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Influence of Musical Groove on Postural Sway

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Timescales of postural fluctuation reflect underlying neuromuscular processes in balance control that are influenced by sensory information and the performance of concurrent cognitive and motor tasks. An open question is how postural fluctuations entrain to complex environmental rhythms, such as in music, which also vary on multiple timescales. Musical groove describes the property of music that encourages auditory-motor synchronization and is used to study voluntary motor entrainment to rhythmic sounds. The influence of groove on balance control mechanisms remains unexplored. We recorded fluctuations in center of pressure (CoP) of standing participants ($N = 40$) listening to low and high groove music and during quiet stance. We found an effect of musical groove on radial sway variability, with the least amount of variability in the high groove condition. In addition, we observed that groove influenced postural sway entrainment at various temporal scales. For example, with increasing levels of groove, we observed more entrainment to shorter, local timescale rhythmic musical occurrences. In contrast, we observed more entrainment to longer, global timescale features of the music, such as periodicity, with decreasing levels of groove. Finally, musical experience influenced the amount of postural variability and entrainment at local and global timescales. We conclude that groove in music and musical experience can influence the neural mechanisms that govern balance control, and discuss implications of our findings in terms of multiscale sensorimotor coupling.

Keywords: groove, entrainment, postural sway, rhythm, musical auditory stimulation

Within the context of sensorimotor control, entrainment describes body synchronization with environmental rhythms. Entrainment is commonly seen in multiple modalities to rhythmic sounds, such as music and speech. Research on voluntary entrainment has looked at variability, stability and adaptability of entrainment, coordination between multiple effectors, and timekeeping mechanisms (Balasubramaniam, 2006; Ross & Balasubramaniam, 2014). It is clear that humans can easily entrain body movements to auditory rhythms (Janata, Tomic, & Haberman, 2012). Involuntary entrainment in neural oscillations is thought to be involved in beat and meter perception (Large & Snyder, 2009; Nozaradan, Peretz, Missal, & Mouraux, 2011; Nozaradan, Peretz, & Mouraux, 2012) and primes us for voluntary motor entrainment to rhythmic sounds (Iversen, Repp, & Patel, 2009; Patel & Iversen, 2014).

A common paradigm for studying entrainment is to measure simple voluntary movements, such as finger tapping. Although some attempts have been made to study more distributed body movements (Burger, Thompson, Luck, Saarikallio, & Toiviainen, 2012; Janata et al., 2012), like the complex ensembles of dance (Burger, Thompson, Luck, Saarikallio, & Toiviainen, 2014), distributed control of various joints and muscles within and between body segments has been difficult to describe and quantify (Balasu-

bramaniam & Turvey, 2004). In this paper, we look at the control of upright balance and its susceptibility toward entrainment to musical rhythms (Yeh, Boulet, Cluff, & Balasubramaniam, 2010; Yeh, Cluff, & Balasubramaniam, 2014; Riley, Balasubramaniam, & Turvey, 1999; Balasubramaniam & Wing, 2002).

Postural Control and Entrainment

It is now well known that visual, vestibular, and sensory information are incorporated into balance control processes (Balasubramaniam & Wing, 2002). Postural sway can exhibit frequency coupling with rhythmically oscillating visual displays (Dijkstra, Schöner, Giese, & Gielen, 1994; Dijkstra, Schöner, & Gielen, 1994), and with rhythmically moving contact surfaces (Jeka, Schöner, Dijkstra, Ribeiro, & Lackner, 1997). Sounds have also been shown to influence postural sway, but the role of auditory feedback in balance control processes is less understood. The existing research supports the idea that balance control can incorporate auditory information (Ross & Balasubramaniam, 2015; Dozza, Horak, & Chiari, 2007; Hegeman, Honegger, Kupper, & Allum, 2005; Tanaka, Kojima, Takeda, Ino, & Ifukube, 2001). However, there is no consensus on which types of sounds reduce sway (Ross & Balasubramaniam, 2015; Dozza et al., 2007; Hegeman, Honegger, Kupper, & Allum, 2005; Tanaka et al., 2001) and which increase sway (Agaeva, Al'tman, Kirillova, 2006; Soames & Raper, 1992). It is clear that balance control mechanisms can use auditory information including multisensory compensation and a dynamically changing sensory strategy (Dozza et al., 2007; Forti, Filipponi, Di Berardino, Barozzi, & Cesarani, 2010). We seek to test whether rhythmic sounds, such as music, can lead to entrainment in sway timing and patterns.

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The most common measure of postural control is the center of pressure (CoP). CoP consists of anterior-posterior and medial-lateral coordinates of the location on the standing surface of the force vector. This singular point reflects the sum of all forces and can reveal changes in balance processes (Balasubramaniam & Wing, 2002). One complication with using postural sway to study entrainment is that CoP is the outcome of complex balance processes and is nonstationary, so assessing entrainment requires tapping into multiple dimensions of entrainment like phase locking, frequency matching, and other aspects of sway patterns. Entrainment can occur with shorter timescale features of the music, such as beat and meter, which is reflected in tight phase or frequency locking. For the purposes of this study, we will refer to shorter timescales of entrainment as *local*. Entrainment can also occur with longer timescale features of the music, such as changes in periodicity and variability in rhythmic patterning, which means that larger scale features of sway match or vary with changes in larger scale features in a stimulus. For the purposes of this study, we will refer to larger timescales of entrainment as *global*.

Musical Groove and Sensorimotor Coupling

Groove describes how some music more than others makes us want to move, and has been shown to feel enjoyable and improve entrainment in the listener. Groove in music has been used to investigate sensorimotor entrainment (Hurley, Martens, & Janata, 2014; Janata et al., 2012; Stupacher, Hove, Novembre, Schütz-Bosbach, & Keller, 2013). Groove spontaneously induces a sense of wanting to move and is consistently perceived and rated by musician and nonmusician listeners, regardless of musical style (Madison, 2006; Madison, Gouyon, Ullén, & Hörnström, 2011; Janata et al., 2012; Witek, Clarke, Wallentin, Kringelbach, & Vuust, 2014). Increasing groove, as determined perceptually, has been shown to lead to increases in spontaneous body movement (Janata et al., 2012), but has not previously been used to study entrainment in postural sway. Music has both local rhythmic and global multiscale features that can be entrained to, which makes it a viable candidate for studying entrainment in postural sway.

