EXPLORING THE EFFECTS OF EFFECTORS: FINGER SYNCHRONIZATION AIDS RHYTHM PERCEPTION SIMILARLY IN BOTH PIANISTS AND NON-PIANISTS

FIONA C. MANNING, ANNA SIMINOSKI, &
MICHAEL SCHUTZ
McMaster University, Hamilton, Canada

WE EXPLORE THE EFFECTS OF TRAINED MUSICAL movements on sensorimotor interactions in order to clarify the interpretation of previously observed expertise differences. Pianists and non-pianists listened to an auditory sequence and identified whether the final event occurred in time with the sequence. In half the trials participants listened without moving, and in half they synchronized keystrokes while listening. Pianists and non-pianists were better able to identify the timing of the final tone after synchronizing keystrokes compared to listening only. Curiously, this effect of movement did not differ between pianists and non-pianists despite substantial training differences with respect to finger movements. We also found few group differences in the ability to align keystrokes with events in the auditory sequence; however, movements were less variable (lower coefficient of variation) in pianists compared to non-pianists. Consistent with the idea that the benefits of synchronization on rhythm perception are constrained by motor effector kinematics, this work helps clarify previous findings in this paradigm. We discuss these outcomes in light of training and the kinematics involved in pianist keystrokes compared to musicians synchronizing movements in other studies. We also overview how these differences across motor effector synchronization and training must be accounted for in models of perception and action.

Received: October 11, 2017, accepted September 29, 2019.

Key words: sensorimotor interactions, motor effector, motor synchronization, temporal prediction, music training

INTERACTIONS BETWEEN MOVEMENT AND SOUND are apparent in numerous behaviors, particularly for the complex motor sequences involved in playing a musical instrument. Effective sensorimotor integration is crucial for these tasks, allowing us to make predictions about upcoming events in time and synchronize movements with those expected events. The processing of auditory information is tightly linked with movement. For example, when listening to rhythmic information, regions of the brain important for the planning and execution of movement are active, even when listeners are completely still (Bengtsson et al., 2009; Chen, Penhune, & Zatorre, 2008; Grahn & Brett, 2007). Recent accounts of audio-motor interactions show that motor activity is important for refining an internal representation of temporal events (Manning & Schutz, 2013; Morillon, Schroeder, & Wyart, 2014), supporting the active sensing framework, which describes how sensory processing occurs in the context of movements (Morillon, Hackett, Kajikawa, & Schroeder, 2015; Schroeder, Wilson, Radman, Scharfman, & Lakatos, 2010). Although this view serves as an effective foundation for describing sensorimotor interactions, the mechanisms underlying movement's impact on perception and how motor training impacts this relationship remain unclear.

The present study explores the effect of extensive training with a specific motor effector, examining how this affects both synchronization and temporal acuity for rhythmic information. Specifically, we assess the perceptual consequences of motor synchronization in trained pianists and non-pianists. Previously we documented benefits to timing abilities when synchronizing with an external beat in percussionists and non-percussionists. We observed greater perceptual benefits in percussionists compared to non-percussionists when performing stick tapping behaviors, which are movements consistent with percussionist training (Manning & Schutz, 2016). Curiously, we observed little difference between percussionists and non-percussionists following finger tapping (Manning, Harris, & Schutz, 2017), movement more widely used in sensorimotor integration studies. Together, these studies suggest that training-specific movements may lead to more pronounced benefits to synchronization abilities compared to movements inconsistent with training (i.e., finger tapping). However, differences exist in the variability of motor synchronization across different effectors irrespective of training (Collier & Ogden, 2004; Fujii & Oda, 2009; Madison,

Music Perception, VOLUME 37, ISSUE 3, PP. 196–207, ISSN 0730-7829, ELECTRONIC ISSN 1533-8312. DOI: https://doi.org/10.1525/MP.2020.37.3.196

2001; Madison & Delignières, 2009), raising important questions regarding the quality of synchronization across finger vs. stick tapping movements. Therefore, these findings may alternatively suggest that limitations to finger synchronization inhibit improvements that might be developed through training, possibly due to the presence of fewer degrees of freedom in finger tapping compared to stick tapping movements (Dounskaia & Wang, 2014; Latash, 2012). This leaves an open question: Would extensive motor synchronization training using finger movement lead to similar training-specific improvements?

