How Music Moves Us: Entraining to Musicians' Movements

Alexander P. Demos & Roger Chaffin
University of Connecticut

We measured the postural sway of two trombonists as they each recorded multiple performances of two solo pieces in each of three different expressive styles (normal, expressive, non-expressive). We then measured the postural sway of 29 non-trombonist listeners as they moved their arms and body, "air-conducting" the recorded sound as if to draw out the emotion from the performance (Experiment 1), and of the two trombonists as they played along with the same recorded performances (Experiment 2). In both experiments, the velocity of listeners' postural sway was more like that of the performer than expected by chance. Listeners entrained more to back-and-forth than to side-to-side sway in Experiment 1 and only to back-and-forth sway in Experiment 2. Entrainment was not due entirely to performer and listener both swaying to the musical pulse in the same way. Listeners in Experiment 1 rated performances as more expressive when they entrained more, suggesting that entrainment enhanced their aesthetic experience of the music. The whole body appears to contribute to unpacking the expressive content of musical communication.

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Musicians sway expressively as they play (Davidson, 2009), and audiences sway as they listen (Clayton, 2007). We asked whether the movements of performers and listeners are related. Simply seeing, hearing, or feeling the actions of another person is often sufficient to elicit intermittent synchronization (Riley, Richardson, Shockley, & Ramenzoni, 2011). If the same thing happens when listening to music, audiences may entrain to the movements of the performer and musicians to fellow performers, just from hearing the musical sound. To find out, we recorded two trombonists as they each played (solo) the same two pieces, and compared their postural sway during the recorded performances with those of listeners "air-conducting"[1] the performances (Experiment 1) and playing along with the recorded performance (Experiment 2).

Entrainment, also called unidirectional coupling, occurs when energy or information passes from one system to another, inducing the second system to adhere to the timing of the first (Pikovsky, Rosenblum, & Kurths, 2001). Previous studies of interpersonal entrainment have mostly examined situations in which participants see (or see and hear) another person, and have examined the synchronization of simple, repetitive movements such as tapping, pendulum swinging, or walking (for reviews, see Schmidt, Fitzpatrick, Caron, & Mergeche, 2011; Repp & Su, 2013). The entrainment that we looked for was both less direct and more complex. We looked for entrainment based on: 1) hearing (rather than seeing); 2) the performances were recorded (rather than live); 3) the movements were complex and quasiperiodic (rather than simple and repetitive); and 4) the sound was music (rather than the incidental by-product of an activity like rocking or walking).

Despite these differences, we expected to find entrainment to the movements of musicians because several studies have reported spontaneous entrainment to the movements of an unseen partner, both simple, repetitive movements, such as rocking in a rocking chair (Demos, Chaffin, Begosh, Daniels & Marsh, 2012), as well as more complex, quasiperiodic movements, such as the postural sway of an unseen interlocutor (Shockley, Santana, & Fowler, 2003; Shockley, Baker, Richardson, & Fowler, 2007). In these studies, similarity of postural sway increased as a result of hearing the sound of an unseen partner's actions. In coordination tasks, background music seems to act like a third person in the room; when music is introduced, spontaneous synchronization with the other person decreases because listeners try to synchronize with both the other person and the music (Demos et al., 2012; Verga, Bigand, & Kotz, 2015).

[1] Participants were told to move their bodies as if drawing out the emotion from the performer but without trying to "count time" with their baton. We use the term "air-conduct" to refer to this activity by analogy with the commonly used term "air-guitar" referring to imaginary playing of a guitar accompaniment.

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LISTENING VS. PLAYING-ALONG

In Experiment 1, we approximated the situation in which listeners spontaneously sway to the sound of music by asking participants to imagine that they were conducting the music so as to draw out the emotion, without trying to "count time." In some respects, this situation was similar to the studies of social coordination (such as Demos et al., 2012; Shockley et al., 2003, 2007; Verga et al., 2015), except that the sound of the other person was replaced by the sound of music. In other respects, our task was similar to a study in which participants entrained to the shoulder movements of an unseen performer playing the Chinese guqin, even though they were unfamiliar with the zither-like instrument (Leman, Desmet, Styns, Van Noorden, & Moelants, 2009). As in our study, listeners were asked to move to music, except that we instructed our listeners more specifically to draw out the emotion in the music rather than just to move to it. If our listeners entrain to the movements of the performer, it will be as though they are spontaneously entraining to another person in the room, as in social coordination studies, through musical sound.

In Experiment 2, we approximated the situation in which musicians play in an ensemble with other musicians by asking the two trombonists to play along with the previously recorded performances. Unlike Experiment 1, the listening and recorded musicians were doing the same task. Thus, any similarity in their movements might be a result of playing the same notes rather than entrainment to the performer. To control for this, we compared similarity in Experiment 2 to a baseline of similarity when playing alone without hearing another performance. To compute the baseline correlations, it was necessary to standardize the durations of the different performances, which we did by time-locking note onsets (see Supplementary Materials accompanying online version of this paper). Thus, the baseline reflected similarity due to playing the same music, including playing the same notes at the same time and any metaphorical suggestions of motion conveyed by the music. To count as entrainment, similarity had to be higher than this baseline. Thus, entrainment would be due to hearing the recorded performance, not to playing the music.

EXPLANATIONS FOR ENTRAINMENT

If we do find evidence of entrainment, it will raise the question of how entrainment could be possible simply through hearing the recorded performance. Four main types of mechanism (not mutually exclusive) have been proposed to account for entrainment to movement, two Gibsonian and two cognitive. The direct realism account suggests that auditory signals provide information about the actions that produce them (Fowler, 1986). For example, when hearing speech, listeners perceive the articulatory gestures responsible for speech sounds. Other researchers in the Gibsonian tradition have invoked dynamical systems theory in attributing entrainment to the resonance that occurs when energy flows between complex systems when they are connected, either physically or by the flow of sensory information between people when they interact (Marsh, 2010; Pikovsky et al., 2001; Riley et al., 2011). From the cognitive perspective, entrainment has been attributed to activation of the motor system by mirror neurons (Kohler et al., 2002; Rizzolatti, Fadiga, Gallese, & Fogassi, 1996), or by mental simulation of an observed action sequence that generates predictions about upcoming actions (Keller, 2012; Keller & Appel, 2010; Novembre, Ticini, Schutz-Bosbach, & Keller, 2014; Sebanz, Bekkering, & Knoblich, 2006).

Our study does not distinguish among these explanations. Instead, we asked whether entrainment occurred, and looked for clues as to how this could happen. Identifying the mechanism responsible for entrainment when music is involved is complicated by the presence of two routes through which entrainment might take place: movement or music. In the studies described above, listeners entrained to movement through hearing the sounds created by another person (Demos et al., 2012; Schmidt et al., 2011; Shockley et al., 2003, 2007; Verga et al., 2015). We will refer to this as "entrainment to movement." For listeners in our study to entrain to movement, the recorded music would have to provide information about the movements of the performer. Music may be capable of doing this because perceptual processing is organized around tasks rather than around sensory modalities (Camponogara, Rodger, Craig, & Cesari, 2017; Rosenblum, Dias, & Dorsi, 2016; Steenson & Rodger, 2015). For example, speech sounds provide listeners with information about the speech gestures (unseen movements of the vocal tract) that produce them (Fowler, 1986; Galantucci, Fowler, & Turvey, 2006). Similarly, musical sounds created by acoustic instruments may convey to listeners the movements that produced them (Gaver, 2003; Godøy, 2010). For example, recorded music contains information about a performer's changing position relative to the microphone in the form of phase changes (Wanderley & Depalle, 2004), and listeners are sensitive to this type of information, even with monophonic recordings (Kim, Zahorik, Carney, Bishop, & Kuwada, 2015).

In our study, the sounds that listeners heard were musical. This provides a second route by which entrainment could take place that we will refer to as "entrainment through music."[2] Entrainment through music would occur if the music suggested the same movements to both performer and listener. Music often seems to suggest motion metaphorically (Clarke, 2001; Shove & Repp, 1995). An often cited example is Schubert's lieder, "Gretchen at the Spinning Wheel," in which the circular motion of the spinning wheel is suggested melodically by the rising and falling patterns of sixteenth notes in the right hand of the piano accompaniment, while the steady pulse of the treadle is suggested rhythmically by the left hand (Zbikowski, 2009). Empirical support for the idea that music conveys movement metaphorically comes from evidence that listeners move spontaneously to musical rhythms (Peckel, Pozzo, & Bigand, 2014; Toiviainen, Luck, & Thompson, 2009, 2010), and that performers sway with the musical phrasing (Demos, Chaffin, & Logan, 2017; MacRitchie, Buck, & Bailey, 2013; Teixeira, Yehia, & Loureiro, 2016; Wanderley, Vines, Middleton, McKay, & Hatch, 2005), and that both listeners and performers make larger movements to more expressive music (see Davidson, 2009, for a review).