In the present experiment, postural sway of participants was recorded during exposure to high and low groove music, as defined by Janata et al. (2012). Because groove in music can induce spontaneous entrainment, and because postural sway is sensitive to auditory information, musical groove should influence spontaneous entrainment in postural sway. Increased corticospinal excitability following rhythmic regularity in musical groove (Stupacher

et al., 2013) should contribute to regularity in intermittent muscular activity in the distributed control of balance. We hypothesized that groove in music would induce regularity in postural sway, and that the level of groove (high vs. low) would influence the rhythmic nature of postural sway to varying degrees. More specifically, it was proposed that high-groove music would have a stronger effect than low-groove music on spontaneous rhythmic regularity in postural sway following the rhythmic properties of the music. We expected that this increase in rhythmic regularity of sway would be reflected in reduced overall sway variability and tighter local and global entrainment. In addition, we expected nonmusicians to be more susceptible than musicians to changes in postural sway with auditory information because nonmusicians have greater groove-induced corticospinal excitability (Stupacher, Hove, Novembre, Schütz-Bosbach, & Keller, 2013).

Method

Participants

Forty healthy participants (25 women, 15 men) of similar age (22.25 ± 4.00 years), height (65.68 ± 4.21 in.), and weight (156.30 ± 39.95 lbs) were recruited from the University of California, Merced undergraduate and graduate student populations. Exclusionary criteria were hearing loss, neurological disorder, arthritis, orthopedic conditions, recent injury, and/or balance disorders at the time of testing. Twenty participants had 3 or more years of musical training and/or experience and were considered musicians for this study. The other 20 participants had fewer than 3 years of musical training or experience and were considered nonmusicians. This protocol was approved by the Institutional Review Board and participants gave informed written consent prior to the experiment.

Stimuli

Six musical stimuli were selected from a collection of music ranked for level of groove (Janata et al., 2012): three high-groove musical clips and three low-groove musical clips (matched for vocals, meter, and tempo; cf. Stupacher et al., 2013). See Table 1 for details about the musical stimuli. The 30-s free samples available on the iTunes website were used. These stimuli were normalized to control for maximum amplitude using custom MATLAB scripts. Stimuli were analyzed using an auditory salience model that is based on how humans process onsets and offsets of sounds

Table 1
Musical Stimuli

	Artist	Groove category	Groove rating (0–127)	Vocals	Meter	BPM
Superstition ⁺	Stevie Wonder	High	108.7	Male	4/4	101
Look-Ka Py Py [#]	The Meters	High	92.5	None	4/4	87
Bad Tune ^s	Earth, Wind & Fire	High	86.2	None	4/4	118
Beauty of the Sea ⁺	The Gabe Dixon Band	Low	32.1	Male	4/4	113
Ray Dawn Balloon [#]	Trey Anastasio	Low	38.5	None	4/4	80
Bryter Layter ^s	Nick Drake	Low	40.4	None	4/4	119

Note. Information taken from the Groove Library, compiled and rated by Janata et al. (2012). Each high groove clip was matched with a low groove clip for similar vocals, meter, and tempo (beats per minute, BPM), following the example of Stupacher et al. (2013), and these matched pairs are indicated by superscript symbols.

(Coath et al., 2007; Coath et al., 2009; Denham, 2008). According to the auditory salience model, the high-groove stimuli had greater salient event density ($M = .097$ salient events per second, $SD = .003$) relative to the low groove stimuli ($M = .068$, $SD = .011$); $t(2) = -4.546$, $p = .034$. Event density has previously been linked with perception of groove (Madison et al., 2011), supporting that the stimuli selected for this study are perceived as having differing levels of groove. Stimuli were also analyzed for audio features using the MIRTtoolbox (Lartillot & Toiviainen, 2007). High-groove stimuli had greater event density ($M = 3.945$, $SD = 1.025$) than low-groove stimuli ($M = 1.553$, $SD = .508$); $t(2.926) = -3.622$, $p = .038$, greater RMS energy ($M = .290$, $SD = .015$) than low-groove stimuli ($M = .247$, $SD = .017$); $t(3.979) = -3.330$, $p = .029$, greater spectral flux ($M = 107.807$, $SD = 14.542$) than low-groove stimuli ($M = 65.967$, $SD = 8.264$); $t(3.170) = -4.333$, $p = .020$, and nominally greater spectral flux in the lowest frequencies (0–800 Hz) ($M = 32.888$, $SD = 2.089$) than in the low-groove stimuli ($M = 21.494$, $SD = 6.073$); $t(2.467) = -3.073$, $p = .070$.

Procedure

Participants were presented with the six musical clips (3 low groove and 3 high groove) three times each and three trials of silence, for a total of 21 trials each lasting 30 s. These trials were randomized for each participant and presented using noise-minimizing headphones. The volume was adjusted to be loud but not uncomfortable, as determined by each participant. For each trial, the start of the stimulus and the initiation of the force platform recording were simultaneous and controlled by an external trigger. Participants were asked to wear noise-minimizing headphones and to stand still on a force platform facing away from the experimenters. They were also asked to keep their eyes on a black crosshair stimulus posted on the wall 229.00 cm in front of them at approximately eye level. Headphone volume was adjusted for participant comfort. Participants were given an opportunity for a break halfway through the experiment (after approximately 15 min). Stimuli were presented through headphones as CoP was sampled by the AMTI Force and Motion platform (Optima BP400600-2000) at 1,000 Hz.

Analyses

Sway variability. Radial sway is a measure that can be used to examine multidirectional variability in postural sway, and is often used to assess CoP maintenance (Lafond, Corriveau, Hébert, & Prince, 2004; Lafond, Corriveau, & Prince, 2004). Radial sway of CoP was calculated for each time step (i) using anterior-posterior (x) and medial-lateral (y) components of sway (Lafond, Corriveau, Hébert et al., 2004; Lafond, Corriveau, & Prince, 2004) following $r_i = \sqrt{x_i^2 + y_i^2}$. In previous work, we found that it takes a few seconds for an auditory stimulus to influence postural sway, so we removed 4 s from the beginning of each trial (Ross & Balasubramaniam, 2015) before calculating an average radial sway for each trial. Average radial sway variability was compared between condition and group. It should be mentioned that although variability in unperturbed standing might indicate less stability, variability in sway does not necessarily indicate less balance control or less stability (Riley & Turvey, 2002; Balasubramaniam,

Riley, & Turvey, 2000). Variability in postural sway may be needed to ensure adaptability, and therefore control (Balasubramaniam et al., 2000; Balasubramaniam & Torre, 2012). We used radial sway as a measure of variability (Figure 1), which has been used to characterize both stability and variability in balance control with varying degrees of success.

Local entrainment. Three measures were used to assess local entrainment: Cross-correlation analysis, spectral coherence, and the normalized pairwise variability index (nPVI). Entrainment between postural sway and beat and/or meter in the stimuli was analyzed using cross-correlation analysis and spectral coherence analysis. Entrainment between the sequential contrasts of postural sway and musical stimuli was analyzed using the nPVI.

