD = 0.014$) of trials were removed from respiration trials. On average, 0.23% ($SD = 0.32$) of trials were removed from zygomaticus trials per block, and 0.57% ($SD = 0.36$) of trials were removed from corrugator trials per block. No skin conductance trials were removed.

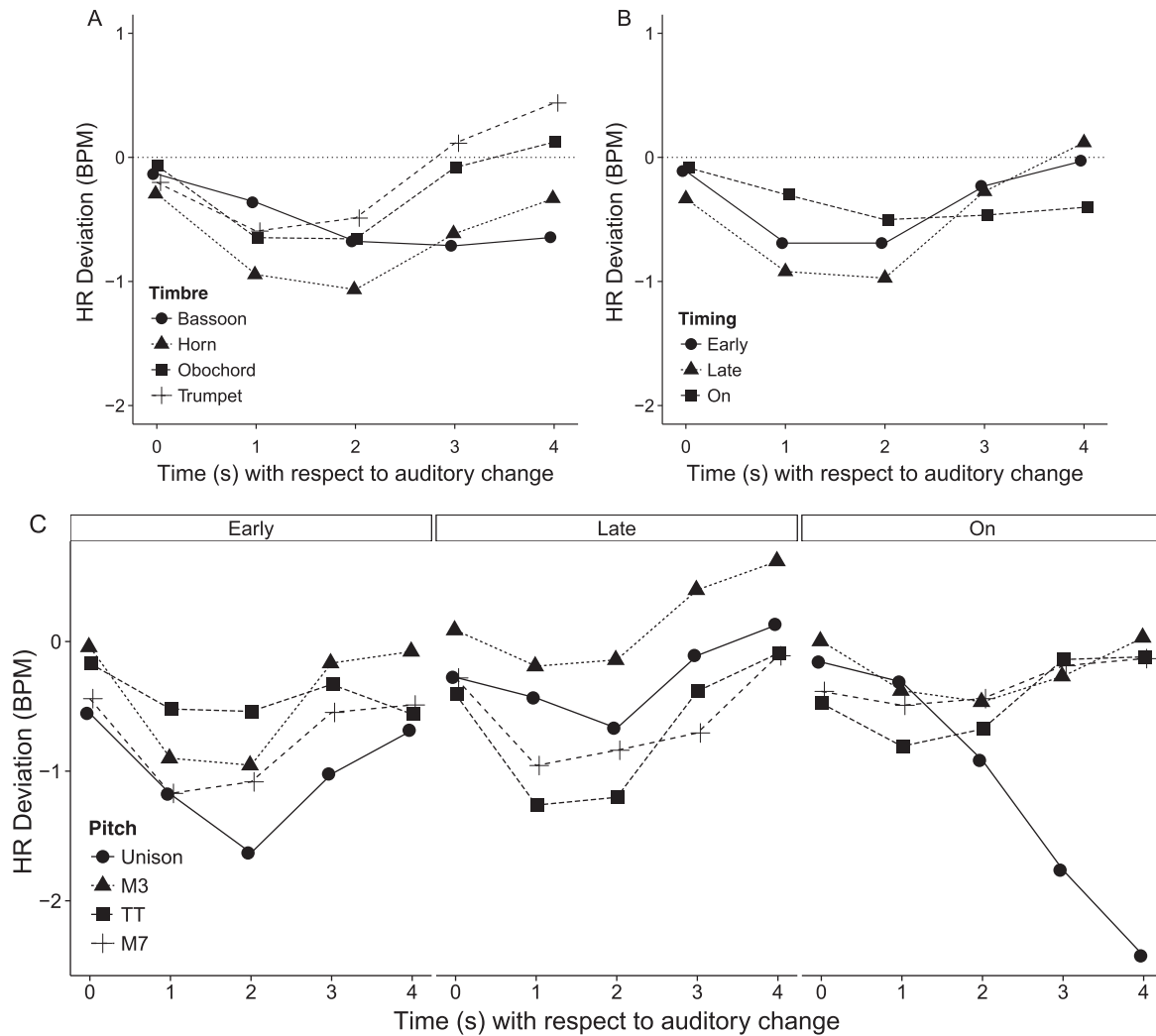


Figure 1. Experiment 1. Effect of changes in timbre (A) and rhythmic isochrony (B) on deviations from baseline heart rate (HR). Effect of pitch change on deviation (C) from baseline heart rate in the early, late, and on-the-beat rhythmic isochrony conditions.

Results

Overall performance for the boredom control task ranged from 84% to 100% across participants ($M = 97\%$, $SD = 4\%$), indicating that participants were paying attention throughout the experiment. Erroneous trials were not removed, the aim of this supplementary task merely being to maintain a general state of vigilance.

To control for the potential effect of interparticipant variations in heart rate variability (HRV) on measures of heart rate, we first included RMSSD as a covariate in all repeated measures analyses of covariance (ANCOVAs) with heart rate as the dependent variable. The mean participant RMSSD was 50 ms ($SD = 43$ ms). However, RMSSD never had a significant effect on HR, and the obtained results never changed as a consequence of including RMSSD as a covariate, so we excluded HRV from all subsequent analyses.

Timbre block. A significant Timbre \times Epoch interaction on heart rate indicated that changes in timbre caused significant changes in heart rate over time, $F(12,456) = 3.42$, $\epsilon = .47$, $p = .004$, $\eta_G^2 = .006$ (Figure 1A). There was a decrease in heart rate over time on trials without auditory change, indicated by the marginally

significant decreasing linear trend in the bassoon condition, $B = -.44$, $t(585) = -1.75$, $p = .080$. Changes to a horn, obochord, or trumpet timbre within the trial elicited a significant quadratic trend for each condition (horn: $B = .66$, $t(585) = 2.51$, $p = .0122$; obochord: $B = 0.58$, $t(585) = 2.00$, $p = .046$; trumpet: $B = 0.506$, $t(585) = 2.27$, $p = .023$), indicating an initial decrease in heart rate in the first 2 s following the change, followed by an increase in the final 2 s of the recorded window. However, pairwise polynomial trend comparisons indicated that only the linear trends demonstrated in the trumpet and obochord conditions differed significantly from the no-change condition ($p < .05$).