However, entrainment through music would require more than just an ability of music to elicit movement; music would have to elicit similar movements from both performer and listener. The ability of music to do this is not known. To find out would require a program of research to identify musical metaphors for motion and assess their capacity for eliciting similar movements on different occasions and from different people (see Repp, 1993). We took a first step by assessing the most obvious way in which entrainment through music might occur, through the musical beat.

Metrical entrainment. One way that entrainment through music might occur is if both performer and listener moved spontaneously to the musical beat in the same way. The tendency of listeners to move to the beat is well documented (Peckel et al., 2014; Toiviainen et al., 2009, 2010), and the tendency of performers to do the same has been frequently reported (see Davidson, 2009, for a review). So, the musical beat might seem to offer a straightforward route to entrainment, perhaps through the impact of the beat on the vestibular system (Todd & Lee, 2015). However, it is not that simple. There are many different ways of moving to the same beat (Large, 2000). First, movements can synchronize with a musical beat at any one of a wide range of *beat ratios*[3]: every beat (1:1), every other beat (1:2), every third beat (1:3), etc. Second, different body parts move at different beat ratios (Burger, Thompson, Luck, Saarikallio, & Toiviainen, 2014; Peckel et al., 2014; Toiviainen et al., 2009, 2010). For example, for music in a triple meter the entire body might sway in an 18-beat cycle, the torso at 9:1, the head at 6:1, the arms at 3:1, and the feet in a 1:1 beat ratio. The entrainment of each body part is affected by both the tempo of the music and by the physical characteristics of different body parts, which may differ between performer and listener (Burger, London, Thompson, & Toiviainen, 2017; Dahl, Huron, Brod, & Altenmüller, 2014). Thus, the number of ways of moving to a musical beat is large and the probability of two people moving to the beat in the same way is correspondingly small. The probability of metrical entrainment may be further reduced if movement is also affected by non-metrical properties of music such as phrasing (Demos et al., 2017; for reviews, see Davidson, 2009; Davidson & Broughton, 2016).

Measurement of entrainment. It is difficult to separate the contributions of the two routes to entrainment (movement and music). Instead, we used the method of subtraction to separate entrainment due to performer and listeners moving to the beat in the same way from entrainment due to other sources. We measured the frequency of *metrical entrainment*, i.e. performer and listener moving in the same way to the music pulse, and determined the frequency of *non-metrical entrainment* by subtraction. (We use the term "metrical" to refer to the regularity of these movements, not in the strict musical sense of corresponding to a musical meter). We cross-tabulated two sets of comparisons: *direct comparisons* between the movements of performer and listener, and *indirect comparisons* assessing how similarly they moved to the musical pulse. We used a binary classification (significant/nonsignificant) rather than the continuous values of the cross-correlation coefficient for reasons

[2] Our choice of the terms "entrainment to movement" and "entrainment through music" skirts a difficulty that is both terminological and conceptual. "Music" refers to both the musical concepts notated in the musical score (or their mental representations) and to musical sounds produced by performers' actions when instantiating a musical score (Cook, 2013, pp 1–8). "Entrainment through music" involves the former, "entrainment to movement" the latter. Entrainment to movement results from information provided by the sound of notes being played. Entrainment through music occurs through the metaphorical suggestion of movement by musical patterns, whether played, notated, or merely thought. We skirt this ambiguity in the word "music" by referring to "entrainment to movement" rather than more explicitly to "entrainment to movement through [musical] sound," which is easily confused with "entrainment [of movement] through [metaphorical suggestions made by] music." The potential confusion is due to the dual status of music as, respectively, performance and concept.

[3] Ratios predicted by musical meter can be found in London (2012). More general ratios can be found in the Farey tree (Bardy, Hoffmann, Moens, Leman, & Dalla Bella, 2015).

TABLE 1. *Identification of Metrical and Non-metrical Entrainment Through Cross-tabulation of the Frequency of Significant (Yes) vs. Nonsignificant (No) Correlations for Direct and Indirect Comparisons*

		Indirect Comparison through the Musical Pulse	
		No	Yes
Direct Comparison of Movements of Performer and Listener	No	Neither	Metrical
	Yes	Non-metrical	Both

explained later. The resulting contingency tables (Table 1) provided the frequency of metrical and non-metrical entrainment and their co-occurrence. The tables show the frequency of metrical entrainment (moving to the beat in the same way), non-metrical entrainment (moving in the same way but unrelated to the musical beat), both metrical and non-metrical entrainment, and neither kind of entrainment.

If we find metrical in the absence of non-metrical entrainment, then the route through music (via the beat) will provide the most plausible explanation. Alternatively, if we find both non-metrical and metrical entrainment, then the simple explanation that listeners entrained through the beat will not be sufficient. It could be that, in Experiment 1, the route through music causes the listeners and performers to sway the same way due to musical metaphors other than the beat, or that listeners entrain by the route through movement, responding to information about how the performer moves conveyed by the musical sound. Thus, the question that Experiment 1 will answer is whether entrainment occurs, and if so whether it is entirely metrical or both metrical and non-metrical. In Experiment 2, however, the route through music was controlled by the baseline in which the musicians played alone, without hearing another performance. If we find additional similarity above baseline (i.e., entrainment), it will not be through music, as that route is controlled. In the absence of other explanation, we will conclude that the listener entrained to movement.

Direction of sway. We measured sway in two directions: back-and-forth (anterior-posterior [AP]) and side-to-side (medio-lateral [ML]). Another clue to the route to entrainment may be provided if listeners entrain more to sway in one direction than another, because the influences on the postural sway of trombonists are different for AP and ML sway. Trombonists must compensate for the back-and-forth movement of the trombone slide or they would fall over. This does not necessarily mean that sway relates to the movement of the trombone slide in a one-to-one fashion. Rather, sway is probably a dynamic product of multiple slide positions across a temporal window of several seconds, together with the angle of the trombone, horizontally and vertically, as well as musical influences such as phrasing, meter, and rhythm.

Other things being equal, AP sway should be more affected by the movement of the trombone slide than ML sway. Although AP and ML sway are both part of the same circular motion of the body, they can function relatively independently or not, depending on the task (Balasubramaniam, Riley, & Turvey, 2000; Winter & Prince, 1996). We have previously reported that, for the performances described here, the two directions of sway were correlated, but detrended fractal analysis suggested that each direction reflected different underlying processes: AP sway was more white noise and ML was more pink (Demos, Chaffin, & Kant, 2014). We inferred that sway was more affected by the movements of the trombone slide in the AP than in the ML direction. Further, we have also previously shown that ML sway was affected by musical phrasing, which influenced the rate and stability of recurrence (Demos et al., 2017). Thus, while AP and ML sway are interrelated for trombone performance, AP sway may be affected more by slide movement and ML sway more by the expressive intentions of the performer.

If listeners entrain to AP sway, this will suggest that they are entraining to movement because they are inferring or responding to the movement of the trombone slide. Entrainment to ML sway will suggest that listeners are entraining to music, for example they might be inferring or responding to phrasing. If entrainment is stronger in one direction more than another, this will suggest that both routes contribute to entrainment and that one route was more influential than the other. If we find less entrainment to ML sway in Experiment 2 than in Experiment 1, this will suggest that the additional entrainment in Experiment 1 was likely driven by the route through music.

Entrainment and musical expression. One effect of entrainment may be to amplify the emotional experience that the music elicits. Entrainment increases positive feelings of social connectedness (Demos et al., 2012; Hove & Risen, 2009; Tarr, Launay, & Dunbar, 2014; Wiltermuth & Heath, 2009), and sharing experiences amplifies feelings (Boothby, Clark, & Bargh, 2014). Further, body movement generally, and postural sway more specifically, is connected to affective response (Stins & Beek, 2007). So, we asked listeners in Experiment 1 to rate the expressiveness and pleasantness of each performance. If listeners rate performances as more expressive or more pleasant when they entrain more, this would suggest that entrainment enhances the aesthetic enjoyment of music (Cross, 2001).

In addition to asking whether entrainment affects listeners' ratings of expressiveness, we also asked if the expressiveness of the performance affected entrainment. We know that the quality of performers' movements (e.g., amplitude, smoothness) changes with their expressive intentions (Davidson, 1994; Demos et al., 2017; Wanderley et al., 2005), suggesting that movement reflects expressive goals. We asked the trombonists to play with normal, exaggerated, or minimal expression. If listeners entrain through a process of empathic resonance (Flaig & Large, 2014) with the performer, then we might expect them to entrain more to more expressive performances.

Our study. In summary, we compared the postural sway of trombonists to that of listeners air-conducting the performances (Experiment 1), and to that of the same musicians playing along with the recorded performances (Experiment 2). If we find entrainment, it will extend the phenomenon of spontaneous entrainment to movement to a new domain. Entrainment in Experiment 2 would show that listeners can entrain to movement, over and above any contributions of entrainment through music. The assessment of metrical entrainment will indicate the extent to which entrainment by either route can be attributed to the musical beat. Entrainment to AP or ML sway will suggest that listeners' movements are related to movement, music, or both. If listeners rate performances as more expressive when they entrain more, or entrain more to more expressive performances, this will suggest that entrainment is part of the process of musical communication.