TIMING DIFFERENCES ACROSS MOTOR EFFECTORS

Sensorimotor synchronization abilities are frequently assessed using finger tapping tasks. However, it is important to consider the role of this specific motor effector—the means with which participants synchronize movements—when studying synchronization. The degree to which finger taps convey information about general synchronization ability is the subject of some debate. One position is that motor synchronization originates from a common motor source, where a single process controls the synchronization of different effectors (Doumas & Wing, 2007; Wing & Kristofferson, 1973). Support for this notion comes from studies comparing outputs across motor effectors, where a relationship is observed between tap asynchronies (Billon, Bard, Fleury, Blouin, & Teasdale, 1996) and variability (Fujii et al., 2011; Keele, Pokorny, Corcos, & Ivry, 1985) of different motor effectors within subjects. However, other studies illustrate marked differences across motor effectors when synchronizing with external auditory events. For example, foot tapping is more asynchronous than finger and stick tapping (Aschersleben & Prinz, 1995; Fraisse, 1982; Fujii et al., 2011).

Interestingly, while variability decreases with practice across both finger and stick tapping (Madison, Karampela, Ullén, & Holm, 2013), finger tapping is significantly more variable (Collier & Ogden, 2004; Madison, 2001) than tapping using a drumstick (Fujii & Oda, 2009; Madison & Delignières, 2009). There are many differences across motor effectors that have substantial impacts on synchronization tendencies and accuracy, including the size of the effector (Toiviainen, Luck, & Thompson, 2010), the sensory feedback that arises due to movement (Finney, 1997; Maduell & Wing, 2007; Wing, 1977), and the trajectory of the movement (Flash & Hogan, 1985; Goble, Zhang, Shimansky, Sharma, & Dounskaia, 2007). Furthermore, experience with a specific motor effector leads to more accurate motor timing using that specific effector, but it is not clear whether this generalizes to effectors other than that which is trained (Stoklasa, Liebermann, & Fischinger, 2012).

The motor control literature describes differences in the degrees of freedom in motor kinematics that may be manipulated using various effectors (Latash, 2014; Todorov & Jordan, 2002). Variation in the degrees of freedom involved in motor control offering either more options for joint manipulation or greater motor redundancy promote precision in movement (Dounskaia & Wang, 2014; Latash, 2012). Certain motor effectors involve different degrees of freedom than others. For example, arm movement consists of more degrees of freedom than does finger movement because of the ability to manipulate more joints, and thus contains more redundancy in the ability to complete a specific motion. A greater number of degrees of freedom in a motor effector can allow for more error correction and manipulation, and thus greater consistency, in movements (Bernstein, 1967; Latash, 2012; Winold, Thelen, & Ulrich, 1994). This is an important consideration when describing movement abilities across different effectors that involve differing numbers of degrees of freedom. Building on this view of movement kinematics, theories of perception and action discuss ways in which motor behaviors are mapped onto relevant perceptual consequences of movements (Hommel, Müsseler, Aschersleben, & Prinz, 2001), which are of particular interest in the present study.