There was also a significant Isochrony \times Epoch interaction on HR, $F(8,304) = 2.92$, $\epsilon = .40$, $p = .034$, $\eta_G^2 = .005$ (Figure 1B). HR decreased over time when there were no deviations in isochrony (on), indicated by a decreasing linear trend, $B = -.32$, $t(780) = -2.21$, $p = .028$. Early and late deviations in isochrony both caused an initial decrease in HR followed by an increase, indicated by significant quadratic trends in both conditions (early: $B = 0.55$, $t(780) = 3.65$, $p = .0003$; late: $B = 0.74$, $t(780) = 5.12$, $p < .0001$). Pairwise polynomial trend comparisons indicated that the linear trend in the on condition was significantly different from the late condition ($p < .05$) and marginally different from the early condition ($p = .093$).

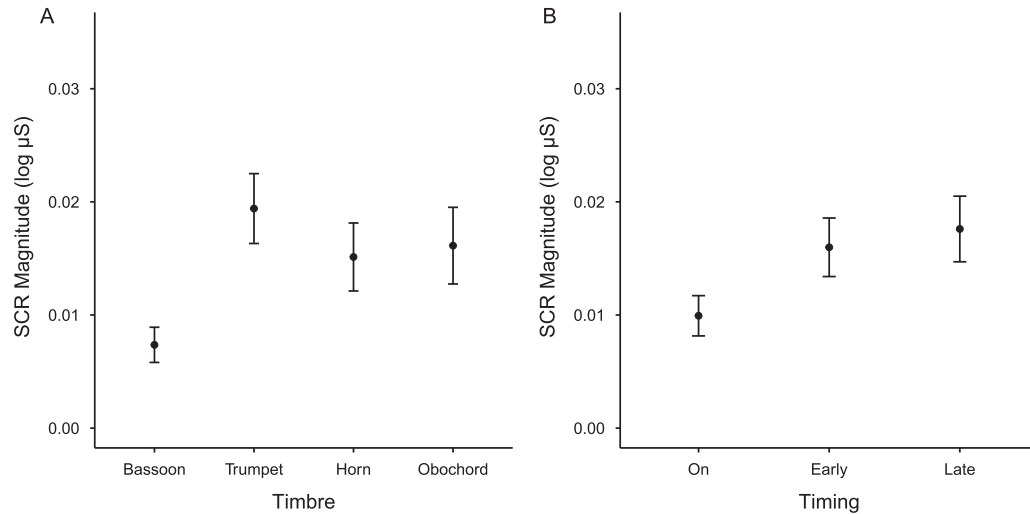


Figure 2. Experiment 1. A: Effect of timbre change on SCR magnitude. B: Effect of deviations from rhythmic isochrony on SCR magnitude in the timbre block. Error bars indicate one standard error about the mean.

Finally, there was a significant effect of timbre on SCR magnitude, $F(3,117) = 3.42$, $\epsilon = .75$, $p = .032$, $\eta_G^2 = .015$ (Figure 2A). Bonferroni-Holm adjusted, one-tailed comparisons indicated that only the trumpet condition elicited a significantly greater SCR magnitude than the bassoon condition ($p = .031$). There was also a marginally significant main effect of rhythmic isochrony on SCR magnitude, $F(2,78) = 2.89$, $\epsilon = .78$, $p = .075$, $\eta_G^2 = .008$ (Figure 2B). Adjusted one-tailed pairwise comparisons indicated that only the late condition elicited a marginally greater SCR magnitude than the on condition ($p = .09$). There was no effect of isochrony or timbre on respiratory rate, proportion of inhalations during the moment of change, corrugator activity, or zygomaticus activity.

Pitch block. There was a significant three-way Pitch \times Isochrony \times Epoch interaction on heart rate, $F(24,912) = 2.22$, $\epsilon = .35$, $p = .023$, $\eta_G^2 = .008$, indicating that the effect of pitch change on heart rate over time was influenced by the rhythmic isochrony condition (Figure 1C). Although the linear trends for all pitch change conditions were significantly different from the unison condition in the absence of rhythmic deviation ($p < .05$), there were no significant polynomial trend differences between unison and change conditions in both the late and early rhythmic deviation conditions. In isochronous (on) conditions, there was a decrease in HR when there was no pitch change, indicated by a decreasing linear trend, $B = -1.88$, $t(195) = -5.55$, $p < .0001$, but there were no significant polynomial trends in all three pitch change conditions. Conversely, in the early conditions, there was an initial decrease followed by an increase in HR in the unison, M3, and M7 pitch conditions, indicated by quadratic trends for each condition (early-unison: $B = 0.804$, $t(195) = 3.80$, $p = .0002$; early-M3: $B = 0.74$, $t(195) = 3.36$, $p = .0010$; early-M7: $B = 0.56$, $t(195) = 2.56$, $p = 0.111$). Similarly, for the late condition, for both no-change and pitch-change conditions there was an initial decrease in HR followed by an increase in HR, indicated by significant quadratic trends for each (late-unison: $B = 0.34$, $t(195) = 2.09$, $p = .0382$; late-M3: $B = 0.39$, $t(195) = 1.77$, $p = .0787$; late-TT: $B = 0.83$, $t(195) = 3.90$, $p = .0001$; late-M7: $B = 0.58$, $t(195) = 2.55$, $p = .0116$). Finally, pairwise trend comparisons indicated that, in the isochronous condition, the linear trend for all three pitch-change conditions was significantly different ($p < .05$) from the

unison condition. However, for the early and late conditions, there was no difference between linear trends for the change conditions and the unison condition.