Experiment 1

METHOD

PARTICIPANTS

The listeners in Experiment 1 were 28 undergraduate and 1 graduate student (females, $N = 20$, age: $M = 19.04$, $SD = 0.73$) at the University of Connecticut. Undergraduates received class credit for their participation. Sixteen of the participants (51.61%) were musicians and six (19.35%) were dancers (defined as having more than four years of training; $M = 8.56$, $SD = 4.05$ for musicians and $M = 10.17$, $SD = 4.26$ for dancers). The rest of the participants had little or no music training ($M = 0.79$, $SD = 1.19$).

STIMULUS MATERIAL

Music. We selected two pieces written by Marco Bordogni (1789-1856) and transcribed by Joannes Rochut for trombone (Rochut, 1928) that had similar difficulty, length, lyric quality, and distribution of musical intervals (Cronbach's Alpha = .932), but differed in musical structure. Rochut No. 4 contains 154 beats and 238 notes in F major with a 3/4 meter in standard ABA form, with a nested question-and-answer structure within each section. Rochut No. 13 contains 170 beats and 245 notes in E-flat major with a 3/8 meter in a short fantasy format with four major sections.

Musicians. The music was performed by two professional trombonists, both male, each with over 25 years of experience as performers and teachers. Both had taught the two pieces. Both prepared their performances before coming to the lab.

Performances. The musicians played each piece twice in each of three expressive styles (normal, expressive, and non-expressive) for a total of 24 performances (2 musicians x 2 repetitions x 2 pieces x 3 expressive styles). We selected 12 performances for use as stimuli in the experiments, randomly selecting one of the two performances in each style by each musician: two normal, two expressive, and two non-expressive (2 musicians x 2 pieces x 3 expressive styles).

Preliminary examination of the recorded performances, reported in the Supplementary Materials, identified four characteristics relevant to the goals of the study. First, the musicians moved differently from each other. This meant that listeners entraining to a performer's movements would move differently depending on the performer. Second, the performers moved in similar ways in their two performances of the same piece in the same style. This suggested that each performer had a consistent movement style that listeners might reflect in their movements. Third, the musicians rarely moved to the beat in the same way in their two performances of the same piece in the same style, supporting the assumption that there were many different ways of moving to the beat. Fourth, metrical and non-metrical similarity both occurred with substantial frequency and independently of each other, making it possible to distinguish metrical and non-metrical entrainment.

There were marked differences between position and velocity (change in position) and between AP and ML sway, leading us to analyze each measure separately. Here, we report only the data for velocity because it showed more entrainment, perhaps because the monoaural recordings that we used provided listeners with more information about the change of direction than about direction of movement. (We do provide position data for the recorded performances in the Supplementary Materials to show there was little overlap between performers).

APPARATUS

Body movement. We measured postural sway as change in the center of pressure (COP) using a Wii Nintendo Balance Board (Nintendo, Kyoto, Japan), which provides reliable, low-cost measurements (Clark et al., 2010). COP reflects movements of head and arms, in addition to the trunk. The Wii Balance Board was connected via Bluetooth to a Dell Inspiron E1505 computer running Windows 7 and Matlab 2011b. Matlab interfaced with the Wii Balance Board using WiiLab Toolbox (Ahmed, 2012). Data were collected using the Matlab Psychophysics Toolbox version 3.0 (Brainard, 1997; Kleiner et al., 2007).

We examined the noise of the apparatus in a single 4-min session with 60 pounds of weight sitting stationary on the balance board while recording at 34 Hz (SD = .085). Data were linearly interpolated to correct for timing variances and low-pass filtered (Butterworth filter) at 16 Hz. COP was measured in centimeters for two directions: medio-lateral (ML), i.e., left-to-right, and anterio-posterior, (AP), i.e., forward-to-back. Root mean square (RMS) of the noise was .048 CM for ML and.032 CM for AP sway. Detrended fluctuation analysis showed that the Wii Balance board generated white noise (Hurst exponent: ML = .502; AP = .505).

Sound. An external USB sound mixer (M-Audio) and Shure microphone were used to record the performances. The microphone was placed on a stand approximately 4 feet above the ground, 4 feet from the performer, and 1 foot left of center. The locations of the microphone and the balance board remained constant across performances. The musical stimuli were denoised at 12 dB. The performances were not normalized; loudness differences between performances remained as performed. The recordings of the performances were played to participants through two external desktop computer speakers at a moderate volume that remained constant throughout the experiment.

PROCEDURE

Performances. The musicians prepared their performances before coming to the lab, separately, for two recording sessions, on two different days. On each visit, they played one piece six times with the musical score in front of them, while we recorded sound and movement. On each visit, the musician warmed up for a few minutes while standing on the Wii Balance Board and then played two performances in each of three expressive styles (normal, expressive, and non-expressive), with short breaks between performances. They played the two performances in each expressive style back-to-back, normal performances first, to serve as a reference for the other less typical, expressive styles. The order of expressive and non-expressive performances was counterbalanced across pieces and musicians.

For the normal style, we asked the musicians to play in a way that they considered natural. For the expressive style, we asked them to play with exaggerated expression. For the non-expressive style, we asked them to play with minimal variation in tempo and dynamics, "like a MIDI performance."

To give an idea of how much each performer moved, we provide the root-mean square values for both position and velocity of postural sway separately for each expressive style and performer in the Appendix (see Table A2). For position, Performer 2 moved more in the ML direction ($M = 4.45$, $SD = 1.69$) than Performer 1 (1.97, $SD = 1.22$), $t(22) = 4.13$, $p < .001$, $d = 1.69$, and Performer 1 moved more in the AP direction ($M = 0.73$, $SD = 0.21$), than Performer 2 ($M = 0.91$, $SD = 0.17$), $t(22) = 2.29$, $p = .03$, $d = 0.94$.

Air-conducting. We gave the listeners a baton to hold in their dominant hand and told them to move like a musical conductor in front of an orchestra, as if drawing out the emotion from the performer but without trying to "count time." We said that their body movements would be recorded and asked them to stand on the Wii Board without moving their feet, but to otherwise move their bodies in any way they chose.

Each participant heard six performances of one piece, one in each expressive style by each of the two musicians, ordered in a partial Latin Square design. After each performance, participants rated the performances, indicating agreement that "I found the music pleasant" on scale of 1 (*strongly disagree*) to 5 (*strongly agree*), and answering the question, "How expressive was the performance you just heard?" on a scale of 1 (*not at all expressive*) to 5 (*extremely expressive*). At the end of the experiment, participants rated their familiarity with the music and provided information about their music training and demographic characteristics. The experiment was self-guided; participants were left alone to avoid making them to feel self-conscious when moving to the music.

ANALYSIS

We used cross-correlation to compare movements across entire performances, which we refer to in this context as *trials*. All comparisons involved performances of the same piece in the same style. For each trial, we performed separate analyses for each direction of sway (AP and ML); there were 174 trials for each direction (29 listeners x 6 performances). We removed the last several notes of each performance to avoid inflating the correlation values by including a small number of notes on which the listeners generally stopped moving, and we removed the first phrase of each piece (8 notes from Rochut 4 and 9 from Rochut 13).

We used the percentage of significant cross-correlations (using the surrogate chance method explained below) for each direction of sway rather than mean cross-correlation as our measure of entrainment. The former can be compared across experimental conditions and across experiments, whereas the latter cannot, because cross-correlation values depend on characteristics of the data likely to change across conditions, such as frequency, variance, and auto-regressive structure (Dean & Dunsmuir, 2016). For example, the cross-correlation magnitudes for AP and ML sway are not comparable because AP and ML sway had different frequencies and auto-recurrence. Thus, the information of interest is not the magnitude, but whether listeners moved with performer more than expected by chance.[4] So, we measured entrainment by tallying the frequency with which cross-correlations were significant or not and summarized these values as a percentage. We will refer to "frequency of significant cross-correlation," "frequency of entrainment," and "similarity," as required by the context. Cross-correlation indicates the extent to which two signals are both mode- and phase-locked. A significant cross-correlation via surrogates indicates that the similarity of two signals is not attributable to chance. Performances were approximately three minutes long, providing ample data to make this assessment.

Direct comparisons. When directly comparing movements of performer and listener, we corrected for phase differences by allowing a lag of up to one-half beat (13 data points) and selecting the highest value within that window (similar to Paxton & Dale, 2013).