EXPERTISE IN MOTOR SYNCHRONIZATION ABILITIES

Musicians and nonmusicians readily synchronize their movements with external auditory information. However, musicians demonstrate a performance advantage in motor timing abilities (Aschersleben, 2002; Matthews, Thibodeau, Gunther, & Penhune, 2016; Repp, 1999, 2010; Repp & Doggett, 2007; Repp, London, & Keller, 2013). Although there appear to be general benefits to timing abilities across musician groups (Matthews et al., 2016), there is also some evidence suggesting that these advantages differ based on musical background, where some groups display greater timing advantages compared to others. For example, percussionists outperform other musicians in motor and perceptual timing tasks (Cameron & Grahn, 2014; Krause, Pollok, & Schnitzler, 2010). Even short-term synchronization training (e.g., approximately 90 minutes of practice) in different motor effectors (e.g., finger and stick tapping) leads to lower movement variability (Madison et al., 2013), demonstrating the immediate benefits of training on synchronization abilities. In motor synchronization tasks, musicians perform better when synchronizing with information following familiar musical conventions. For example, musicians exhibit more highly coordinated movements with a decreasing compared to increasing tempo (Loehr, Large, & Palmer, 2011), a tendency observed in musical phrases called phrase-final lengthening (Palmer & Krumhansl, 1990; Repp, 1998). Additionally, extensive music training using a given motor effector (e.g., synchronizing using violins, trumpets, etc.) leads to more accurate synchronization than finger tapping (Stoklasa et al., 2012). Long- and short-term training clearly benefits sensorimotor synchronization, and experience with particular musical contexts and motor effectors appear to have a clear impact on synchronization abilities.

We previously found that extensive training in drumming improved perceptual sensitivity to timing in percussionists synchronization with sticks (Manning & Schutz, 2016; Manning et al., 2017). Those results can be interpreted in two ways: either (a) percussionists' training with stick tapping means that movement is more beneficial to their rhythm perception, or (b) stick tapping is more beneficial to rhythm perception than finger tapping, regardless of training and expertise. Clarifying those results is of great importance to the rhythm community, as finger tapping has traditionally been used as the standardized way of assessing timekeeping (as summarized by Repp, 2005). Consequently, finding that stick tapping offers better performance for timing tasks even amongst participants trained in finger tapping would raise interesting questions about best practices for a range of issues currently assessed primarily (or exclusively) with finger tapping.

Here we aim to clarify previous findings by exploring whether extensive motor synchronization training improves finger synchronization and rhythm perception in pianists. We selected pianists as our primary group of interest since they are highly trained with movements resembling finger tapping, which is often used in synchronization studies (see Repp, 2005, for a review). We predicted that pianists would gain a greater benefit to timing perception abilities than non-pianists following synchronization through finger movements, and this would suggest that extensive training with a particular motor effector refines both synchronization abilities and the perceptual benefits that arise due to this movement. Alternatively, if pianists show similar benefits to perception from finger synchronization compared to non-pianists, this would demonstrate that the limits to motor synchronization abilities using finger movements (Madison et al., 2013; Stoklasa et al., 2012) possibly due to few degrees of freedom (Bernstein, 1967; Latash, 2012) may mitigate the perceptual effects of motor training. This important distinction is critical for understanding the role of motor training in musical expertise and its impact on prediction abilities.

Method

PARTICIPANTS

Two groups of participants completed this experiment; trained pianists and non-pianists. Thirty piano players participated (20 female, 10 male) ranging in age from 17 to 22 years ($M = 18.40$, $SD = 1.25$). The pianist group had a range of 7 to 15 years of formal piano lessons ($M = 11.20$, $SD = 1.99$) and 7 to 17 years of general music training ($M = 11.91$, $SD = 2.41$). One participant was excluded from the pianist group because they did not meet the study criteria of over seven years of formal training. Thirty non-pianists (19 female, 11 male) within an age range of 17 to 25 years ($M = 18.67$, $SD = 1.47$) participated through the McMaster Universities' online research participation system. Non-pianists reported a range of music training on instruments other than piano (0-10 years; $M = 3.50$, $SD = 2.99$). We compared total music training between pianists and non-pianists, showing that pianists had significantly more music training overall, $t(56) = 11.97$, $p < .001$. We excluded two non-pianists from the analysis; one for equipment failure and one for not properly following instructions. Monetary compensation or course credit was given in exchange for their participation. This study met the criteria set by the McMaster University Research Ethics Board.