Cross-correlation analysis was used to assess whether there was a relationship between events in radial sway and events in the stimuli, and to compare across condition and group. We discretized the radial sway and stimuli in order to have time series of events that were comparable. Radial sway was discretized using a distance from mean CoP threshold of 1.5 mm, with an event indicating this threshold was crossed. The stimuli were discretized using event detection (mironsets function of the MIRTtoolbox, Lartillot & Toiviainen, 2007). See Figure 2 for an example of the stimulus time series extraction method. Cross correlations at lag zero between the stimuli and postural sway traces were calculated and correlation coefficients were transformed to z scores using the Fisher r -to- z transform. Cross correlations at multiple lags were calculated (± 500 ms), but because there was no lead or lag, lag zero coefficients were chosen for the analysis.

Entrainment between stimuli and sway was examined using spectral coherence. To isolate components of the stimuli with which entrainment was expected to occur we extracted the temporal envelopes using a Hilbert function, as implemented by the MIRTtoolbox (Lartillot & Toiviainen, 2007). The resulting time-varying amplitude waveforms and the radial sway were passed through a Butterworth low-pass filter with a cut-off frequency of 10 Hz to isolate rhythm-related signal. The filtered amplitude waveforms and filtered radial sway were then transformed into the frequency domain using a discrete Fourier transform. See Figure 3 for one trial's amplitude envelope spectrum plotted against the radial sway spectrum and Figure 4 for amplitude envelope spectra plotted against the radial sway spectra of all trial types for all subjects. Musical beats and meter were identified by a human listener for each stimulus, and beat and meter frequencies are included in Figures 3 and 4. The stimuli amplitude envelope spectra and radial sway spectra were then compared using magnitude squared coherence. Coherence estimates were transformed to z scores using the Fisher r -to- z transform.

The normalized pairwise variability index (nPVI) measures the average degree of surface contrast (or variability) between two successive interevent interval durations in a time series of discretized events, and can therefore be considered a measure of local variability. The nPVI first computes the absolute difference between two successive interevent interval durations and is then normalized by the mean duration of the pair. All normalized values are averaged and multiplied by 100, which yields the nPVI estimate. Time series with higher (e.g., closer to 100) nPVI estimates are interpreted as having larger durational contrasts between successive interevent intervals, relative to lower nPVI estimates. The nPVI has typically been used to study speech and musical rhythm

(Grabe & Low, 2002; Low, Grabe, & Nolan, 2000; Patel & Daniele, 2003; Ramus, 2002), but can be applied to any time series. For each trial, we created an nPVI matching score, $nPVI_{\text{difference}}$, which is the absolute difference between an nPVI estimate for postural sway and an nPVI estimate for the auditory stimuli. A smaller $nPVI_{\text{difference}}$ value indicates more matching between postural sway and the auditory stimuli. We used the $nPVI_{\text{difference}}$ for each trial to test for differences across condition and group.

Global entrainment. Two measures were used to assess global entrainment of postural sway to properties of the stimuli: normalized multiscale coefficient of variation (nMSCV), and a resonator model that extracts periodicity profiles. The nMSCV measures the distance between local coefficient of variation estimates at particular timescales and the overall coefficient of variation across all time samples. The average coefficient of variation was computed for increasing time scales starting at bin size = 2, and increased in multiples of two up to bin size = 128 (i.e., 7 bin sizes: 2 (40 msec), 4 (80 msec), 8 (160 msec), 16 (320 msec), 32 (640 msec), 64 (1280 msec), and 128 (2560 msec)). For each timescale, coefficient of variation was estimated across a sliding nonoverlapping window from the start to the end of each time series. For each trial, the average coefficient of variation values at each bin size were summed, normalized by the overall coefficient of variation, and then divided by the total number of bins (i.e., 7 bins; 2, 4, 8, 16, 32, 64, 128). Figure 5 is an example of an MSCV profile, which is used to compute the nMSCV estimates. The nMSCV is not bounded by a specific range but generally spans from 0.0 to 1.0, where higher nMSCV estimates indicate that the coefficient of variation at small bin sizes (e.g., bin size = 2) are approximating the overall coefficient of variation, whereas smaller nMSCV estimates indicate that the coefficient of variation across increasing bin sizes increases slower toward the overall coefficient of variation. A random time series will have an nMSCV value of 1.0, which indicates that there is little heterogeneity of variability across various temporal scales. Smaller nMSCV values suggest more heterogeneity of variability across temporal scales and are interpreted as having more multiscale structure. The nMSCV is a novel analysis of the multiscale structure of a time series. Similar to assessing matching for the nPVI estimates, for matching of nMSCV estimates, we created a matching score, $nMSCV_{\text{difference}}$, which is the absolute difference between an nMSCV estimate for postural sway and an nMSCV estimate for the auditory stimulus in a particular trial.

The resonator model generates a periodicity spectrum and a mean periodicity profile (MPP), which is an average amplitude spectrum of periodicities over time (Tomic & Janata, 2008). MPPs can be generated for musical stimuli and movement data and have been used to measure entrainment to multiple periods between music and movement (Janata et al., 2012; Hurley et al., 2014). We consider this a global measure of entrainment because it abstracts the peak periodicities from the frequency spectrum and averages those peak periodicities over the duration of the time series (in contrast with spectral coherence, which includes all frequencies within the specified frequency range, and does not involve averaging over time). Cross-correlations were transformed to z scores using the Fisher r -to- z transform. We compared z -transformed cross-correlations between stimulus MPPs and sway MPPs to quantify multiperiod matching between stimuli and postural sway.

Results

Sway Variability

Radial sway was reduced with increasing levels of groove: radial sway was greatest in the silent condition and least in the high groove condition (musicians/silence $M = 4.32$, $SE = .49$, musicians/low groove $M = 3.69$, $SE = .32$, musicians/high groove $M = 2.97$, $SE = .17$, nonmusicians/silence $M = 4.61$, $SE = .48$, nonmusicians/low groove $M = 3.83$, $SE = .16$, nonmusicians/high groove $M = 3.15$, $SE = .10$), as shown in Figure 1A. Radial sway was compared using a 3 condition (silence, low groove, high groove) \times 2 group (musicians, nonmusicians) analysis of variance (ANOVA) with repeated measures. We found a main effect of condition, $F(2, 19) = 9.315$, $p < .001$, with no significant group effect, $F(1, 19) = .608$, $p = .445$ and no significant condition \times group interaction, $F(2, 19) = .030$, $p = .970$. Pairwise tests using the Bonferroni adjustment for multiple comparisons revealed a decrease in radial sway between silence and high groove conditions ($p = .007$) and between low groove and high groove conditions ($p = .003$). Radial sway of the individual stimuli did not vary as a function of groove rating, as shown in Figure 1B (musicians/Beauty of the Sea $M = 3.23$, $SE = .25$, musicians/Ray Dawn Balloon $M = 3.75$, $SE = .40$, musicians/Bryter Layter $M = 4.09$, $SE = .53$, musicians/Bad Tune $M = 2.77$, $SE = .20$, musicians/Look-Ka Py Py $M = 3.20$, $SE = .26$, musicians/Superstition $M = 2.92$, $SE = .24$, nonmusicians/Beauty of the Sea $M = 3.42$, $SE = .25$, nonmusicians/Ray Dawn Balloon $M = 3.56$, $SE = .22$, nonmusicians/Bryter Layter $M = 4.50$, $SE = .44$, nonmusicians/Bad Tune $M = 2.92$, $SE = .20$, nonmusicians/Look-Ka Py Py $M = 3.28$, $SE = .19$, nonmusicians/Superstition $M = 3.24$, $SE = .19$).