Indirect comparisons (through the beat). We examined the synchronization of AP and ML sway with the musical beat at whole-number ratios between 1:1 (one cycle per beat) and 1:18 (one cycle per 18 beats). For each performance, we generated 18 families of sine-like waves where the peak of the wave represented the location of the beat (or ratio of the beat). We took the difference scores of the waves to match our direct comparison. We then assessed the correspondence of each sine-like wave with the performer's velocity by taking the absolute value of the strongest cross-correlation within a lag of one-half of the period of each ratio of interest to correct for phase (see Demos et al., 2012, for an example of this method). We used this method of measuring beat-synchrony rather than a traditional method, such as Fourier transform analysis, because the latter cannot be used for live music. In natural performance, the time between musical beats is not constant. Movements synchronized with the "irregular" beat do not create the clear peaks normally used to identify synchrony with Fourier analysis. Alternative methods that warp the data to equalize time between beats, such as Functional Data Analysis (Ramsay, 2006), were not used because we could not assume stable lag between the listener and performer. We determined whether synchronization with the beat was above chance using the surrogate chance method (described below).

First, for purposes of description, we identified the *predominant beat ratio* for each performance as the ratio with the strongest relationship to movement. Next, to make the indirect comparisons, we summarized synchronization with all beat ratios (1-18) with a *beat vector:* 18 cross-correlation values, each between 0 and 1, representing beat synchrony for each whole-number ratio between 1:1 and 1:18. Then, to assess whether movements followed the musical beat in the same way in different performances, we correlated beat vectors from different performances of the same piece in the same expressive style. These *beat vector correlations* provided the indirect comparisons by measuring the degree to which two performances synchronized with the beat in the same way. Positive values meant that the movements of the two performances embodied the musical beat in the same way; negative values that they embodied the musical beat differently. For example, a significant negative value might indicate that one performer swayed every 6 beats, while the other swayed every 2 beats. To determine whether the beat vector correlations were due to chance, we generated probability values by bootstrapping (95th percentile method, 5000 iterations; Efron & Tibshirani, 1994).

Chance entrainment/surrogates. There was no obvious baseline for determining the level of cross-correlation expected by chance. Standard tables of critical values for

[4] Alternative methods such as recurrence quantitation have advantages over cross-correlation for determining the magnitude and stability of the entrainment (for a review, see Demos & Chaffin, 2017). However, those methods introduce other challenges because of the number of parameters differs between listeners and performers in Experiment 1, but not Experiment 2. Thus, we choose to present cross-correlations with surrogate analysis to simplify the analysis procedures.

determining *p* values for correlations were not appropriate because they assume that observations are independent, which was not the case for our time-series data. So, we generated a baseline representing chance-level similarity separately for each cross-correlation by a form of bootstrapping for time-series analysis called phase-shuffled surrogate analysis (Theiler, Eubank, Longtin, Galdrikian, & Farmer, 1992). We used the same procedure for both direct (between listener and performer) and indirect comparisons. First, we generated 500 phase surrogates for each listener's movements by shuffling their data to create a distribution of surrogate cross-correlation values when there was no relationship. We used a shuffling method, called Iterative Amplitude Adapted Fourier Transform (IAAFT Surrogates), which shuffles the phase (but leaves intact the frequency and amplitude distribution of the time series), thus maintaining the mean, variance, and autoregressive structure of the data (Schreiber & Schmitz, 1996, 2000). Next, we generated confidence intervals using the (nonparametric) 95% percentile method around the distribution of surrogate cross-correlation values.[5] If the observed cross-correlation value was outside the confidence interval, then the two signals were more similar than expected by chance and we concluded that entrainment had occurred.[6] Finally, we tallied the frequency of significant and nonsignificant cross-correlations across the 174 trials for each direction of sway. (We also list mean cross-correlation values for significant and nonsignificant trials in Appendix Table A1. These provide an estimate of effect size and show the mean magnitude correlation values, but cannot be directly compared across conditions, direction of sway, or experiments).

We examined the cross-correlations in two ways. First, we compared the percentage of significant cross-correlations across performance styles and direction of sway, conducting separate analyses for the direct and indirect comparisons. Significant effects identify statistically reliable differences in the frequency of entrainment (significant cross-correlation) across performance styles and directions of sway. Second, we cross-tabulated the frequency of significant correlations for the direct and indirect comparisons, as shown in Table 1, to determine the frequency of direct entrainment. We did not perform separate analyses on the frequencies for each cell of the cross-tabulation. The cross-tabulations are descriptive, showing the extent to which metrical and non-metrical entrainment occurred together in the same trial, or separately in different trials.

Statistical analysis. We used logistic mixed effects models to assess the effects of direction of sway (AP vs. ML), expressive style (normal vs. expressive and normal vs. non-expressive), and musical experience of the listener. To examine listeners' ratings of the performances, we used linear models and included two additional predictors: the degree of metrical and non-metrical entrainment. In both, we treated within-subject variables as random effects (trials and expressive style), and between-subject variables as fixed but not as random, using the LME4 package in R (Bates, Maechler, Bolker, & Walker, 2015). The random effects in these models take account of the multiple random effects of the repeated measures factors (trial and expressive style), relative to the musical piece. (See Pinheiro & Bates, 2000, for details of the method and Demos & Chaffin, 2017, for discussion of how mixed models apply to music.) For the linear models, the fixed effects were assessed as *Z*-values (Barr, Levy, Scheppers, & Tily, 2013). We employed the most conservative maximal random effects model that would converge for all comparisons following guidelines provided by Barr et al. (2013).

RESULTS

MUSICIAN VS. LISTENERS: DIRECT COMPARISONS

Figure 1 shows an example of intermittent entrainment. The movements were complex and quasiperiodic, not the simple oscillations found in pendulum swinging and rocking tasks. In Figure 1, the velocities overlap at around 84 seconds of elapsed time since the beginning of the performance. Periods of similarity like these repeatedly occurred across the 3+ minutes of the performance. We refer to these intermittent similarities as "entrainment" because they occurred more often than

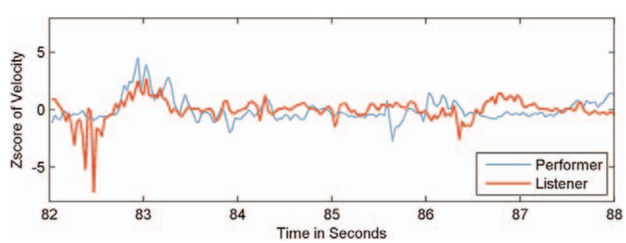

FIGURE 1. Example of intermittent entrainment from a trial on which there was significant entrainment of the listener's ML sway to the sway of the performer playing Rochut 4 in a normal expressive style. (See color version of this figure online.)

[5] The cross-correlation value in the surrogate was determined using the same lag as the real cross-correlation pairing.

[6] Note that this is a more stringent criterion than standard tables of critical values for determining *p* values based on the white-noise hypothesis (that each data point is independent of the next).

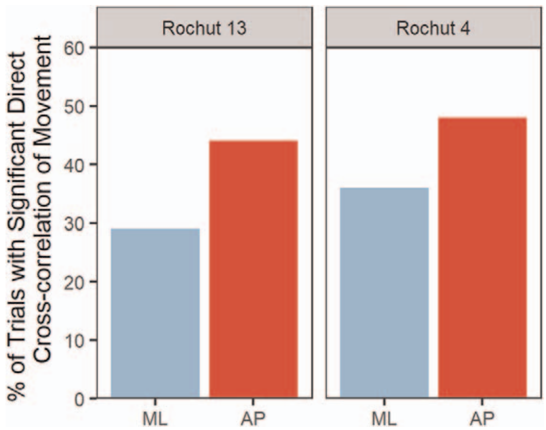

FIGURE 2. Direct comparisons: Percentage of trials exhibiting significant entrainment to the movements of the performer. (See color version of this figure online.)

expected by chance, reflecting the influence of the performer.

Figure 2 shows the percentage of trials during which the comparison of listeners' and the performer's movements indicated entrainment (significant cross-correlation), separately for the ML and AP directions and for each piece. There was entrainment on about a third of trials (29% to 48% depending on piece and direction), indicating that listeners changed their direction of sway at approximately the same time as the performer.

Figure 2 shows that the listeners entrained to the performer's postural sway in both the ML and AP directions, and that entrainment was more frequent for the latter. The logistic mixed model summarized in Table 2 shows that this difference was significant. The negative effect for direction indicates that significant entrainment occurred more frequently in the AP than in the ML direction. There was no effect of expressive style or musical experience. A second model that included the beat vector correlation as an additional predictor is not reported because it did not improve the statistical fit, suggesting that the greater frequency of entrainment of AP sway could not be attributed to entrainment to the musical beat.