MATERIALS AND STIMULI

An iMac computer presented the stimuli using custom software designed for the MAPLE Lab and listened through Sennheiser HDA200 headphones. The stimuli were similar to those used in a previous study (Manning & Schutz, 2013), consisting of an isochronous sequence of beats at an interonset interval (IOI) of 500 ms presented as a woodblock tone (general MIDI #115). The sequence totaled seventeen beats, with a meter of 4/4 induced through pitch differentiations (see Figure 1). The first beat of the grouping of four had a higher pitch of 523 Hz (C5), with the following three beats having a lower pitch of 392 Hz (G4). This sequence repeated four times, but in the last repetition the three lower tones were replaced with silence. After the silence, a final probe tone (523 Hz, C5) played either on time with the previous isochronous sequence (e.g., at the expected point in time), or delayed by 15% (75 ms) or 30% (150 ms) of the IOI. The "on-time" probe tone occurred in 50% of the trials, while the two delayed probe tones

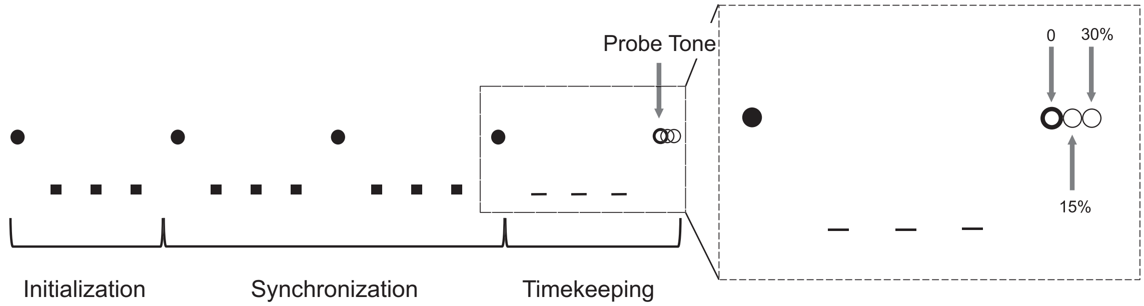

FIGURE 1. One trial of the auditory event sequence. Trial segments are labeled. The timekeeping segment is enlarged to show more detail. Circle represent higher pitch tones, squares represent lower pitch tones, and lines indicate silent events. Unfilled circles display possible probe tone positions.

each occurred in 25% of the trials. The participants were aware of the possible probe tone delays and responded to each trial by selecting their response on the screen with a computer mouse.

PROCEDURE

Participants sat in front of a Yamaha P-255 digital piano and the computer monitor in a sound-attenuated booth. Each participant encountered two different conditions; a movement condition and no-movement condition. In the movement condition, participants moved in time to the sequence of beats by pressing C5 on the piano using their dominant hand. As participants pressed the key, they heard the corresponding sound of the keypress (C5; 523 Hz). They started tapping the key when they felt comfortable with the timing of the sequence, and continued to play through the probe tone. In the second condition (no-movement condition), participants remained as still as possible while listening to the beat sequences. Eight blocks were completed; half in the movement condition and half in the non-movement condition, all blocks appeared in a randomized order. The experiment contained eight trials per block, for a total of 64 trials, with the timing of the probe tone presented in a randomized order. Five practice trials were performed in the movement condition before starting the experimental blocks. After each trial, participants identified whether the probe tone was consistent in timing to the isochronous sequence (e.g., occurred "on-time") or if it was inconsistent with the timing of the sequence. Participants also indicated how confident they were in their perceptual response on a scale from 1 (*not at all confident*) to 5 (*very confident*). Both groups of participants followed the same procedure. An exit survey was administered to gather demographics and music training history.