Local Entrainment

Discretized radial sway had a stronger correlation to musical events of the stimuli in the high-groove condition than in the low-groove condition, as shown in Figure 3A. Correlation coefficient z scores (musicians/low groove $M = .22$, $SE = .006$, musicians/high groove $M = .27$, $SE = .008$, nonmusicians/low groove $M = .22$, $SE = .003$, nonmusicians/high groove $M = .27$, $SE = .005$) were compared using a 2 condition (low groove, high groove) \times 2 group (musicians, nonmusicians) ANOVA with repeated measures. We found a main effect of condition, $F(1, 19) = 131.576$, $p < .001$, with no significant group effect, $F(1, 19) = .610$, $p = .444$ and no significant condition \times group interaction, $F(1, 19) = .044$, $p = .835$.

Stimuli amplitude envelope spectra and radial sway spectra exhibit greater magnitude squared coherence in the high-groove condition than in the low-groove condition. As shown in Figure 3C and D and Figure 4A and B, this coherence may reflect entrainment to beat or to meter frequencies. Intersubject variability in sway and entrainment is reflected in individual participants' sway spectra, shown in Figure 4. An inspection of Figure 4 reveals that individual trials show peaks at beat and meter frequencies. The results of the coherence analysis support individual entrainment in sway to the rhythm-related frequencies in the stimuli. Coherence estimate z scores (musicians/low groove $M = 1.20$, $SE = .005$, musicians/high groove $M = 1.26$, $SE = .005$, nonmusicians/low groove $M = 1.21$, $SE = .005$, nonmusicians/high groove $M = 1.26$, $SE = .006$) were compared using a 2 condition

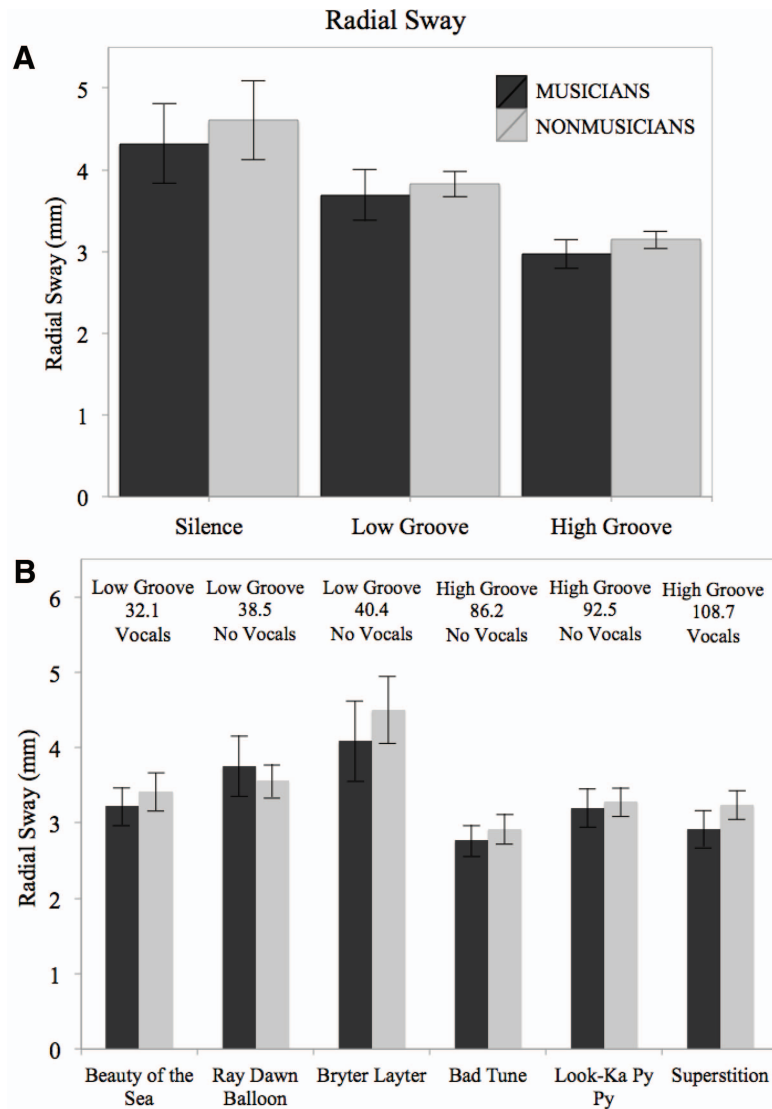


Figure 1. (A) Radial sway variability of CoP by condition. Error bars represent ± 1 standard error from the mean. (B) Radial sway variability of CoP by stimulus, in order of ascending groove rating. Groove category, groove ratings (Janata et al., 2012), and information about vocals are included for each stimulus. Error bars represent ± 1 standard error from the mean.

(low groove, high groove) \times 2 group (musicians, nonmusicians) ANOVA with repeated measures. We found a main effect of condition, $F(1, 19) = 159.164$, $p < .001$, with no significant group effect, $F(1, 19) = 0.796$, $p = .384$ and no significant condition \times group interaction, $F(1, 19) = 1.750$, $p = .202$.

The nPVI estimates of postural sway were compared using a 2 condition (low groove, high groove) \times 2 group (musicians, nonmusicians) ANOVA with repeated measures. We found that the nPVI estimates for postural sway were smaller for musicians ($M = 21.66$, $SE = .90$) relative to nonmusicians ($M = 29.14$, $SE = .83$), $F(1, 19) = 5.852$, $p = .026$, suggesting that musicians have less postural sway variability from successive intervals across a trial. No other main effects or the interaction were significant, $ps > .05$ (see Figure 6A).

The nPVI_{difference} estimates were compared using a 2 condition (low groove, high groove) \times 2 group (musicians, nonmusicians)

ANOVA with repeated measures. A significant main effect of group, $F(1, 19) = 6.552$, $p = .019$ suggested there was more matching for the nonmusicians ($M = 21.93$, $SE = .68$) relative to the musicians ($M = 29.03$, $SE = .72$). A significant main effect of condition, $F(1, 19) = 5.595$, $p = .029$ suggested there was more matching for high groove trials ($M = 24.82$, $SE = .68$) relative to low groove trials ($M = 26.07$, $SE = .77$). The interaction was not significant, $p > .05$ (see Figure 6C).