Although there was no effect of pitch change on respiratory rate over time, deviations in isochrony elicited changes in the respiratory response (Figure 3), indicated by a marginally significant Epoch \times Isochrony interaction, $F(8,304) = 2.60$, $\epsilon = .25$, $p = .080$, $\eta_G^2 = .002$. In the on condition, there was a decrease in respiratory rate, indicated by a decreasing linear trend, $B = -0.251$, $t(195) = -5.45$, $p < .0001$. However, there were no significant polynomial trends for the early and late conditions, suggesting that respiration rate did not decrease over time when there were deviations in isochrony. Pairwise polynomial trend comparisons indicated that the linear trends for the on condition were marginally

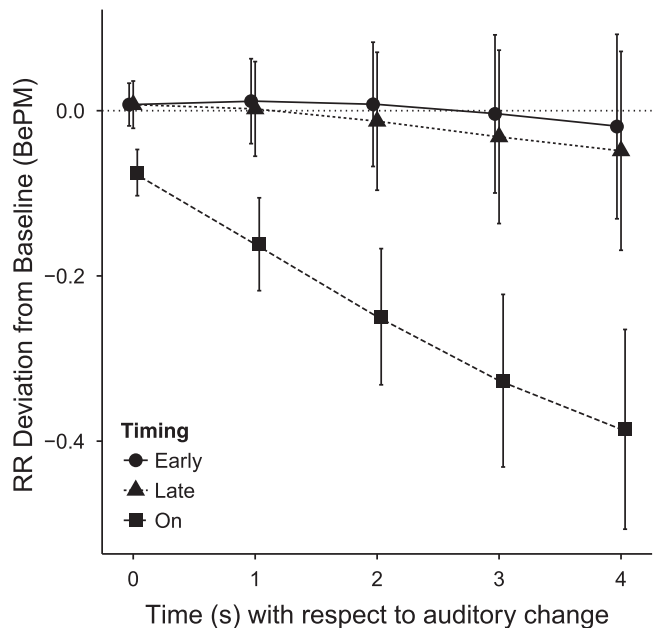


Figure 3. Experiment 1. Effect of deviations from rhythmic isochrony on respiratory rate (RR) in the pitch block (BrPM = breaths per minute). Error bars indicate one standard error about the mean.

significantly different from those for the early ($p < .1$) and late ($p = .10$) conditions.

There was no effect of pitch or timing on SCR magnitude, zygomaticus activity, corrugator activity, or proportion of inhalations during the moment of change.

Discussion

The results indicate that some autonomic physiological measures, but no somatic facial motor measures, were sensitive to simple changes in pitch, timbre, and rhythmic isochrony.

Heart rate was the most sensitive measure, responding to changes in all three parameters. When there was no change in timbre, pitch, or rhythmic isochrony, polynomial trend analysis indicated that, on average, there was a decrease in heart rate over time, reflecting continual habituation to the repeating, standard stimulus. However, changes in timbre, pitch, and rhythmic isochrony all elicited a biphasic heart rate response, which consisted of an initial deceleration followed by a period of acceleration. Given that existing research has classified an initial heart rate deceleration followed by an acceleration back toward baseline as part of the orienting response (Graham & Clifton, 1966; Öhman, Hamm, & Hugdahl, 2000), results in the current experiment indicate that various changes in timbre, pitch, and deviations from isochrony elicit the heart rate component of the orienting response.

SCR magnitude was also sensitive to auditory change. The SCR component of orienting was only observed in the timbre block, where changes in timbre and deviations from isochrony caused larger SCR magnitudes. However, post hoc tests indicated that only the trumpet timbre and late deviation condition elicited a significantly larger SCR response compared to the no-timbre change and isochronous conditions, respectively. Moreover, there was no effect of pitch or an analogous effect of isochrony deviation in the pitch block on SCR.

Finally, although there were no changes in respiratory rate in response to changes in pitch or timbre, respiratory rate was sensitive to deviations in isochrony. In the pitch block, there was a decrease in respiratory rate over time in the isochronous condition, but no decrease was observed in either the early or late conditions.

Although we predicted that the magnitude of the physiological response would be related to the degree of auditory change, the influence of individual timbre dimensions (spectral flux, spectral centroid, attack time) on autonomic response magnitude was not clear in the present experiment. The trumpet timbre was the only timbre change that caused a significantly greater SCR magnitude from the no-change condition, and the trumpet and oboe timbres were the only changes that elicited significantly different heart rate trends. This finding might suggest that the orienting response is more sensitive to changes in spectral flux (the primary dimensional manipulation in the trumpet condition) and attack time (the primary dimensional manipulation in the oboe condition). However, given that we only included one timbre for each dimension of interest, we cannot draw any general conclusions about the relative influence of each dimension within the scope of this study. Nevertheless, to the best of our knowledge, the isolated effects of timbre change on autonomic physiology have not yet been examined, and we thus provide novel evidence that changes in timbre along various dimensions can affect some autonomic components of the orienting response.

Consistent with our predictions, deviations from rhythmic isochrony caused changes in autonomic components of the orienting response. Deviations from isochrony caused a pattern of deceleration followed by acceleration in heart rate relative to the isochronous con-

dition in both the pitch and timbre blocks, changes in respiratory rate pattern in the pitch block, and increases in SCR magnitude in the timbre block. This finding provides evidence that disruptions of temporal expectations affect autonomic responding. However, similar to changes in timbre, given that there was only one degree of deviation in each temporal direction, we cannot draw general conclusions of the relative influence of early versus late deviations from isochrony. Interestingly, our finding that differences in the heart rate response as a function of pitch change were only present in the isochronous condition suggests that violations in isochrony may override the influence of pitch changes (in the early and late conditions).

Finally, although the degree of auditory change was clearly operationalized for changes in pitch, there did not appear to be a relationship between interval size and the magnitude of the heart rate response. This finding is consistent with previous work indicating that, although heart rate is sensitive to pitch change, the degree of pitch change does not affect the magnitude of the heart rate response (Siddle & Heron, 1976).

To extend our exploration to additional auditory parameters, we conducted a second experiment that assessed the effects of pitch, timbre, loudness, tempo, and duration changes on physiological response. We conducted Experiment 2 in the absence of a temporal isochrony manipulation to better isolate the effects of these parameters.

Experiment 2

Method

Participants. Forty participants (20 male; $M = 21$ years, $SD = 2$ years) took part in the experiment. None of the participants had taken part in Experiment 1. As in Experiment 1, they gave informed consent, completed a questionnaire on their musical experience, and had their hearing tested.