Results

SYNCHRONIZATION RESULTS

To measure synchronization ability, we calculated each participant's mean keystroke asynchrony, the alignment between their keystrokes and the auditory sequence, and the coefficient of variation (CV), a measure of variability between each of the participants' keystrokes. The synchronization segment of the beat sequence consisted of events 5 through 13 (see Figure 1) where participants aligned keystrokes with the sound. In order to facilitate the broadest range of comparisons with the tapping literature, we calculated both the signed and absolute keystroke asynchronies, as well as CV for this segment of the trial. Additionally, we calculated the signed and absolute asynchrony at the probe tone (event 17). To calculate the signed keystroke asynchrony, we subtracted the timing of the auditory event from the timing of the keystroke recorded on the midi piano. The tap asynchrony at the probe tone was calculated similarly, using the *expected* probe tone onset. Positive values indicate that the keystroke occurred after the expected auditory event, while negative values indicate the keystrokes occurred before the auditory event in the sequence (see Figure 2a). A two-tailed independent samples t-test showed that signed keystroke asynchronies were marginally different between pianists and non-pianists during the synchronization segment of the trials, $t(56) = 1.90$, $p = .06$, and we did not observe a significant difference between groups at the probe tone, $t(56) = 1.07$, $p = .29$. Similarly, we analyzed the absolute (i.e., unsigned) asynchrony for keystrokes throughout the synchronization segment of the trial and at the probe tone (Figure 2b). A two-tailed independent samples t-test showed that absolute keystroke asynchronies did not differ significantly between pianists and

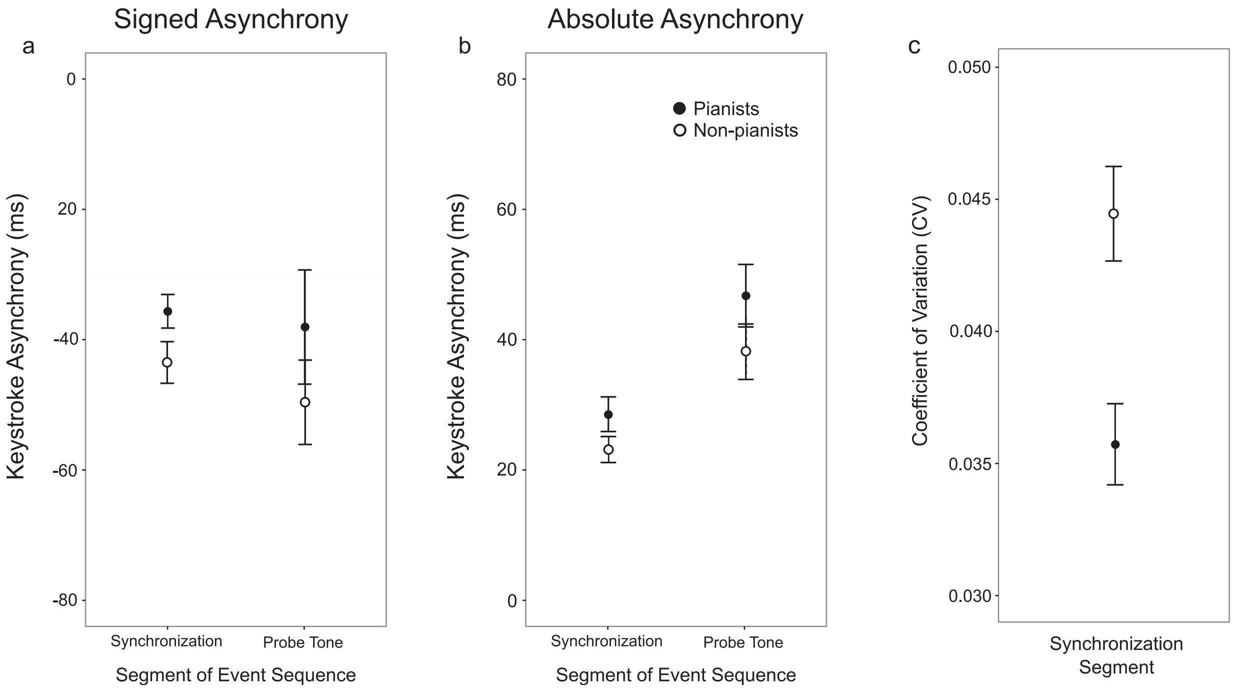

FIGURE 2. The keystroke signed asynchrony (a), absolute asynchrony (b), and the coefficient of variation (c) at segments of the auditory event sequence for pianists and non-pianists. Error bars indicate the standard error of the mean.

non-pianists through either the synchronization segment of the trials, $t(56) = 1.61$, $p = .12$, or at the probe tone, $t(56) = 1.33$, $p = .19$. The CV for the synchronization segment was calculated by dividing the standard deviation of the keystroke interresponse interval (IRI) by the mean IRI in each movement trial (see Figure 2c). Pianists and non-pianists showed a significant difference in their keystroke variability, $t(56) = 3.70$, $p < .001$, where pianists were more consistent in their keystrokes compared to non-pianists.