Global Entrainment

The nMSCV estimates were compared using a 2 condition (low groove, high groove) \times 2 group (musicians, nonmusicians) ANOVA with repeated measures. We found that the nMSCV estimates for postural sway were smaller for musicians ($M = .31$,

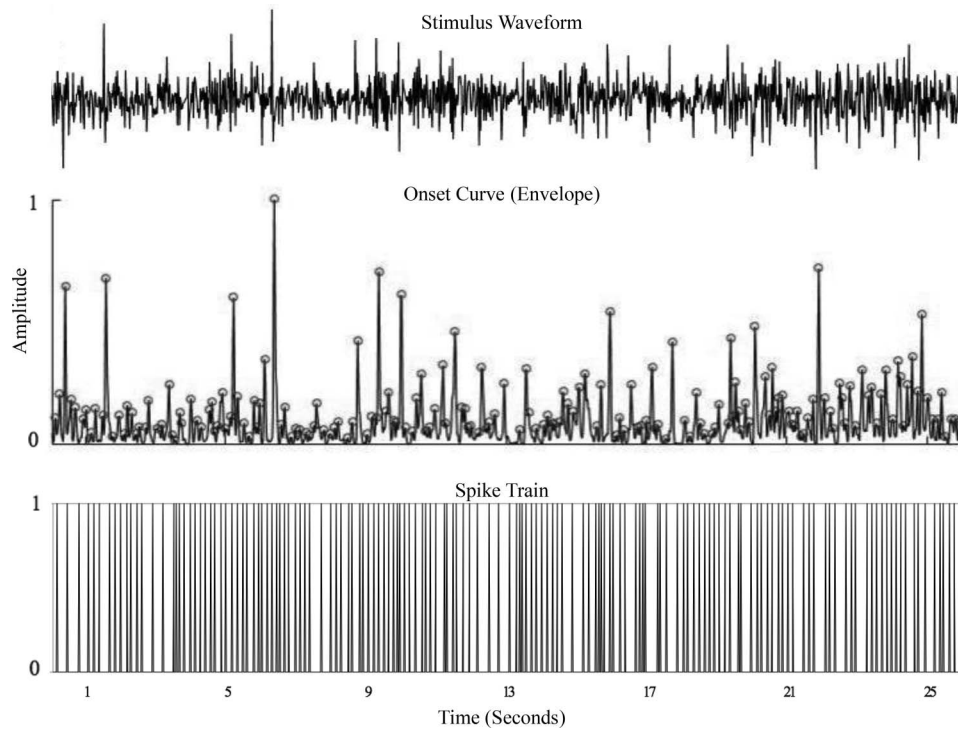


Figure 2. Event detection for Superstition (by Stevie Wonder). Musical events were extracted from the stimuli using the onset detection algorithm in the MIRTtoolbox (Lartillot & Toivainen, 2007), which detects successive bursts of energy in a waveform and determines peaks in the resulting onset detection curve. Times of onset peaks were used to make discretized spike trains of the event series of each stimulus.

$SE = .009$) relative to nonmusicians ($M = .43$, $SE = .009$), $F(1, 19) = 8.596$, $p = .009$, suggesting that the variability of postural sway of musicians varies across multiple temporal scales of measurement more than for nonmusicians. No other main effects or the interaction were significant ($p > .05$; see Figure 6B).

The $nMSCV_{\text{difference}}$ estimates were compared using a 2 condition (low groove, high groove) \times 2 group (musicians, nonmusicians) ANOVA with repeated measures. A significant main effect of group, $F(1, 19) = 8.763$, $p = .008$ suggested there was more matching for the nonmusicians ($M = .34$, $SE = .008$) relative to the musicians ($M = .45$, $SE = .009$). A significant main effect of condition, $F(1, 19) = 106.334$, $p < .001$ suggested there was more matching in the low groove trials ($M = .37$, $SE = .008$) relative to the high groove trials ($M = .41$, $SE = .008$). The interaction term was not significant ($p > .05$; see Figure 6D).

Increased global matching in the low-groove condition was supported by the periodicity analyzing resonator model. MPP correlation coefficient z scores (musicians/low groove $M = .85$, $SE = .007$, musicians/high groove $M = .77$, $SE = .006$, nonmusicians/low groove $M = .89$, $SE = .02$, nonmusicians/high groove $M = .82$, $SE = .02$) were compared using a 2 condition (low groove, high groove) \times 2 group (musicians, nonmusicians) ANOVA with repeated measures. We found a main effect of condition with low groove being more correlated with sway than high groove, $F(1, 19) = 1799.207$, $p < .001$, and an effect of group, with nonmusicians' sway being more correlated to stimuli than musicians' sway, $F(1, 19) = 5.668$, $p = .028$. There was no condition \times group interaction, $F(1, 19) = 0.100$, $p = .755$.

Discussion

We observed reduced sway variability while listening to music relative to the silent condition, with high-groove music reducing sway more than low-groove music (see Figure 1). This supports that groove in music can influence neural mechanisms implicated in balance control, and that increasing level of groove has an increasing impact on sway variability. We expected that an increase in rhythmic regularity of sway while listening to music would result in reduced sway variability. The reduction of sway with increasing level of groove supports this hypothesis.

Furthermore, we show a stronger local correlation between musical events and postural sway in the high-groove condition when compared with the low-groove condition. Spectral coherence analysis supports that this is likely due to involuntary entrainment to the beat and meter frequencies in the music, and that this shorter timescale (local) entrainment is stronger with high-groove than with low-groove music.

Auditory Features of Groove

There are numerous factors that could be contributing to perception of and motor response to groove in music, including RMS energy, RMS variability, pulse clarity "attack," spectral flux, and low-frequency spectral flux (Stupacher, Hove, & Janata, 2014). This is in line with the results of our stimuli analyses, which revealed differences in RMS, spectral flux, and low-frequency spectral flux between the high- and low-groove music samples. Many of these individual features have been shown to influence