Stimuli. The stimulus sequence structure was identical to Experiment 1 with the following exceptions: (a) the number of events was dependent on the location of the target tone—the tone on which a change in auditory parameter occurs or not—to allow for 13 events to occur after the target tone, resulting in a response window of 8 s following the target. The auditory stimuli thus consisted of isochronous sequences of 24 to 28 events. The duration of the sequences ranged from 14 to 17 s to allow for a better analysis of respiration rate; (b) no sequences contained deviations from isochrony; and (c) in addition to pitch and timbre variations, sequences contained variations in duration, tempo, or sound level as summarized below.

Variations in loudness (sound level). All sequences were composed of 500-ms bassoonlike tones and contained an IOI of 600 ms. Six sequences contained no change in sound level (65 dB SPL), six sequences an increase to 70 dB, six an increase to 75 dB, and six an increase to 80 dB.

Variations in duration. All sequences had IOIs of 600 ms between bassoonlike tones. Reference tones were 600 ms in duration, rather than 500 ms, to allow for an adequate decrease in duration for change trials. Six sequences contained no change in duration from the reference tone, six a decrease to 450 ms, six a decrease to 300 ms, and six a decrease to 150 ms in duration.

Variations in tempo. To allow for an adequate amount of change within this parameter, reference tones had an IOI of

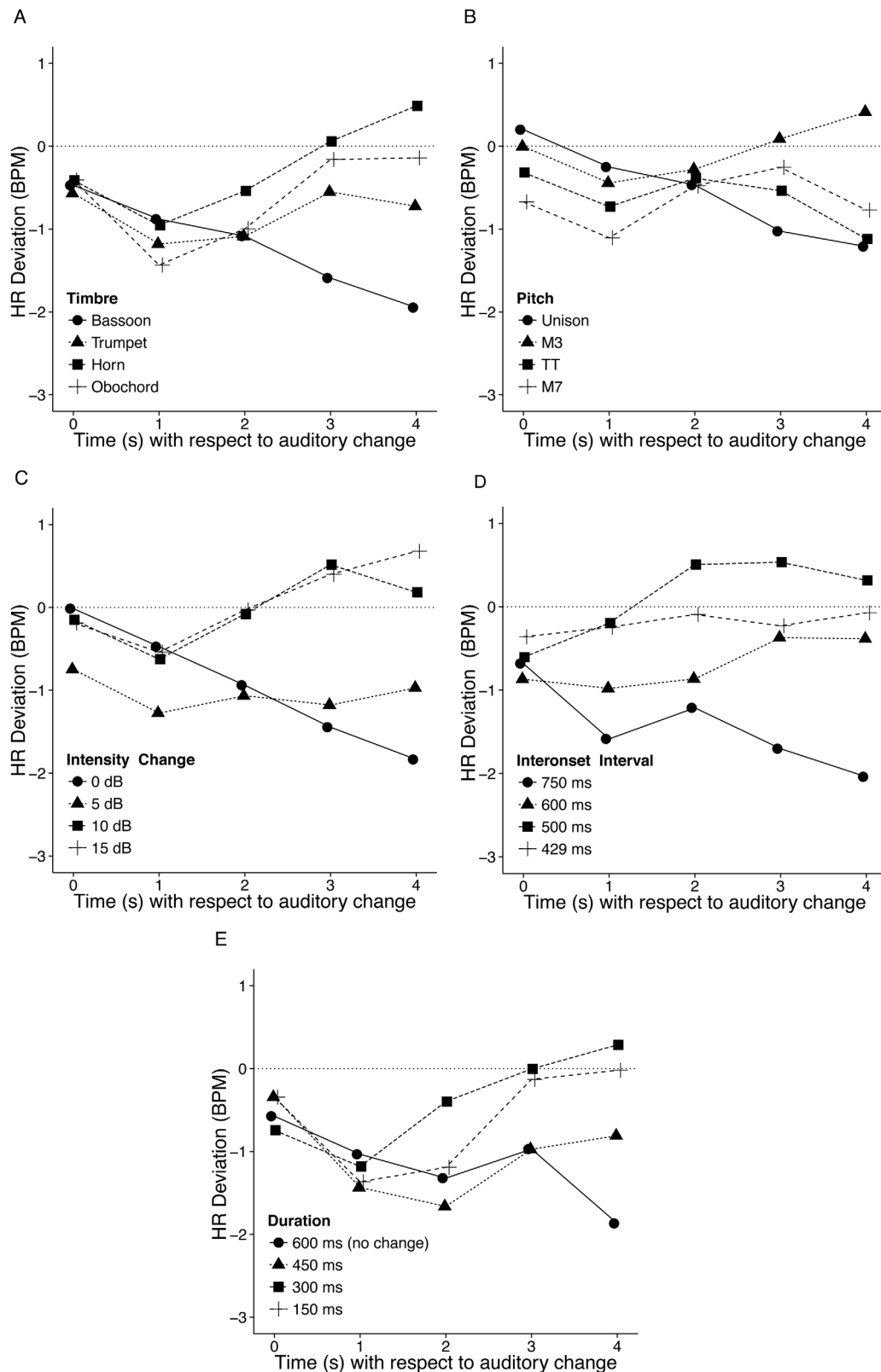


Figure 4. Experiment 2. Effect of changes in timbre (A), pitch (B), intensity (C), interonset interval (D), and tone duration (E) on deviation from baseline heart rate.

750 ms (80 BPM), and all bassoonlike tones were 300 ms in duration. Six sequences contained no change in IOI, six a decrease to an IOI of 600 ms (100 BPM), six a decrease to

an IOI of 500 ms (120 BPM), and six a decrease to an IOI of 429 ms (140 BPM). A decrease in IOI creates an increase in tempo.