PERCEPTUAL RESULTS

To examine responses in each condition for each group, we computed the percentage of "on-time" responses (displayed in Figure 3)—the percentage of time participants indicated they thought the probe tone occurred on time (irrespective of its actual offset). We conducted a 2 (movement condition) X 3 (probe tone offset) within-subjects ANOVA for each participant group. This test yielded a significant interaction between movement condition and offset for the pianists, $F(2, 58) = 18.43$, $p < .001$, $\eta^2 = 0.14$, and non-pianists, $F(2, 58) = 7.24$, $p = .002$, $\eta^2 = 0.06$, indicating that the difference between the movement conditions changed at one or more probe tone offsets. We also observed a main effect of movement condition for both pianists, $F(1, 29) = 16.22$, $p < .001$, $\eta^2 = 0.11$, and non-pianists, $F(1, 29) = 12.50$, $p = .001$, $\eta^2 = 0.06$, and a main effect of probe tone offset for pianists, $F(2, 58) = 146.39$, $p < 0.001$, $\eta^2 = 0.54$, and non-pianists, $F(2, 58) = 101.18$, $p < .001$, $\eta^2 = 0.58$. Post hoc comparisons between movement and no-movement trials at the probe tone offsets yielded no significant difference between movement conditions at the 0% probe tone offset for either pianists, $t(58) = 1.83$, $p = .07$, or non-pianists, $t(58) = 1.22$, $p = .19$; however, significant differences between movement and no-movement conditions were observed at the 15% probe tone offset for both pianists, $t(58) = 2.99$, $p = .004$, and non-pianists, $t(58) = 2.00$, $p = .05$, as well as the 30% probe tone offset for both pianists, $t(58) = 5.64$, $p < .001$, and non-pianists, $t(58) = 2.40$, $p = .02$.

A mixed model ANOVA including participant group as a between-subjects factor yielded a significant interaction between movement condition and probe tone offset, $F(2, 116) = 24.66$, $p < .001$, and main effects of movement conditions, $F(2, 116) = 28.51$, $p < .001$, and probe tone offset, $F(2, 116) = 240.45$, $p < .001$. Importantly, we did not observe a three-way interaction, $F(2, 116) = 1.75$, $p = .18$, indicating no significant difference between groups across movement conditions or any probe tone offsets. We also found no two-way