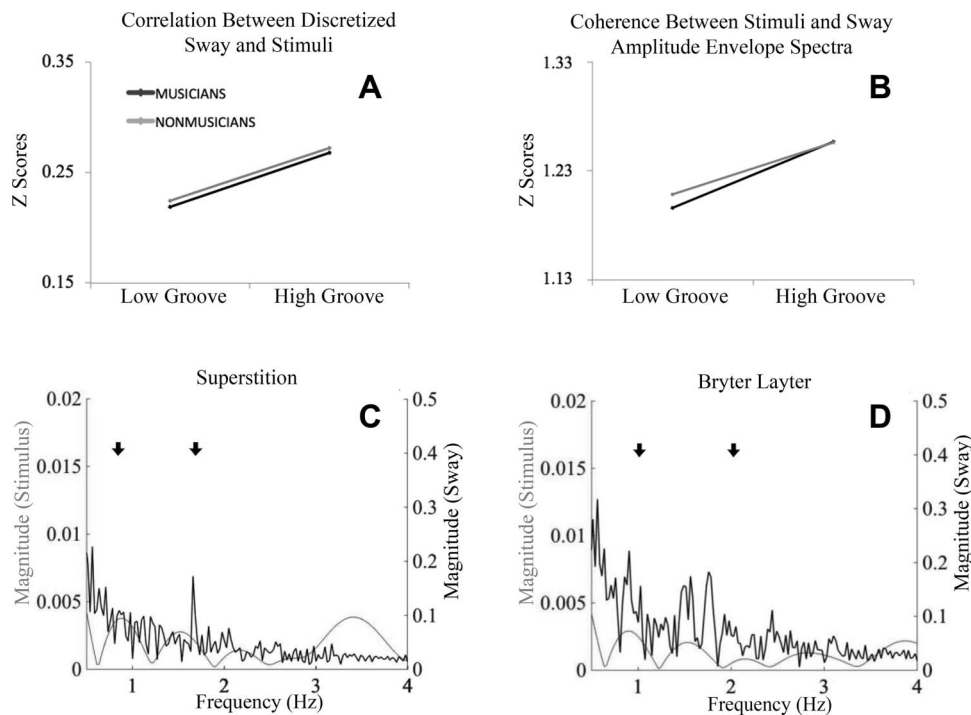


Figure 3. Evidence of local entrainment in postural sway at beat and meter frequencies of the musical stimuli. (A) Correlation coefficients (z transformed r scores) of the discretized sway and stimuli. (B) Spectral coherence (z transformed r scores) between amplitude envelope spectra of the stimuli and radial sway. A low-pass Butterworth filter (<10 Hz) was used to isolate rhythm-related signal. (C) One high groove trial, with stimulus Superstition. The Superstition spectrum is plotted against the radial sway spectrum from that trial. Arrows indicate the beat and meter frequencies of Superstition, as determined from human listener judgments of the location of the beat. (D) One low-groove trial, with stimulus Bryter Layter. The Bryter Layter spectrum is plotted against the radial sway spectrum from that trial. Arrows indicate the beat and meter frequencies of Bryter Layter, as determined from human listener judgments of the location of the beat.

body movement (Burger et al., 2012; Van Dyck et al., 2013), and their presence in music could also have an influence on body movement.

Other acoustic features that have been linked with perception of groove are event density (Madison et al., 2011) and structural complexity (Witek et al., 2014). We have verified that our high- and low-groove stimuli differ in event density and perceptually salient event density. Witek et al. (2014) showed that structural complexity in music is related to enjoyment and desire to move. They reported an inverted U-shaped relationship between degree of syncopated drum patterns and questionnaire ratings about wanting to move and enjoyment of the music; pleasure and desire to move increased as degree of syncopation increased, until a point when pleasure and desire to move decreased with further increase in degree of syncopation (Witek et al., 2014). There seems to be an ideal level of complexity for maximal enjoyment and “grooviness”.

The question remains of what the element of groove is that influences desire and ability to entrain. Hurley et al. (2014) proposed that musical features that modulate attention contribute to groove rating, enjoyment, and entrainment. This would support that music with more attention modulating features could lead to greater local entrainment in sway. Focusing attention on posture can increase sway variability, and focusing attention on an external motor task can reduce sway variability because of an increased reliance on automatic

balance control processes (McNevin & Wulf, 2002). With an increase in groove in the music, there could be an increase in attention on the music. If this is the case, then sway variability might be expected to decrease because of more reliance on automatic balance control processes when attending more to the high-groove music than to the low-groove music or silence.

In addition, if listening to high-groove music is more cognitively demanding than listening to low-groove music and silence, then sway variability might also be expected to decrease due to more reliance on automatic balance control processes (Cluff, Gharib, & Balasubramanian, 2010). Passively listening to music is not a performance-related task, although it is possible that passive beat perception and time keeping during listening might demand attention and other cognitive resources. However, if beat perception requires sufficient attention and other cognitive resources to drive a reduction in sway, then our results would seem to suggest that beat perception while listening to high-groove music requires more cognitive resources than beat perception while listening to low-groove music.

Postural Sway Entrainment to Groove

Another possible explanation is that reduced sway variability is a side effect of increased regularity in sway due to rhythmic/local entrainment. An increase in correlation between sway and stimuli,