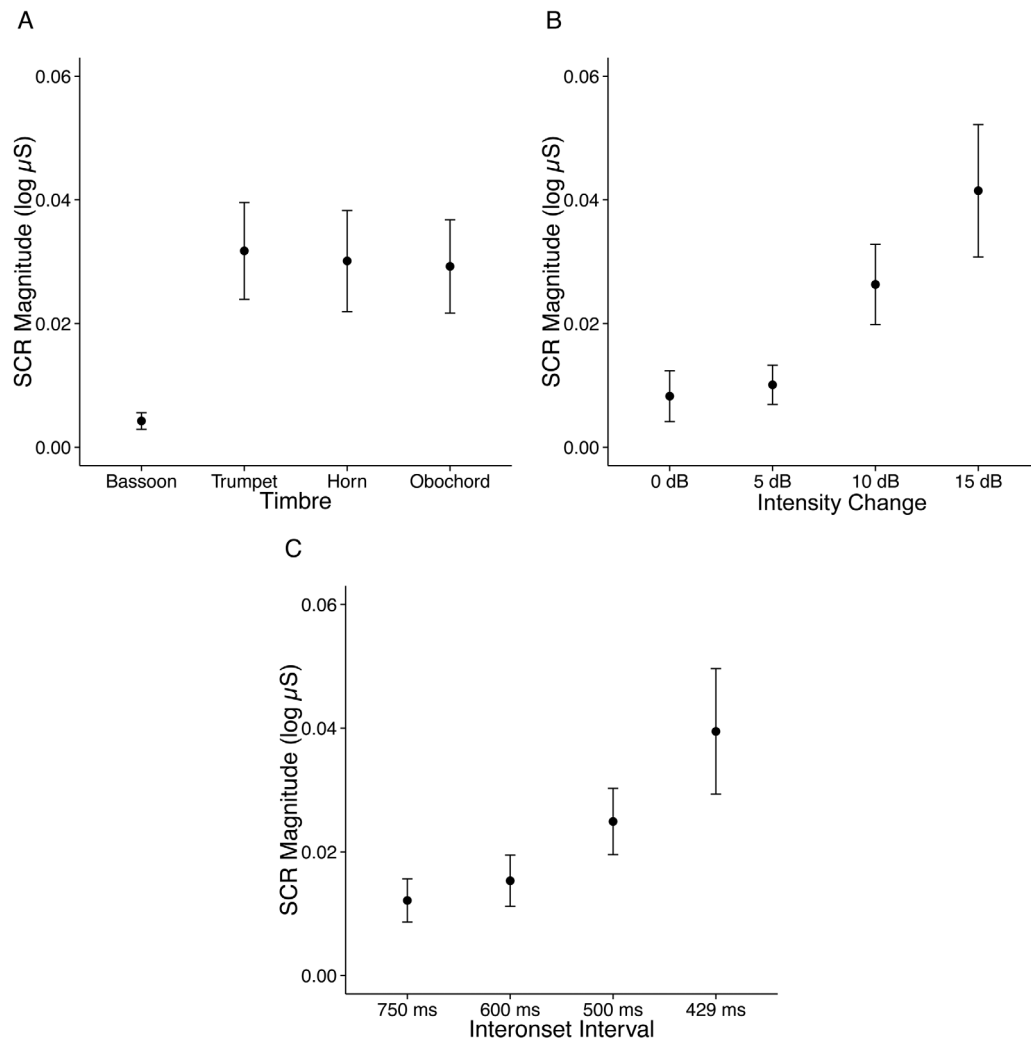


Figure 5. Experiment 2. Effect of changes in timbre (A), intensity (B), and tempo (C) on SCR magnitude. Error bars indicate one standard error about the mean.

Procedure. The procedure was identical to Experiment 1 with the following exceptions. Each participant completed five experimental blocks of 24 trials. Each block was approximately 12 min in duration. Participants were presented with two practice trials before each block (no change, maximal change). An optional break was given after the first and third blocks. Participants were given the chance to notify the experimenter if they wished to pause.

Analyses. The analysis was identical to Experiment 1 with the following exception: for auditory change parameters where auditory change was increased in equal-sized intervals (i.e., intensity and tempo blocks), a polynomial trend analysis was conducted on the degree of change to assess whether SCR magnitude was related to the degree of auditory change. One participant's heart rate data were excluded due to consistent artifacts in the BVP (blood volume pulse) signal. After excluding this participant, on average 4.3% of the remaining heart rate trials were removed from each block ($SD = 0.44\%$) due to signal artifacts. An average of 1.5% of the skin conductance trials were removed from each block ($SD = 0.4\%$). Two participants were also excluded from the zygomaticus activity analysis due to recurring artifacts in the signal, and

one participant was excluded from the respiration rate analysis, again due to recurring artifacts in the signal.

Results

Aside from one participant who scored 37%, overall performance for the boredom-control task ranged from 80% to 100% across participants ($M = 94\%$, $SD = 5.3\%$), indicating that most participants were paying attention throughout the experiment. The participant with 37% performance accuracy was removed from the analysis, but otherwise erroneous trials were not removed.

To control for the potential effect of interparticipant variations in HRV on measures of heart rate, we again included RMSSD as a covariate in all repeated measures ANCOVAs with heart rate as the dependent variable. The mean participant RMSSD was 55 ms ($SD = 55$ ms). As in Experiment 1, RMSSD never had a significant effect on HR, and the obtained results never changed, so we excluded HRV from all subsequent analyses.

Timbre block. Changes in timbre caused changes in HR over time, indicated by a significant Timbre \times Epoch interaction, $F(12,444) = 4.06$, $\epsilon = .41$, $p = .002$, $\eta_G^2 = .019$ (Figure 4A). When there was no auditory change, HR decreased over time,

indicated by the negative linear trend in the bassoon condition, $B = -1.19$, $t(190) = -3.02$, $p = .0029$. Conversely, the horn timbre change caused an increase in HR over time, indicated by a significant increasing linear trend, $B = 0.94$, $t(190) = 2.43$, $p = .016$. The oboe chord timbre change also caused an increase in HR after an initial deceleration, indicated by a significant quadratic trend, $B = 0.69$, $t(190) = 2.83$, $p = .005$. The trumpet timbre change elicited a triphasic response: there was an initial decrease, followed by an increase, and then another decrease in HR, indicated by a marginally significant cubic trend, $B = -0.43$, $t(190) = -1.91$, $p = .057$. Finally, pairwise linear trend comparisons indicated that the trend of the no-change condition for heart rate over time was significantly different from all change conditions ($p < .05$).

Due to artifacts in the SCR signal, 0.9% of trials were excluded. Changes in timbre had a significant effect on SCR magnitude, $F(3,114) = 3.17$, $p = .027$, $\eta_G^2 = .043$, where changes in timbre elicited increases in SCR magnitude (Figure 5A). After Bonferroni-Holm corrections, one-tailed comparisons indicated that the horn ($p = .098$), oboe chord ($p = .098$), and trumpet ($p = .080$) conditions elicited a marginally significantly greater SCR magnitude than the no-change bassoon condition.