TABLE 2. *Nested Logistic Mixed Effects Models of Significant Entrainment of the Listener to the Performer for Direct and Indirect Comparisons*

	Direct Comparisons		Indirect Comparisons	
Fixed Effects	Estimate	SE	Estimate	SE
(Intercept)	−0.73*	(0.34)	−0.38	(0.39)
Expressive Performance	0.03	(0.36)	0.33	(0.32)
Non-Expressive Performance	0.22	(0.36)	−0.63	(0.36)
Direction [ML=1]	−0.64*	(0.27)	−1.00**	(0.35)
Performer	0.37	(0.26)	−0.27	(0.32)
Piece [Rochut 4=1]	0.29	(0.24)	0.32	(0.31)
Musical Experience of Listener	0.19	(0.24)	−0.12	(0.30)
Random Factors				
[listeners nested in piece]				
(Intercept)	0.38		0.55	
Direction	0.69		0.34	
Exp	1.55		0.65	
Non-Exp	1.06		2.27	
Performer	0.46		1.28	
Direction x Exp	0.54		3.83	
Direction x Non-Exp	0.62		5.23	
Goodness of Fit				
Deviance	517.52		393.77	
AIC	652.35		463.77	
BIC	447.52		598.6	

*p < .05, **p < .01, ***p < .001

MUSICIAN VS. LISTENERS: INDIRECT COMPARISONS THROUGH THE MUSICAL BEAT

Predominant beat ratio. Listeners entrained at one beat ratio or another on the great majority of trials. Figure 3 summarizes entrainment to the beat in histograms showing the percentage of trials in which there was a statistically significant correlation with the movements of listeners at each beat ratio, separately for ML and AP sway and for each piece. Listeners entrained with the beat at above chance levels on 87.5% to 96.8% of trials, depending on the piece and direction of sway. Listeners showed no preference for ratios related to the triple meter of the music (1, 3, 6, 9, 12, 15, 18) over non-metrical ratios (ML = 51%; AP = 49%), and generally moved at different ratios in different performances of the same piece (Repeat ratio twice: ML = 8.8%, AP = 13.3%; repeat ratio thrice: ML = 0.8%, AP = 0.8%). In summary, participants were very likely to entrain with some ratio of the musical beat. We refer to such entrainment as *metrical*, despite the fact that the dominant beat ratios were unrelated to the time signature of the music. We turn now to beat vector correlations to answer the question of whether listeners' entrainment with the beat was influenced by how the performer moved to the beat.

Metrical entrainment. Figure 4 shows the frequency of metrical entrainment; that is, the percentage of trials with significant beat vector correlations, separately for the ML and AP directions and for each piece. There was significant metrical entrainment on a substantial number of trials (21%–51%), indicating that listeners changed their direction of sway on the same beat as the musician more often than expected by chance on about a third of trials, overall.

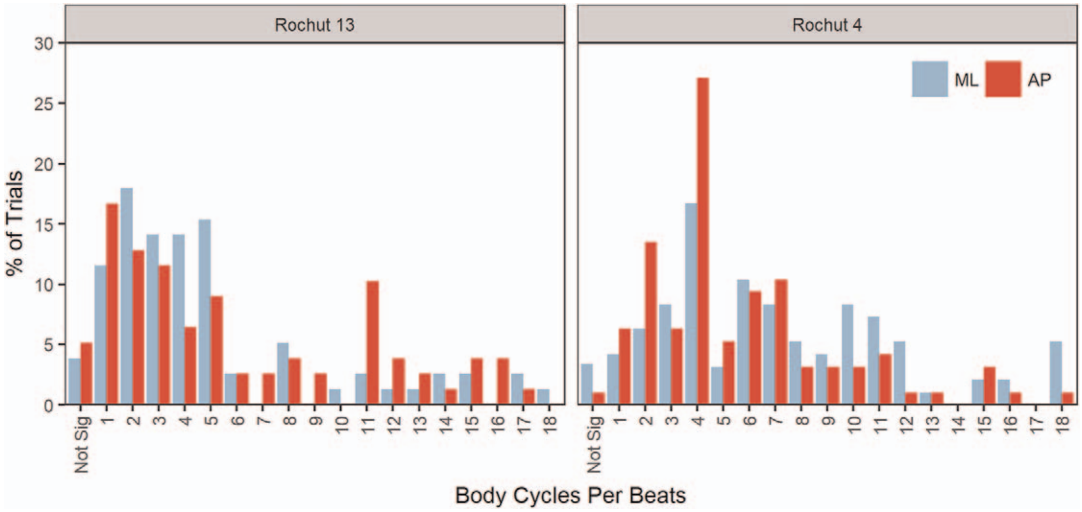

FIGURE 3. Percentage of trials exhibiting significant entrainment at each beat ratio, for the ML and AP directions, and for each piece. (See color version of this figure online.)

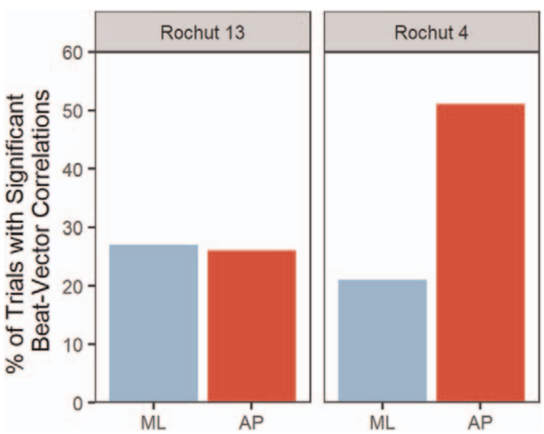

FIGURE 4. Indirect comparisons: Percentage of trials exhibiting significant beat vector correlation (metrical entrainment) between movements of performer and listener. (See color version of this figure online.)

To find out which variables affected metrical entrainment, we entered the number of significant beat vector correlations (nonsignificant/negative = 0; significant = 1) as the dependent variable in logistic mixed effects models like those for the direct comparisons. Table 2 summarizes the results. As with the direct comparisons, there was a significant effect for direction of movement, indicating that entrainment was more frequent for AP than for ML sway, and entrainment was unaffected by expressive style or musical experience.

Cross-tabulation of direct and indirect comparisons. We determined how much of the entrainment in Figure 2 was metrical vs. non-metrical by cross-tabulating the frequency of significant and nonsignificant correlations for direct and indirect comparisons (Figures 2 and 4, respectively). Table 3 shows three separate cross-tabulations for ML sway, AP sway, and both combined. In combining ML and AP sway, we counted comparisons as significant if either ML or AP sway or both were significant. Each tabulation shows the proportion of trials on which entrainment (significant cross-correlation) was metrical (top right), non-metrical (bottom left), both (bottom right), and neither (top right).

Listeners entrained both metrically and non-metrically, indicating that they were moving to something more than just the musical beat. They were responding to non-metrical aspects of either the performer's movements or the music. Non-metrical entrainment occurred with substantial frequency, occurring in the absence of metrical entrainment on approximately a quarter of the trials (ML &/or AP = 26.44%) and in conjunction with metrical entrainment on approximately a third of trials (ML &/or AP = 34.48%), for a total of 60.92% for metrical and non-metrical entrainment combined. Metrical entrainment was slightly less frequent, occurring in the absence of non-metrical entrainment on about one-fifth of trials (ML &/or AP = 20.69%), for a total of 55.17% for metrical and non-metrical entrainment combined. Thus, both non-metrical and metrical entrainment occurred with substantial frequency (60.92% and 55.17%, respectively), and there was entrainment of some type on most trials (81.61%).

Listeners' perception of the performances. To find out which variables affected ratings of pleasantness and

TABLE 3. *Percentage of Trials on Which Direct and Indirect Comparisons of Movement were Significant or Not (No/Yes), Separately for the ML and AP Directions, and for Both Directions Combined (ML or AP or Both): Experiment 1*

			ML Direction Indirect Comparison (beat vector corr.)		AP Direction Indirect Comparison (beat vector corr.)		ML &/or AP Directions Indirect Comparison (beat vector corr.)	
			No	Yes	No	Yes	No	Yes
Direct Comparison	Between listener and performer (Cross-Correlation)	No	51.72%	14.94%	33.33%	20.69%	18.39%	20.69%
		Yes	24.71%	8.62%	27.01%	18.97%	26.44%	34.48%

TABLE 4. *Mixed Effects Models of Listeners' Ratings of Pleasantness and Expressiveness of Performances*

Ratings	Pleasantness		Expressiveness 1		Expressiveness 2	
Fixed Effects	Estimate	*SE*	Estimate	*SE*	Estimate	*SE*
(Intercept)	3.3***	(0.245)	2.917***	(0.228)	3.103***	(0.191)
Expressive Style	0.021	(0.174)	0.386*	(0.165)	0.374**	(0.122)
Non-Expressive Style	−0.458**	(0.175)	−0.566***	(0.172)	−0.276*	(0.124)
Performer	0.257†	(0.143)	0.09	(0.156)	−0.074	(0.115)
Piece [Rochut 4 vs. 13]	0.111	(0.188)	0.014	(0.171)	−0.135	(0.160)
Musical Experience of Listener	0.181	(0.186)	−0.287†	(0.171)	−0.417**	(0.160)
Non-metrical Entrainment	0.136	(0.202)	0.366†	(0.193)	0.276†	(0.145)
Metrical Entrainment	−0.029	(0.223)	0.307	(0.213)	0.334*	(0.159)
Pleasantness					0.657***	(0.057)
Random Effects						
(Intercept) | SS:Piece	0.081		0.00		0.072	
Exp | SS:Piece	0.03		0.011		0.021	
Non-Exp | SS:Piece	0.039		0.079		0.017	
Performer| SS:Piece	0.019		0.18		0.098	
Residual	0.844		0.769		0.409	
Goodness of Fit						
Deviance	484.688		473.036		379.382	
AIC	522.687		511.036		419.382	
BIC	582.709		571.058		482.563	
Deviance Test*(Chi-Square [df])*	.99 [19]		3.57 [19]		93.65*** [20]	

† $p < .06$, *$p < .05$, **$p < .01$, ***$p < .001$

expressiveness, we used mixed models to examine the effects of expressive style, performer, musical piece, musical experience of the listener, and frequency of entrainment. We coded metrical and non-metrical entrainment separately as orthogonal dimensions by classifying trials on which both types occurred as metrical (rather than non-metrical) entrainment. Table 4 summarizes the models. First, we used the same model to analyze ratings of pleasantness and expressiveness. Then we analyzed expressiveness in a second model that controlled for pleasantness by entering it as a Z-score. As we will see, pleasantness and expressiveness were correlated, so the second expressiveness model told us how listeners rated expressiveness independently of pleasantness.