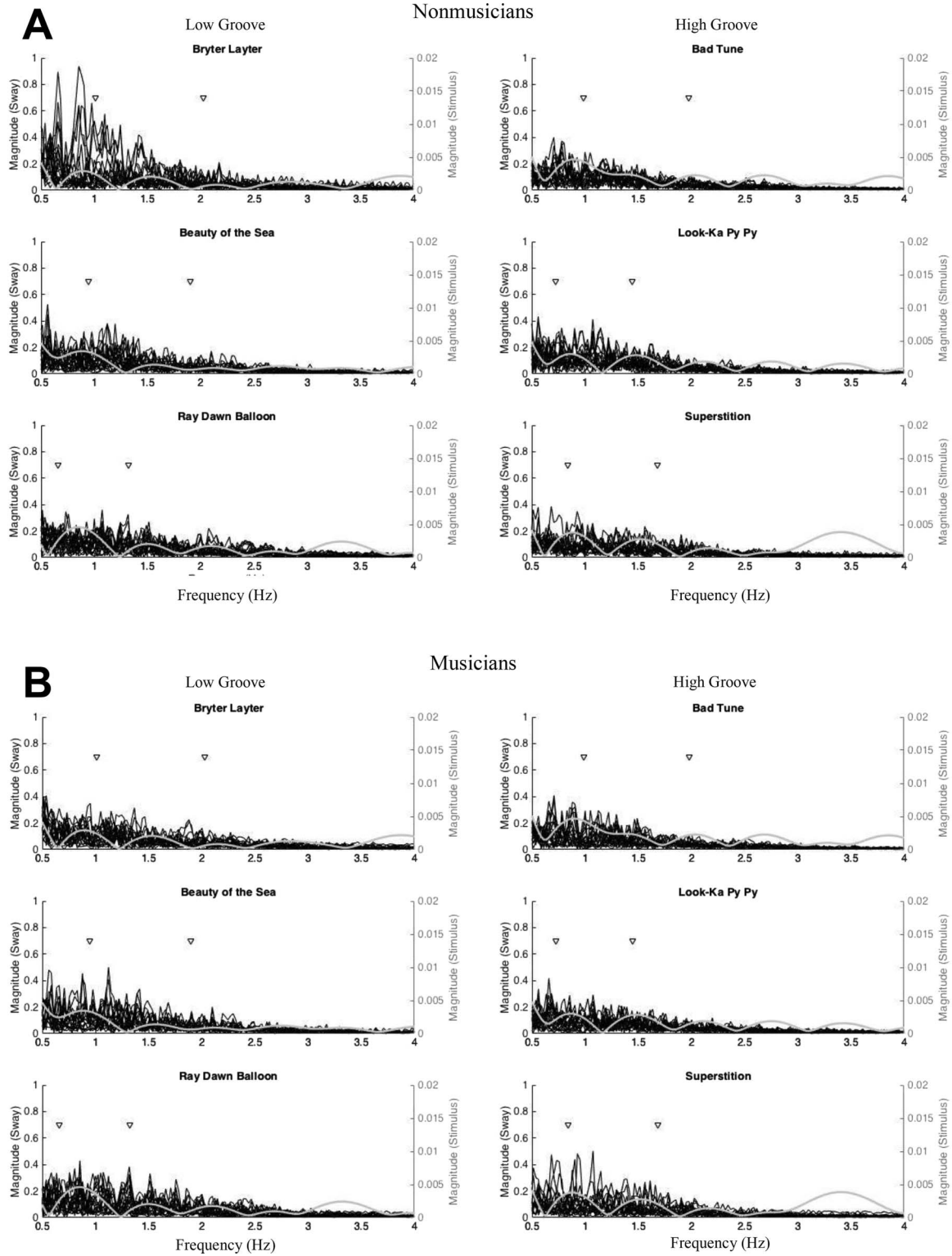


Figure 4. Stimuli amplitude envelope spectra plotted against radial sway spectra for nonmusicians (A) and musicians (B). Black lines indicate individual subjects averaged within trial type. Gray lines indicate stimuli amplitude envelope spectra. Arrows indicate the beat and meter frequencies of the stimuli, as determined from human listener judgments of the location of the beat.

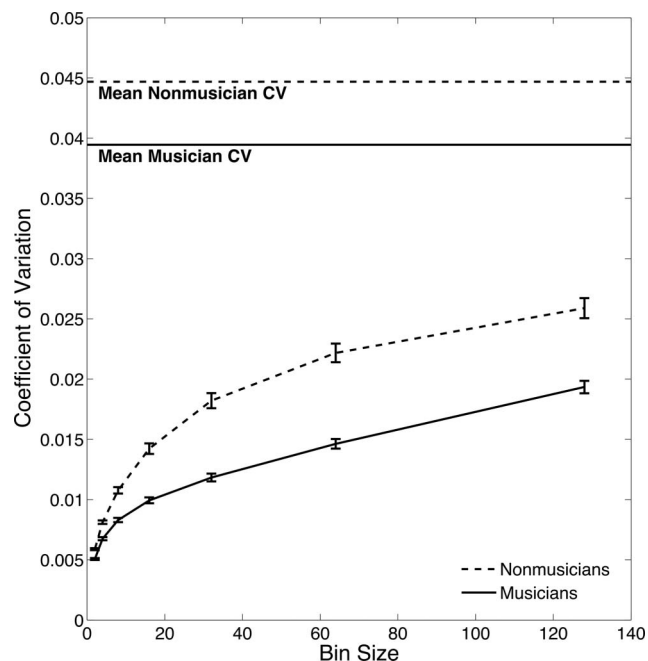


Figure 5. Example nMSCV profile. X-Axis is the bin size. Y-Axis is mean coefficient of variation. Horizontal lines indicate mean coefficient of variation for each time series. Error bars represent ± 1 standard error from the mean. nMSCV is computed by summing the mean CV function, dividing by CV, and normalizing by dividing by number of bins ($n = 7$). Note the time scales for the seven bins are 40 msec, 80 msec, 160 msec, 320 msec, 640 msec, 1,280 msec, and 2,560 msec.

an increase in spectral coherence between sway amplitude envelope spectra and stimuli (see Figure 3), and similar local variability all provide supporting evidence for local entrainment. Further support can be found by the increase in sway amplitude at the stimuli beat and meter frequencies, also shown in Figure 3C and D and Figure 4A and B. Increased rhythmic regularity in postural sway following the rhythms in the music can explain the reduced overall sway variability with increasing level of groove.

We show evidence for global entrainment to changes in variability over time and to the complex metric structure of the music, and show that global entrainment is stronger for low-groove music than for high-groove music. Nonmusicians may be more susceptible to global entrainment than musicians. To our knowledge, there is no previous research on multiscale entrainment of postural sway to music. Previous work has shown that people can entrain to complex musical stimuli (Rankin, Large, & Fink, 2009) and other auditory stimuli that exhibit long-range correlation properties (Hove, Suzuki, Uchitomi, Orimo, & Miyake, 2012; Marmelat, Torre, Beek, & Daffertshofer, 2014; Stephen, Stepp, Dixon, & Turvey, 2008; Stephen & Dixon, 2011). Although the goal of the current study was not to assess coordination with fractal auditory stimuli, we did measure the extent to which multiscale variability of postural fluctuations matched corresponding patterns in musical stimuli.

Low-groove stimuli had lower salient event density than high-groove stimuli, and this might relate to more diffuse periodicities in low-groove music. If so, this might explain why we observed

greater MPP correlation coefficients during low-groove trials: low-groove music has more periodicities to possibly entrain to, and therefore the postural fluctuations occupied multiple periodic patterns. However, although groovy music has been described as containing multiple nested periodicities (Merker, 2014), it has not been shown that low groove has more periodicities than high groove. We expect that future analyses of groove will examine in more detail the metrical complexities and nested periodicities in music that has low or high groove ratings. Janata et al. (2012) found that the number of peaks in stimulus MPPs did not differ as a function of groove, but did observe increased peaks in MPPs when subjects freely tapped to the mid groove and low groove music relative to high groove music. Therefore, it is possible that the effect of global entrainment observed in the current study is not purely stimulus-driven and reflects other factors not otherwise accounted for in the current study. The results from the nMSCV difference analyses support this explanation. Although we did not observe differences in postural sway nMSCV estimates as a function of groove, there was more global matching of postural sway with low-groove musical stimuli.

Entrainment is possible with beat, meter, or other more global aspects of music. As Figure 3 shows, the prominent beat frequency does not line up with any one peak in the low-groove Bryter Layter spectrum. Instead, there is a cluster of peaks around the beat frequency and a stronger peak at the meter frequency marker. This is because the beat is not emphasized in this particular piece of music, however the meter is emphasized. Thus it is easier and more spontaneous to synchronize with the meter than the beat in this particular stimulus. In addition, the high-groove musical clip, Superstition, has a clearly prominent frequency at the beat frequency, but less prominent meter. We chose to use spectral coherence to assess local entrainment because it can reveal information about whether entrainment is occurring and if this entrainment is to beat or meter frequencies.