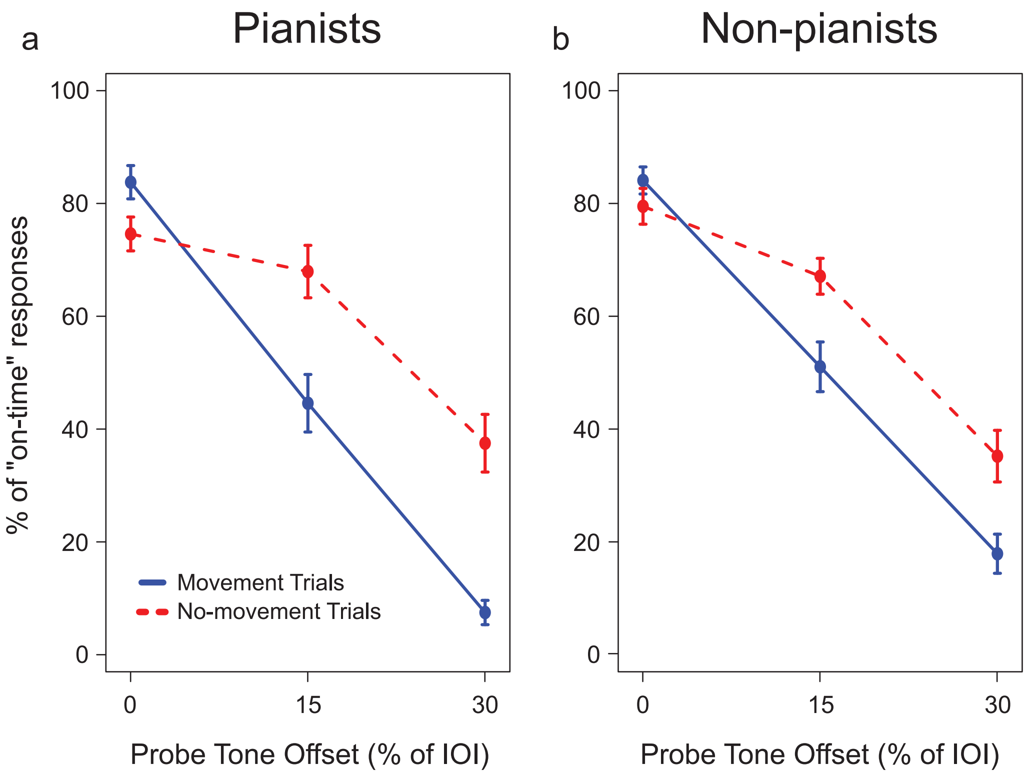

FIGURE 3. Percentage of "on-time" responses for pianist (a) and non-pianist (b) groups in movement and no-movement trials. Error bars indicate the standard error of the mean.

interactions between group and movement condition, $F(2, 116) = 1.27$, $p = .26$, or group and probe tone offset, $F(2, 116) = 0.05$, $p = .95$, and no main effect of group, $F(1, 58) = 1.43$, $p = .24$.

COMPARISONS BETWEEN PERCEPTUAL AND SYNCHRONIZATION RESULTS

To assess the relationship between synchronization and responses, we examined how keystroke asynchrony at the anticipated probe tone related to response accuracy using a binary logistic regression analysis (Figure 4). The keystroke asynchrony for each trial was determined by calculating the absolute difference between the timing of the final keystroke and the anticipated timing of the probe tone. For pianists we found that the timing of the final keystroke predicted the accuracy of the perceptual timing judgment. As the asynchrony between the timing of the keystroke and the auditory event increased by 1 ms, the odds of correctly identifying the timing of the probe tone decreased by 0.88%, $\chi^2 = 40.31$, $p < .001$; odds ratio (OR) = 0.98. A similar, but less pronounced, relationship was observed in non-pianists, whereas the keystroke asynchrony increased, the odds of identifying

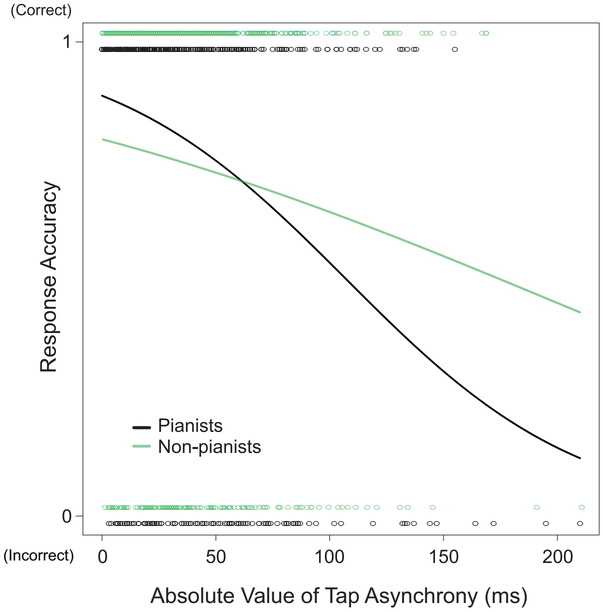

FIGURE 4. A binary logistic regression analysis comparing the absolute tap asynchronies from the expected onset of the probe tone to the response accuracy on a trial-by-trial basis for both pianists and non-pianists.

the correctness of probe tone timing decreased by 0.80%, $\chi^2 = 6.45$, $p = .011$; odds ratio (OR) $= 0.99$. This suggests that for both pianists and non-pianists, the timing of the final keystroke in the sequence predicted the accuracy of probe tone judgments. More accurately timed movements may have lead to a greater probability of correctly identifying misaligned probe tones, and this was particularly the case for pianists.