There was no effect of timbre on corrugator activity, zygomaticus activity, respiration rate, or proportion of inhalations during the moment of change.

Pitch block. There was a marginally significant Pitch \times Epoch interaction on heart rate, $F(12,444) = 2.08$, $\varepsilon = .37$, $p = .078$, $\eta_G^2 = .012$ (Figure 4B). When there was no auditory change, HR decreased over time, indicated by the negative linear trend in the unison condition, $B = -1.17$, $t(190) = -3.12$, $p = .0021$. A pitch increase of M3 caused an initial decrease, followed by increase in HR, indicated by a quadratic trend, $B = 0.46$, $t(190) = 2.05$, $p = .042$. Similarly, a pitch increase of M7 caused a triphasic HR response consisting of an initial decrease, followed by increase, then decrease in HR, which was indicated by a cubic trend, $B = -.60$, $t(190) = -2.79$, $p = .006$. Pairwise linear trend comparisons indicated that only the major third and major seventh condition had significantly different trends compared to the no-change condition ($p < .05$).

There was no effect of pitch change on SCR magnitude, corrugator activity, zygomaticus activity, respiration rate, or proportion of inhalations during the moment of change.

Intensity block. There was a significant Intensity \times Epoch interaction on heart rate, $F(12,444) = 4.70$, $\varepsilon = .45$, $p = .0003$, $\eta_G^2 = .027$ (Figure 4C). When there was no auditory change, HR decreased over time, indicated by the negative linear trend in the 0 dB condition, $B = -1.46$, $t(190) = -4.29$, $p < .0001$. Intensity increases of 10 dB caused a triphasic HR response consisting of an initial decrease, followed by increase, then decrease in HR, as indicated by a cubic trend, $B = -.61$, $t(190) = -3.06$, $p = .0026$. Intensity increases of 15 dB caused an increase in HR, indicated by an increasing linear trend, $B = .86$, $t(190) = 2.41$, $p = .017$. Pairwise linear trend comparisons indicated that the trend of the no-change condition for heart rate over time was significantly different from all change conditions ($p < .05$).

There was a significant effect of intensity on SCR magnitude, $F(3,114) = 3.30$, $\varepsilon = .66$, $p = .043$, $\eta_G^2 = .056$ (Figure 5B), where greater increases in intensity caused greater mean SCR magnitudes. A trend analysis conducted on intensity indicated a significant increasing quadratic trend: there is a nonlinear relationship between intensity change and SCR magnitude,

$B = -0.026$, $t(156) = -2.92$, $p = .004$. Adjusted one-tailed pairwise comparisons indicated that the 15 dB increase caused a significantly greater SCR magnitude than the no-change condition ($p = .036$) and the 5 dB condition ($p = .05$).

There was no effect of intensity change on respiratory rate, corrugator activity, zygomaticus activity, or proportion of inhalations during the moment of change.

Tempo block. There was a significant Tempo \times Epoch interaction on heart rate, $F(12,444) = 2.81$, $\varepsilon = .47$, $p = .014$, $\eta_G^2 = .015$ (Figure 4D). When there was no change in tempo, HR decreased over time, indicated by the negative linear trend in the 750-ms IOI condition, $B = -.897$, $t(190) = -2.45$, $p = .015$. An increase in tempo to a 500-ms IOI caused an increase in HR, indicated by the increasing linear trend for the 500-ms condition, $B = .77$, $t(190) = 2.02$, $p = .045$. There were no significant polynomial trends for the 429-ms and 600-ms conditions. Pairwise linear trend comparisons indicated that the trend of the no-change condition for heart rate over time was significantly different from the 600-ms and 500-ms conditions ($p < .05$) and only marginally significant for the 429-ms condition ($p = .085$).

Due to artifacts in the skin conductance signal, 1.4% of trials were excluded from the analysis. There was a marginally significant effect of IOI change on SCR magnitude, $F(3,114) = 3.42$, $p = .051$, $\varepsilon = 0.51$, $\eta_G^2 = .050$ (Figure 5C). A trend analysis on tempo indicated a significant increasing linear trend, $B = .020$, $t(156) = 2.67$, $p = .0084$, where greater increases in tempo (decreases in IOI) caused greater SCR magnitudes. After Bonferroni-Holm adjustments, one-tailed pairwise comparisons indicated that the largest IOI change (429 ms) elicited a significantly greater SCR than the 750-ms, no-change condition ($p = .035$), as well as a marginally significantly greater SCR compared to the 600-ms condition ($p = .063$).

There was no effect of tempo on corrugator activity, zygomaticus activity, respiration rate, or proportion of inhalations during the moment of change.

Duration block. There was a significant Duration \times Epoch interaction on heart rate, $F(12,444) = 3.98$, $\varepsilon = .527$, $p = .0006$, $\eta_G^2 = .019$ (Figure 4E). When there was no change in tempo, HR decreased over time, as indicated by the marginally significant decreasing linear trend in the 600-ms duration condition, $B = -.820$, $t(190) = -1.88$, $p = .062$. A change in duration to 450 ms elicited an initial decrease followed by increase in HR, indicated by a quadratic trend, $B = 0.92$, $t(190) = 4.83$, $p < .0001$. The 300-ms duration change caused an increase in HR over time, indicated by an increasing linear trend, $B = 1.01$, $t(190) = 2.24$, $p = .027$. The largest change in duration (150 ms) caused an initial decrease and then increase in HR, indicated by a quadratic trend, $B = 0.84$, $t(190) = 3.96$, $p = .0001$. Pairwise comparisons indicated that the linear trends for the 300-ms and 150-ms conditions were significantly different from the no-change condition ($p < .05$), and that the quadratic trend for the 450-ms condition was different from the no-change condition ($p < .05$).