There were two effects of theoretical interest and two additional effects. First, listeners accurately distinguished between the three expressive styles of performance, rating expressive performances as more expressive and non-expressive performance as less expressive and less pleasant than normal performances. The significant positive effects for the expressive style in both expressiveness models indicates that listeners rated expressive performances as more expressive than normal performances. The significant negative effects for the non-expressive style in all three models indicates that listeners rated non-expressive performances as both less expressive and less pleasant than normal performances. The presence of these effects of expressive style in the second expressiveness model indicates that they were not due to pleasantness, which was included as a predictor in the model.

Second, as expected, listeners rated performances as more expressive when they entrained more. The effect of metrical entrainment was significant in the second expressiveness model, and there was a nonsignificant trend in the same direction for non-metrical entrainment. The absence of both effects from the first expressiveness model indicated that controlling for pleasantness in Expressiveness Model 2 clarified the relationship between entrainment and expressiveness. Entrainment affected ratings of expressiveness but not pleasantness, providing additional evidence that listeners did not treat pleasantness and expressiveness as equivalent.

There were two additional effects. First, as anticipated, pleasantness and expressiveness were positively related. Second, expressiveness was negatively related to the musical experience of the listener, significantly in the second expressiveness model. Thus, listeners with more music training rated performances as less expressive, but not as less pleasant, perhaps because they found the exaggerated style of the expressive performances to be less musical.

DISCUSSION

Listeners spontaneously entrained, changing direction of sway at approximately the same time as the performer. Our study adds music listening to the long list of situations in which people spontaneously coordinate their movements with others (for reviews, see Repp & Su, 2013; Schmidt et al., 2011). What was different about our study is, first, that listeners heard a recording rather than directly seeing (Marsh, 2010, 2013), hearing (Demos et al., 2012; Shockley et al., 2003), or touching the other person (Sofianidis, Hatzitaki, Grouios, Johannsen, & Wing, 2012). Second, movements were complex and quasiperiodic (the swaying of a musician during performance) rather than simple repetitive movements like rocking and tapping. Third, the sounds that listeners responded to were musical rather than incidental by-products of actions performed for other purposes, such as walking or rocking.

The entrainment that we observed is reminiscent of the study in which listeners entrained to the movements of an unseen performer playing the Chinese guqin (Leman et al., 2009). The authors of that study suggested that listeners "mirrored" the actions that produced the sound, invoking both mirror neurons and action simulation as mechanisms. The latter approach suggests that listeners' general knowledge of how stringed instruments produce sound could allow them to infer the types of movements made by the musician, e.g., plucking strings and changing of pitch, and information about timing of movements was provided by note onsets. Similarly, the air-conductors in our study would have had a general idea of how the trombone works, along with information about the timing of note onsets. However, for the trombone, the release of breath responsible for note onset is not readily apparent, and the large-scale movements of the trombone slide that are readily apparent are not related in simple, one-to-one fashion to note onsets or pitch. Thus, it is unclear what information about movement our listeners were responding to, making it hard to know what mechanism was responsible for the entrainment.

Although we do not know exactly what acoustical cues our listeners were responding to, our data provide some clues. First, entrainment was both metrical and non-metrical in approximately equal measure (55% and 61% respectively). Also, metrical and non-metrical entrainment occurred independently of each other; metrical entrainment occurred in the absence of non-metrical entrainment on a fifth (21%) of trials, and non-metrical entrainment occurred in the absence of metrical entrainment on more than a quarter (26%). Since we defined metrical entrainment broadly, it is unlikely that the non-metrical entrainment that we observed was achieved by musician and listener moving to the beat in some fractional ratio of the meter not included in our measure of metrical entrainment. This rules out the simple, commonsense explanation that entrainment occurred entirely through the music due to performer and listener moving in the same way to the beat, leaving open the question of whether the route was through movement, music, or both, for both metrical and non-metrical entrainment.

Second, listeners entrained to both ML and AP sway, and more to the latter. This suggests that entrainment occurred by both routes and that the route through movement was more important. However, other interpretations are possible. For example, the surrogate method for assessing significance may have been more sensitive for AP than for ML sway because of differences in periodicity. In Experiment 2, the presence of a baseline provided a firmer basis for conclusions about the path to entrainment.

Third, listeners rated performances as more expressive when they entrained (see Table 4), suggesting that entrainment and ratings of expressiveness reflected the same influences and processes. In contrast, listeners did not entrain more to more expressive performances (see Tables 2 and 3), even though their ratings indicated that they recognized the differences between expressive styles (see Table 4). Thus, listeners' emotional response to the music was determined more by their degree of entrainment than by the playing of the performer. While this study cannot determine the direction of causality, it seems that entrainment may amplify listeners' emotional response to music, perhaps because aligning the motor systems of listener and musician also results in emotional alignment (Hasson, Ghazanfar, Galantucci, Garrod, & Keysers, 2012).

Experiment 2

Six months after recording the performances used as stimuli in Experiment 1, the two musicians returned to the lab to perform the same two pieces again, this time while listening to the performances recorded earlier. As in Experiment 1, we measured similarity by the frequency of significant cross-correlation between performer's and listener's movements, in this case between recorded musician and listening musician. Unlike Experiment 1, the listeners in Experiment 2 were also playing the music. Thus, their movements were affected both by what they heard and by the act of performing the music.

To separate the contribution of these two influences, we compared similarity in Experiment 2 to the baseline similarity when playing alone in the recorded performances. To compute the baseline, it was necessary to standardize the durations of the different performances, which we did by time-locking note onsets. This meant that the baseline also controlled for similarity due to playing the same notes at the same time. Thus, entrainment (similarity significantly above baseline) will be due to moving in the same way as the recorded musician more than the minimum needed to play the same notes at the same time.

The baseline assessed the similarity of movement attributable to the music, including any metaphorical suggestions of motion conveyed by the music. Thus, if we find additional similarity above baseline (i.e., entrainment), it will not be entrainment through music. In the absence of other explanation, we will conclude that it is entrainment to movement. This sets a high bar for entrainment to movement. Entrainment would mean that playing along with the recorded performance made the listening musician move more like the recorded musician than can be expected by chance if the listening musical had simply played the same notes at the same time.

The performances that the listening musicians played along with (by the recorded musician) could be their own (a *within musician* comparison) or the other musician's (a *between musician* comparison). The within-musician baseline for the direct comparisons was 100%, that is, similarity between performances of the same piece by the same musician in the same style was significantly above chance on every trial (Supplementary Materials, Figure 2). This made it impossible for within musician similarity in Experiment 2 to be any higher, and thus provide evidence of entrainment to movement. Therefore, we limited our conclusion to between musician comparisons.

The between musician similarity of the recorded performances ranged from 38% to 46%, depending on the direction of sway (ML vs. AP) and type of comparison (direct or indirect; Supplementary Materials, Figures 2 and 4). The high level of these baselines suggests that the act of producing notes, and perhaps metaphorical motion implied by music, strongly influenced movement. Additional between-musician similarity, above the baseline, will indicate the additional influence of entrainment to movement.

METHOD

PROCEDURE

The musicians were instructed to play along with each recording, following its musical expression (i.e., tempo and dynamics) as closely as possible. As when originally making the recordings, the musicians prepared before coming to the lab, and came separately, for two recording sessions, playing a different piece on each day with the order of pieces counterbalanced across musicians. On each visit, the musicians played the same piece six times, following along with six different performances. The recordings were the same as those heard by the participants in Experiment 1 and included one in each style from each performer: two normal, two expressive, and two non-expressive. Thus, for each pair of recorded performances in the same style, one was by the listening musician (a within musician comparison), and the other was by the other musician (a between musician comparison). The order of recorded performances was randomized separately for each performer and each session.

At the beginning of the session, the musician warmed up for a few minutes while standing on the Wii Balance Board. Before playing along with each recording, the musician listened to the recording, the better to follow its expressive variation. The musicians listened to the recordings through headphones. While playing, they removed the cup from one ear to clearly hear the sound of their own performance. They were not informed which performer or style they were hearing.