Entrainment to different properties of musical stimuli, like beat and meter, suggests that the tendencies to entrain to music might be influenced by a collection of properties of music and experience of the listener. From numerous analyses, spanning local and global components of postural sway and musical stimuli, we found an interesting pattern of entrainment: At shorter timescales, people spontaneously entrain to high-groove music, and at longer timescales, people spontaneously entrain to low-groove music.

It could be that low-groove music has a less defined and predictable beat structure relative to high-groove music, and because of this, participants spontaneously entrain to different parts of the stimuli throughout each trial. For high-groove music, with a more defined and predictable beat structure, participants spontaneously entrain more to these local rhythmic features consistently.

Previous work has shown increased spontaneous body movement while listening to high-groove music, and better voluntary entrainment to high-groove music when compared with low-groove music (Janata et al., 2012). Further, high-groove music can influence corticospinal excitability (Stupacher et al., 2013), and there is some evidence that high-groove music can influence involuntary physiological responses measured as heart rate and EEG power in multiple frequency bands (Stewart, 2014). Our results are evidence that both high- and low-groove music can lead to changes in automatic balance control behavior that can be explained by local and global entrainment.

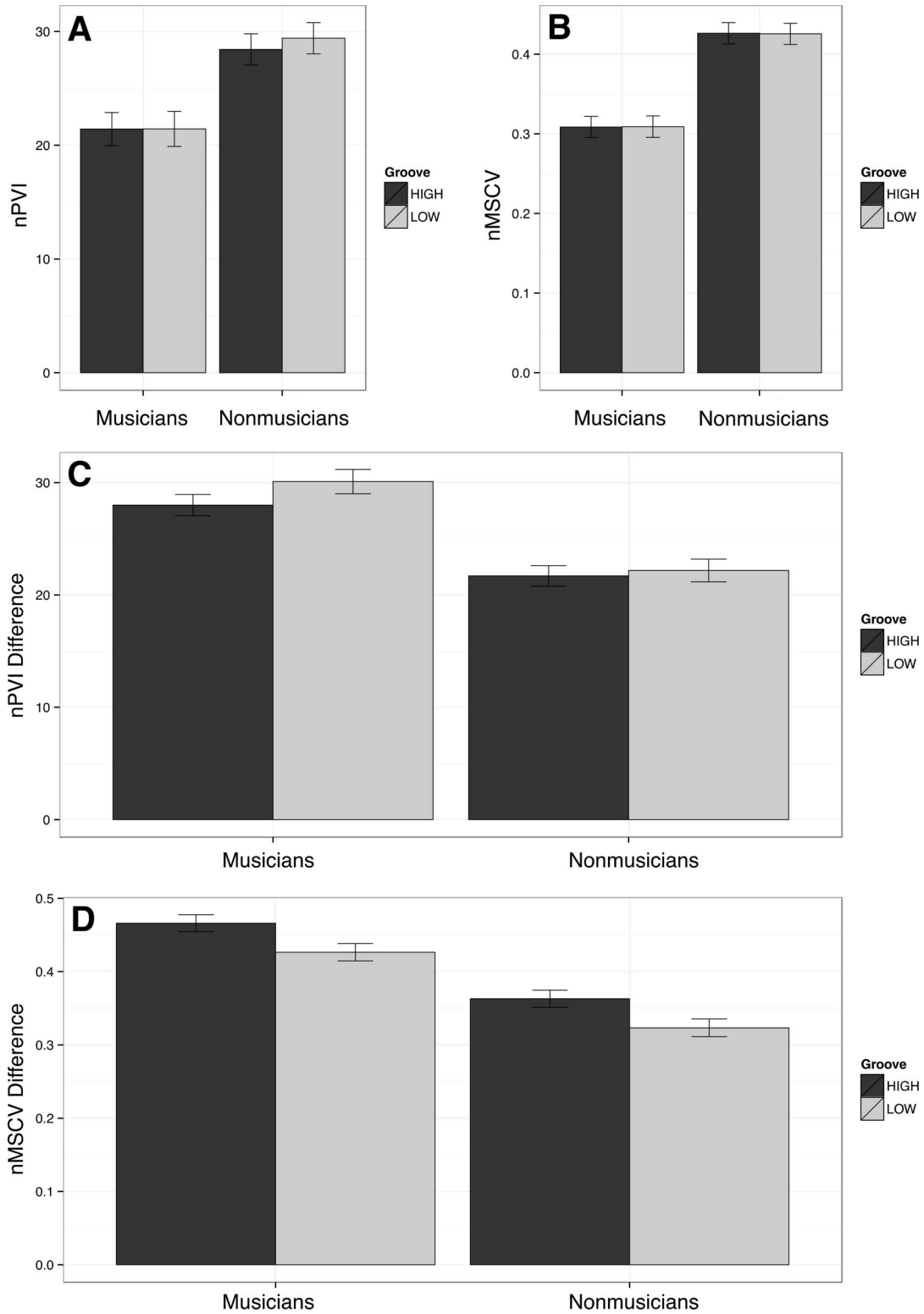


Figure 6. Mean postural sway nPVI (A) and nMSCV (B) estimates for group and groove factors. (C) Mean nPVI difference estimates for group and groove factors (Note that smaller estimates correspond to more matching). (D) Mean nMSCV difference estimates for group and groove factors (note that smaller estimates correspond to more matching). Error bars represent ± 1 standard error from the mean.

Musical Experience

We found that musical experience influenced the amount of postural variability and entrainment at local timescales. Our data support that musical experience decreases the amount of sway variability from successive intervals across a trial, and decreases the degree of nPVI matching. We also found that musical experience influenced the amount of postural variability and entrainment at global timescales. Our data support that musical experience increases the variability of sway across multiple temporal scales, but decreases nMSCV matching. Matching between postural sway periodicity and music periodicity profiles is also influenced by musical experience, with musical experience decreasing correlation between sway and stimulus. As hypothesized, nonmusicians were more susceptible than musicians to changes in postural sway and entrainment with auditory information. This can be explained with increased regularity in distributed intermittent muscular activity in the control of balance due to greater groove-induced corticospinal excitability in nonmusicians (Stupacher et al., 2013) following rhythmic regularity in musical groove.

Future Directions

Now that it has been shown that groove induces both shorter and longer timescales of entrainment in postural sway, there are numerous directions that could be explored. Postural sway variability should be measured during overt modulation of attention using nonrhythmic auditory stimuli. Although we provide support that groove can lead to entrainment in sway, it is still unknown whether auditory attention-modulating stimuli can also influence sway variability.

Shorter and longer timescales of entrainment to high and low groove music could also be explored in other types of motor behaviors, such as walking and speech. The role of entrainment to auditory stimuli, such as music, could be explored in the context of motor learning and rehabilitation. Auditory environments influence movements in predictable and potentially useful ways, and groove can be used to investigate this auditory–motor interaction, even in seemingly automatic balance control processes.

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