There was also a main effect of duration on proportion of inhalations during the moment of auditory change, $F(3,114) = 2.84$, $p = .041$, $\eta_G^2 = .052$, where participants inhaled marginally more often in the 300-ms ($p = .064$) duration condition, relative to the 150-ms duration condition, after Bonferroni-Holm corrections for multiple comparisons. Note, however, that the no-change condition has the lowest HR deviation and the 300-ms condition has the highest deviation. There was no effect of duration on SCR magnitude,

zygomaticus activity, corrugator activity, or respiration rate over time.

Discussion

The results of Experiment 2 suggest that, in the absence of rhythmic irregularities, heart rate and skin conductance components of the orienting response are sensitive to simple changes in timbre, pitch, intensity, tempo, and duration. Facial motor activity and respiratory rate were not affected by auditory change. Heart rate was the most sensitive measure, responding to change for all parameters except pitch (which had a marginally significant effect). There was generally a decrease in heart rate over time when there was no auditory change and some combination of heart rate deceleration and/or acceleration in response to auditory change. SCR magnitude was sensitive to changes for all parameters except pitch and duration. For parameters where a polynomial trend analysis was conducted on the degree of change (i.e., intensity and tempo), results indicated that the magnitude of the SCR was proportional to the degree of auditory change.

Changes in timbre affected both the heart rate response and SCR magnitude. All timbre changes caused heart rate responses that differed from the continuous deceleration of the no-change condition. Trend analyses indicated an overall heart rate acceleration for the horn condition and an initial deceleration followed by an acceleratory component for the trumpet and oboe conditions. All changes in timbre caused larger SCR magnitudes compared to the no-change condition, although there were no differences between conditions. Given that we only included one timbre for each dimension of interest and that there were no differences between the three timbre-change conditions, as in Experiment 1, we again could not draw firm conclusions regarding the relative influence of individual timbre dimensions. Acoustic changes in perceptually relevant timbre dimensions, such as spectral centroid (Toiviainen et al., 1998) and rise time (Lyytinen et al., 1992), have been shown to cause the MMN, and research suggests that different timbre dimensions may be processed separately in auditory sensory memory (Caclin et al., 2006). Our findings add to the body of work on the neural correlates of timbre change by indicating that changes in timbre also affect autonomic responding. Future work could lend insight into the influence of timbre change on autonomic responding by exploring a wider variety of timbres, as well as by considering the role of timbre saliency, a quality referring to how well a timbre captures one's attention (Chon & McAdams, 2012).

Similar to the results of Experiment 1, increases in pitch elicited heart rate but not SCR components of the orienting response. Interestingly, only the 4-semitone (M3) and 11-semitone (M7) pitch-increase conditions elicited heart rate responses that differed significantly from the continuous deceleration of the no-change condition—both involved an initial deceleration, followed by an acceleration in heart rate (and an additional deceleration in the M7 condition). Given that the M3 is a smaller interval than the TT (6 semitones), this finding is contrary to our prediction that the physiological response would reflect the size of the pitch change. Moreover, the null effects of pitch change on SCR magnitude in this experiment are inconsistent with previous findings, which have shown that larger SCRs are elicited by larger changes in pitch (Siddle & Heron, 1976). Our null effects on SCR may thus be the result of the limited pitch range we employed in this study. Whereas Siddle and Heron (1976) investigated decreases in pitch from 1000 Hz to either 670 Hz (smaller pitch change, 8.3 semitones) or 380 Hz (larger change, 22.7 semitones), our largest pitch

change was an increase from 311 Hz to 659 Hz (11 semitones), as this range corresponds more closely to the successive pitch intervals observed in music.

Consistent with previous research on orienting, we found that increases in stimulus intensity affected the heart rate response and SCR magnitude. Whereas there was a decrease in heart rate in the no-change condition, the 10 dB increase caused an initial deceleration, followed by heart rate acceleration, and the 15 dB increase elicited an overall acceleratory response. These results might suggest that, although smaller increases in intensity elicit an orienting response (indicated by an early decelerating component), larger intensity changes elicit a defensive response (primarily an acceleration in heart rate). Increases in intensity also caused increases in SCR magnitude. Trend analysis indicated a quadratic trend of intensity change on SCR magnitude, suggesting that the size of the SCR magnitude is proportional to the amount of intensity decibel increase. These findings corroborate research indicating that differences in stimulus intensity affect cardiovascular and electrodermal activity (Turpin, Schaefer, & Boucsein, 1999).

Increases in tempo caused changes in the heart rate response and skin conductance response. Heart rate decreased over time when there was no change in tempo, and increased over time in response to the 500-ms IOI change. Interestingly, for the 429-ms and 600-ms IOI conditions, there were no significant polynomial trends, suggesting that there was neither acceleration nor deceleration in heart rate for these conditions, although these responses still differed significantly from the deceleration of the no-change condition. These results suggest that there is no clear relationship between the nature of the heart rate response and the degree of tempo change. For the skin conductance component of orienting, however, the effect of tempo change on SCR magnitude was more apparent. Increases in tempo were linearly proportional to SCR magnitude, where larger tempo changes caused larger SCR magnitudes. Overall, our findings can be related to previous research on music listening, which shows that increases in musical tempo cause increases in heart rate and skin conductance level (Gomez & Danuser, 2007). However, little research has been conducted on the link between tempo and physiology outside the context of music listening, and, as such, our findings provide novel evidence that an increase in tempo can elicit autonomic components of the orienting response.

Lastly, decreases in tone duration affected the heart rate response but did not affect SCR magnitude. Although HR decreased over time when there was no change in duration, trend analyses indicated that the 450-ms and 150-ms duration changes caused an initial deceleration followed by acceleration in heart rate. Although it was not the largest decrease in duration, the 300-ms duration condition elicited an overall increase in heart rate over time. These results might suggest that there is no clear relationship between the heart rate response and the degree of duration change or, alternatively, that it may be partially explained by the respiratory data. Participants tended to inhale more often on the no-change and 300-ms conditions, which may have exaggerated the heart rate response in the 300-ms condition, although we did not observe an exaggerated heart rate response in the no-change condition. Our findings on duration can be compared to previous research on orienting assessing longer duration decrements (from 15-s stimulus to 5 s), in which there is also no effect of auditory duration change on the SCR (Siddle, Kyriacou, & Heron, 1978). Moreover, our findings are consistent with existing research indicating that human listeners are sensitive to changes in shorter auditory duration ranges, where decreases in auditory duration elicit the MMN in the ERP signal (Näätänen, Paavilainen, & Reinikainen, 1989).