ANALYSIS

As in Experiment 1, we determined the significance of each cross-correlation using surrogate methods and tallied the percentage of trials on which the cross-correlation was significant. Comparisons between conditions were different from Experiment 1 in three ways. First, we allowed a lag between performances of one-quarter beat (up to seven data points) and selected the highest value within that window. We allowed a shorter lag time than in Experiment 1 because in playing along with the performances, the listening musicians in Experiment 2 tracked the musical sound more closely than the air-conductors in Experiment 1. Second, we compared frequencies of significant cross-correlations using binomial tests and proportions of significant cross-correlations (ML vs. AP sway) using two-tailed Z-tests for proportions. We used non-parametric testing rather than mixed models, as in Experiment 1, because we had a small number of trials.

Third, as described above, we compared the percentage of significant cross-correlations to baseline rates of between musician similarity provided by comparing the recorded performances of the two musicians of the same piece in the same expressive style. We used the same baseline rate for both directions of sway, conservatively using the value for the direction of sway that showed the higher baseline rate as the baseline value against which to compare the observed similarity for both directions of sway. The between musician baseline was 45.83% for direct comparisons, and 33.33% for indirect comparisons (see Supplementary Materials, Figures 2 and 4 respectively).

RESULTS

DIRECT COMPARISONS

Figure 5 shows an example of the sway of the recorded and listening trombonist during a 15-second period of one performance. Intermittent similarities are evident between 75 and 77 seconds. Although higher than in Experiment 1, similarity was relatively loose. Even though the performing and listening musicians were both playing the same notes at the same time, the multiple degrees of freedom available allowed their movements to differ.

DIRECT COMPARISONS WITHIN AND BETWEEN MUSICIANS

Figure 6 shows the frequency of significant similarity for the direct comparisons of sway in each direction, within and between musicians. For between musician comparisons, the frequency of similarity was significantly above the baseline of 45.83% for AP sway (75.00%, binomial, $p = .04$), indicating entrainment to movement in the AP direction. Thus, when playing along with the other musician, the listening musician changed direction of AP sway at approximately the same time as the recorded musician on 75% of trials when he could hear the other musician compared to 46% of trials when he could not. This means that the listening musician entrained on 29% (75%–46%) of trials. Frequency of similarity was also above baseline for ML sway, but not significantly so (58.33%, binomial, $p = .28$), suggesting that movement in the ML direction was not influenced by entrainment.

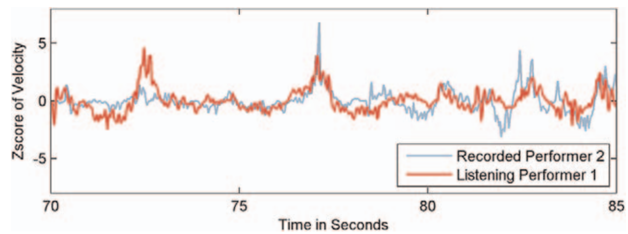

FIGURE 5. Example of intermittent similarity from a trial on which there was significant similarity to the ML sway of the recorded musician playing Rochut 4 in a normal expressive style. (See color version of this figure online.)

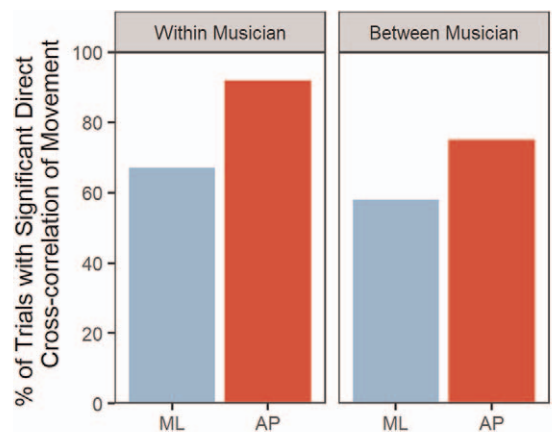

FIGURE 6. Direct comparisons: Percentage of trials exhibiting significant similarity as a function of direction of sway (ML or AP) and whether the listener heard a performance by himself (within musician) or by the other trombonist (between musician). (See color version of this figure online.)

The frequency of similarity was nonsignificantly higher in the AP than in the ML direction (83.33% vs. 62.50%; $Z = 1.62$, $p = .11$); and nonsignificantly higher for within than between comparisons (AP: 91.67% vs. 75.00%, $Z = 1.09$, $p = .27$; ML: 66.67% vs. 58.33%, $Z = .42$, $p = .67$). Between musician similarity was marginally higher in Experiment 2 than in Experiment 1 (AP: 75.0% vs. 45.98%%, $Z = 1.95$, $p = .05$; ML 58.33% vs. 33.33%, $Z = 1.76$, $p = .08$).

INDIRECT COMPARISONS: SYNCHRONIZATION THROUGH THE BEAT

Figure 7 shows the frequency of significant similarity for the indirect comparisons of sway in each direction, within and between musicians. Frequencies for these beat-vector correlations ranged from 0% to 50% of trials. As with the direct comparisons, there was

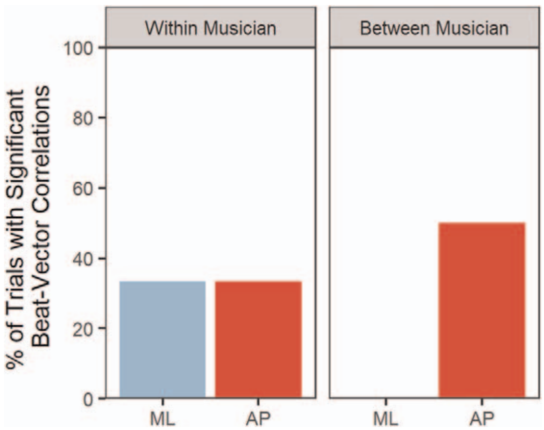

FIGURE 7. Indirect comparisons: Percentage of trials exhibiting metrical similarity as a function of direction of sway (ML or AP) and whether the listener heard a performance by himself (within musician) or by the other trombonist (between musician). (See color version of this figure online.)

entrainment for AP but not for ML sway. For between musician comparisons, frequencies were significantly above the baseline of 33.33% for AP sway, (50.0%, binomial, $p = .01$), but did not reach significance for ML sway (0%, binomial, $p = .99$). Thus, when playing along with the other musician, the listening musician regularly changed direction of AP sway on the same beat. Similarity was marginally higher for AP than for ML sway (41.67% vs. 16.66%, $Z = 1.91$, $p = .06$), as in Experiment 1. For ML sway, frequency was significantly higher for within than for between musician comparisons (33.33% vs. 0%, $Z = 2.19$, $p = .03$). For AP sway, in contrast, frequency was nonsignificantly higher for between than for within musician comparisons (33.33% vs. 50.0%, $Z = .83$, $p = .41$). Between musician similarity in Experiment 2 was not significantly different than in Experiment 1 (AP: 50.00% vs. 39.65%, $Z = 0.71$, $p = .48$; ML 0.00% vs. 23.56%, $Z = -1.90$, $p = .06$).

CROSS-TABULATION OF DIRECT AND INDIRECT COMPARISONS

To determine whether non-metrical entrainment occurred, we cross-tabulated the direct and indirect comparisons between musicians (Table 5). (Within musician comparisons were not cross-tabulated because their high baseline made it impossible to determine whether entrainment to movement had occurred). We limit our description to the two directions combined, as the differences between them were not significant for the direct comparisons and only marginally significant for the indirect comparisons. Entrainment of some kind occurred on every trial. The listening musician entrained non-metrically in the absence of metrical entrainment on exactly half of the trials (50.00%) and in conjunction with metrical entrainment on almost half (41.67%), for a total of 91.67% of the trials showing non-metrical entrainment. Metrical entrainment, in contrast, rarely occurred in the absence of non-metrical entrainment (8.33%).

DISCUSSION

The listening musician entrained to the movements of the recorded musician and around half of this entrainment cannot be attributed to the musical beat. Since our baseline level of entrainment included any similarity due to metaphorical suggestions of motion in the music, we conclude, in the absence of other explanation, that the listening musician entrained to the movement of the recorded musician. Thus, the listening musician entrained to the non-metrical movement of the recorded musician. Playing along with the recorded performances changed how the listener swayed, not just the timing of his notes (as they were aligned in the baseline). Since we instructed the listening musician to mimic the performance, not the movements, this means that the listening musician spontaneously swayed, non-metrically, in the same manner as the recorded musician in order to play along with him.