As a final note, effect sizes were somewhat larger overall for SCR magnitude relative to heart rate and respiration rate in Experiment 2. Rather than necessarily indicating a greater effect of auditory change on skin conductance than the other autonomic measures, however, this difference can likely be attributed to the fact that there were more independent factors for epoch-based analyses (as they included the epoch factor). This point is unsurprising given that the effect size of a particular factor generally decreases as the number of overall factors causing the effect increases (Ahadi & Diener, 1989; Levine & Hullett, 2002). A similar interpretation applies to the discrepancy between effect sizes of auditory change on heart rate in Experiments 1 and 2. Whereas the effect size of timbre and pitch change on heart rate in Experiment 1 seems miniscule in comparison to the effect size of these parameters in Experiment 2, this result can likely be attributed to the addition of isochrony as a factor in the first experiment.

General Discussion

The results of the current study extend our understanding of the relationship between auditory processing and autonomic response patterns. Previous research using the MMN as an index of auditory change detection has shown that auditory processing is sensitive to changes in pitch (Jacobsen, Schröger, Horenkamp, & Winkler, 2003), duration (Näätänen et al., 1989), timbre (Caclin et al., 2006), and intensity (Jacobsen, Horenkamp, & Schröger, 2003). This study provides evidence that these parameters, along with other musically relevant parameters such as tempo and timbre, can also elicit measurable changes in autonomic response patterns. Heart rate was sensitive to changes in all parameters (isochrony, pitch, timbre, loudness, tempo, duration), SCR magnitude was sensitive to timbre, loudness, and tempo, and respiratory rate was sensitive to deviations from isochrony. We did not find any effects of auditory change on zygomaticus or corrugator EMG activity.

Interestingly, our findings in some ways align with research investigating the structural properties of music that underlie what are thought to be emotion-related physiological changes. We demonstrate that physiological responses elicited by musical stimuli can also be caused by similar acoustic changes in controlled, simple sequences. For example, our finding that deviations from isochronous regularity caused changes in heart rate can be related to Sloboda's (1991) research on self-reported heart racing, which was associated with musical syncopation (unexpected or offbeat rhythms in music), and unexpected, early occurrences of musical events. We also found that tempo increases caused increases in SCR magnitude and, in some conditions, increases in heart rate over time. Comparable relationships between tempo and physiology have been found during music listening: happy musical excerpts with fast tempi elicit greater SCR magnitudes than sad excerpts with slow tempi (Khalfa, Peretz, Blondin, & Robert, 2002), and faster musical tempi have been linearly associated with higher skin conductance level and heart rate (Gomez & Danuser, 2007).

In both experiments, we observed increases in SCR magnitude and changes in heart rate in response to timbre changes. Similarly, increases in percussiveness in music, a property related to the attack-decay components of timbre, have been linked to increases in skin conductance level (van der Zwaag, Westerink, & van den Broek, 2011). Finally, a comprehensive investigation of low-level acoustic parameters relating music, emotion, and physiology found a linear relation between loudness, tempo, pitch level, and timbre ("sharpness") and subjective ratings of emotional arousal, which were in turn correlated with increases in heart rate (Coutinho &

Cangelosi, 2011). Again, our research suggests that changes in loudness, tempo, pitch, and timbre also cause acceleration in heart rate in the context of simple, controlled auditory sequences.

Taken together, these data present important methodological considerations for researchers interested in using physiological measures to index emotion. It is clear that many of the physiological changes displayed during music listening that reflect autonomic nervous system activity—which are often reported as evidence of emotion induction—can also be elicited by simple acoustic sequences that are unlikely to elicit emotional responses. These results may therefore suggest that physiological responses elicited during music listening are just as likely to index orienting and attention as they are to reflect genuine emotion episodes (e.g., happiness, anger, or fear). Indeed, the absence of any significant variations in facial muscle activity witnessed in these studies provides evidence in support of this view, since the zygomaticus and corrugator muscles often serve as robust indicators of positive and negative affect, respectively.

However, these findings do not rule out the possibility that simple auditory changes could induce emotional responses. The stimuli in this study may have elicited defensive responses, which are typically associated with negative affect, and some researchers have even suggested a link between orienting and emotion (for a review of this topic, see Bradley, 2009). We thus cannot definitively conclude that our current stimuli were nonemotional—only that they were much simpler auditory sequences that elicited similar physiological responses to those found in other music listening studies. That being said, a classic marker of negative affect, corrugator response, was absent from any of our stimuli.

It is worthwhile to mention some limitations in the present study, which stem primarily from the scope of auditory change examined. First, on most acoustic parameters, only unidirectional change was examined (e.g., only increases in loudness or decreases in duration). We therefore cannot draw any conclusions about the effect of directionality of change from the physiological responses measured here, although there may be important asymmetries in the response profile for acoustic changes in parameters like loudness, where sudden increases are more likely to orient listeners to the auditory stimulus than sudden decreases. Second, we chose to explore acoustic changes on magnitudes resembling those that occur in a musical context, thereby constraining our investigation to relatively small degrees of change. As a result, this constraint may have obscured potential relationships between auditory change magnitude and physiological response magnitude for parameters like pitch, where fewer effects emerged in the experiments reported here. Finally, it was difficult to make meaningful comparisons between different parameters, as the perceived magnitude of the range of change was not equalized between blocks. It is thus possible that there were fewer effects observed in the pitch block, not because changes in pitch are less salient, but because the largest pitch change was perceived as smaller in magnitude than the largest loudness change.

Nonetheless, our findings highlight the importance of using converging methods to accurately capture emotional responses during music listening—to collect physiological measurements in combination with subjective ratings of emotion induction. This approach would be consistent with dominant accounts of emotion theory that describe affective changes as a multicomponent construct involving both changes in subjective feeling and physiology (Bradley & Lang, 2000b; Juslin & Västfjäll, 2008; Mauss, Levenson, McCarter, Wilhelm, & Gross, 2005; Scherer, 2005), and would strengthen the validity of claims made about the music-emotion link.

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