The entrainment to movement that we observed is reminiscent of the finding that speakers align their postural sway with that of an unseen partner (Shockley et al., 2003, 2007). In one experiment, pairs of participants read aloud two-syllable words that varied in similarity: a different word with a different stress pattern for each member of the word pair, or a different word

TABLE 5. *Percentage of Trials on Which Direct and Indirect Comparisons Between Musicians Were Significant or Not (Yes/No), Separately for the ML and AP Directions, and for Both Directions Combined (ML or AP or Both): Experiment 2.*

		ML Direction Indirect Comparison (beat vector corr.)		AP Direction Indirect Comparison (beat vector corr.)		ML + AP Directions Indirect Comparison (beat vector corr.)	
Between Musician		No	Yes	No	Yes	No	Yes
Direct Comparison	No	41.67%	0.00%	8.33%	16.67%	0.00%	8.33%
(Cross-Correlation)	Yes	58.33%	0.00%	41.67%	33.33%	50.00%	41.67%

with the same stress pattern, or the same word (Shockley et al., 2007, Experiment 2). Similarity of movement increased with the similarity of the words, but only when compared within pairs of participants, not when compared with another participant reading the same word with a different partner. Postural coordination was not simply a matter of saying the same word at the same time; the partner's presence made a difference. The authors conclude that patterns of sway were mediated by articulatory movements conveyed by speech sounds. Similarly, in our study, entrainment was not simply a matter of playing the same notes at the same time; the recorded performance made a difference. We conclude that the pattern of AP sway was mediated by movements of the trombone slide conveyed by the musical sound.[7]

In playing along with the recorded performance, the listening musician was trying to synchronize the onset and offset of his notes with those in the recorded performance. In doing so, he synchronized the movements of his trombone slide with those of the performer. This, in turn, required synchronizing AP sway, in order to counterbalance the movement of the slide. If AP sway was a one-to-one response to individual movements of the trombone slide, it would have been the same as in the baseline performances. The fact that the similarity of AP sway was above baseline suggests that AP sway was a dynamic response to sequences of slide movements. The musicians moved differently depending on the context, a co-articulation effect for the trombone similar to the co-articulation of speech (Viswanathan, Magnusson, & Fowler, 2010). Thus, the listening musician entrained his AP sway with that of the recorded musician in order to reproduce the sequence of slide gestures, in the same way that the entrainment of listeners in Shockley et al.'s (2007) increased with the similarity of their speech gestures.

[7] There is an apparent inconsistency in the analyses of direction of sway. Although AP sway entrained and ML sway did not, similarity was not significantly higher for AP than for ML sway, unlike Experiment 1, where the difference was significant. The absence of a significant difference in Experiment 2 may be due to lower power due to the smaller number of observations or the more conservative statistical test. Alternatively, the experienced trombonists in Experiment 2 may have used a wider range of strategies for maintaining balance than the novice air-conductors in Experiment 1. We observed that the trombonists used multiple techniques to maintain stability in response to movements of the slide. In addition to swaying forward or back, they also turned to left and right, and bent at knees and waist, angling the trombone up and down. Many of these movements would have been reflected in both ML and AP sway and may have lessened the difference between the two directions, compared to Experiment 1.

General Discussion

The movements of listeners swaying to recorded music were similar to the movements of the performer they were hearing. Thus, our results extend the phenomenon of spontaneous social coordination of movement to a new domain (Repp & Su, 2013; Schmidt et al., 2011; Sofianidis et al., 2012). Listeners spontaneously entrained their postural sway both when air-conducting and when playing along with the performance. The movements required of listeners were very different in the two tasks (conducting and playing), and yet listeners in both responded to the sound of the musical performance by changing their direction of sway at approximately the same time as the performer more than expected by chance. The presence of entrainment in both experiments suggests that it is a robust phenomenon that occurs under a variety of conditions, and raises the question of how entrainment could be possible simply through hearing recorded performance. It is important to note that our studies involved only two musicians and two pieces of music. Additional studies are required to confirm that entrainment occurs with other musicians, pieces, and instruments.

Our study was not designed to distinguish between the various mechanisms proposed to explain entrainment (direct realism, dynamical systems, mirror neurons, action simulation). Instead, we have begun the task of distinguishing two routes to entrainment that are, at least partly, distinct from the mechanism. Listeners may entrain directly to the movements of the performer, or listener and performer may entrain indirectly by both moving to musical metaphors of motion in the same way. The distinction adds to the complexity of explaining entrainment when acoustic music is involved. We were able to identify three characteristics of entrainment that may help to guide future studies. We discuss each in turn.

First, listeners entrained both metrically and non-metrically. Non-metrical entrainment occurred on a majority of trials (61% and 92% in Experiments 1 and 2 respectively), often in the absence of metrical entrainment (26% and 50% of trials in Experiments 1 and 2 respectively). Thus, listeners often entrained to the movements of the performer independently of the musical beat. This rules out the possibility that entrainment in either experiment could be entirely due to both performer and listener moving to the musical beat in the same way. Instead, listeners in Experiment 1 were responding either to the movements of the performer or to non-metrical musical metaphors for motion, or both. By controlling for the route through music, Experiment 2 showed that the performing musicians entrained, mostly non-metrically, to the movements that produced the sounds, i.e., entrainment through movement.

Second, listeners entrained more strongly to AP than to ML sway in both experiments. In Experiment 2, the entrainment of AP sway suggests that to play in the same way as the performer, the listening musician moved the slide in the same way, and that this led him to sway in the same way in order to compensate for the movement of the slide. While not surprising, this is not trivial, for two reasons. First, AP sway was not a simple product of playing the same notes at the same time, but was a complex product of playing sequences of notes, similar to the way that speech gestures are affected by neighboring speech sounds through co-articulation (Viswanathan et al., 2010). Second, ML sway entrained in Experiment 1 but not in Experiment 2. This suggests that the entrainment of ML sway in Experiment 1 was, at least partly, through music, since the baseline in Experiment 2 controlled for similarity through this route.

Third, the relationship between the low-level, intermittent entrainment that we observed and ratings of expressiveness suggests that entrainment is part of listeners' affective response to music and may be part of a larger mechanism of social bonding. One possibility is that entrainment evokes the feeling that one is sharing the experience with the other person (Demos et al., 2012; Hove & Risen, 2009; Wiltermuth & Heath, 2009) and sharing an experience heightens the emotional response (Boothby et al., 2014). Other possibilities are that music directly modulates the neural systems responsible for emotion (Flaig & Large, 2014; Molnar-Szakacs & Overy, 2006), or that coupling of nervous systems is a fundamental characteristic of human communication (Hasson et al., 2012). Our result suggests that the whole body is involved in unpacking the expressive content of human communication (Phillips-Silver & Trainor, 2007; Todd & Lee, 2015).

In conclusion, listeners spontaneously entrained to the performer's movements, intermittently changing their direction of sway at approximately the same time as the performer. Our results raise, but do not answer, the question of how entrainment was possible, simply from hearing the recorded sound of a performer's playing. Our study suggests that by understanding the contributions of movement and music to the tendency to move spontaneously to music we may better understand the role of movement in human communication.

Author Note

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Correspondence concerning this article should be addressed to Alexander P. Demos, Department of Psychology, 1007 West Harrison Street (M/C 285), Chicago, IL 60607-7137. E-mails: ademos@uic.edu or alexander.demos@gmail.com

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Appendix A

TABLE A1. *Mean [and standard deviation] cross-correlation values for direct comparisons of movement in the recorded performances and in Experiments 1 and 2 for whole trials on which similarity was significant and not significant. These values represent the effect sizes for the degree of overlap.*

		Position		Velocity	
Source	Type of Comparison	Mean [*SD*] Sig Trials	Mean [*SD*] NS Trials	Mean [*SD*] Sig Trials	Mean [*SD*] NS Trials
Recorded performance	Within individual	0.414 [0.095]	0.203 [0.061]	0.329 [0.133]	–
	Between individuals	0.226 [0.063]	0.095 [0.067]	0.098 [0.041]	0.041 [0.017]
Experiment 1	Between individuals	0.192 [0.064]	0.091 [0.053]	0.071 [0.024]	0.051 [0.022]
Experiment 2	Within individual	0.360 [0.095]	0.087 [0.054]	0.175 [0.071]	0.069 [0.035]
	Between individuals	0.287 [0.055]	0.149 [0.094]	0.107 [0.052]	0.053 [0.011]

TABLE A2. *Mean [and standard deviation] root-mean squared values of the postural way in the recorded performances (stimulus) for position and velocity separately for each performer and expressive style.*

		Position			Velocity		
Sway	Performer	Normal	Exp	Non-Exp	Normal	Exp	Non-Exp
ML	1	2.736 [0.575]	2.761 [0.468]	0.408 [0.124]	0.159 [0.029]	0.163 [0.037]	0.041 [0.006]
	2	4.639 [1.297]	5.422 [1.439]	3.304 [1.923]	0.245 [0.033]	0.198 [0.023]	0.101 [0.014]
AP	1	0.971 [0.084]	1.061 [0.042]	0.696 [0.069]	0.081 [0.008]	0.081 [0.011]	0.051 [0.005]
	2	0.858 [0.140]	0.860 [0.063]	0.470 [0.056]	0.106 [0.010]	0.095 [0.009]	0.068 [0.005]