Discussion

This experiment explores the relationship between movement and perception by asking participants to complete a rhythmic discrimination task while either moving or sitting stationary. By using a paradigm, equipment, and software for these finger synchronization experiments consistent with our previous stick tapping experiments (Manning & Schutz, 2016; Manning et al., 2017), we are able to make direct comparisons with previous data. This allows us to clarify whether our previous findings regarding superior performance by percussionists using drumsticks (but not fingers) reflected either: (a) their percussion training, or (b) differences in timekeeping when using sticks vs. fingers.

TIMING PERCEPTION: FINGER SYNCHRONIZATION SIMILARLY HELPS BOTH GROUPS

Although we found more accurate perceptual judgments in the movement conditions for both groups of participants, surprisingly we observed no difference between perceptual timing judgments in pianist and non-pianist groups. Finding that movement similarly affected both pianists and non-pianists clarifies past findings by discriminating between two competing interpretations. Previous studies of stick tapping found a benefit of movement—i.e., better performance on the rhythm discrimination task in the movement (tapping) vs. nonmovement task (Manning & Schutz, 2013). Although previous work illustrates that percussionists benefit more from stick tapping than non-percussionists (Manning & Schutz, 2016), finger tapping did not enhance percussionists' perceptual abilities related to rhythm perception (Manning et al., 2017). Those findings could previously have been interpreted in two ways—either indicating: (a) percussionists' training makes movement more beneficial to their rhythm perception, or (b) stick tapping is more beneficial to rhythm perception than finger tapping—regardless of training and expertise.

Questions regarding the efficacy of finger tapping in assessing timing are timely, given variability in motor synchronization when implementing finger movements (Collier & Ogden, 2004; Fujii & Oda, 2009; Madison, 2001; Madison & Delignières, 2009; Madison et al., 2013) and previous suggestions that stick tapping might differ from finger tapping in crucial ways. In particular, the lack of difference between groups of participants holds implication for previous work reporting no difference between musician groups (e.g., drummers, pianists, string players, and singers) on finger tapping and rhythm perception tasks (Matthews et al., 2016). Similarly, our study suggests that even musicians trained to use finger movements may be restricted by inherent variability in finger tapping synchronization.

Our findings suggest the need for greater consideration of motor effector when examining synchronization, particularly in musician groups. Theories of perception and action that consider motor synchronization, including the active sensing framework (Morillon et al., 2015) and the theory of event coding (Hommel et al., 2001), are often supported using findings from finger tapping studies (e.g., Aschersleben, 2002; Aschersleben & Prinz, 1995; Chemin, Mouraux, & Nozaradan, 2014; Morillon et al., 2014; Repp, 2005). By examining additional motor effectors when studying questions pertaining to synchronization, we will have a more comprehensive view of how motor kinematics inform these theories.

PROBE TONE POSITION

Participant responses differed between the movement and no-movement conditions, indicating a clear effect of movement on perception. However this effect of movement differed across different values of the probe tone's offset—as indicated by a significant interaction between movement condition and probe tone position. Specifically, we observed no significant difference between movement and no-movement trials when the probe tones occurred on-time (e.g., at a 0% offset); however, this difference was significant when the probe tones occurred later than anticipated (e.g., at a 15% or 30% offset). This is broadly consistent with our previous studies using a similar task, which report an asymmetry in the accuracy of perceptual responses around the probe tone—i.e., that movement improved task performance more in trials with late vs. early probe tones. It is similarly consistent with previous results showing little difference between movement and no-movement conditions with a probe tone that occurred when anticipated—i.e., at the proper time.

Previous literature on temporal prediction reports that attention increases prior to (and peaks at the onset of) anticipated events (Large & Jones, 1999; McAuley & Kidd, 1998). This heightened attention at the probe tone typically leads to greater accuracy in temporal detection tasks (Barnes & Jones, 2000; McAuley & Jones, 2003). It is possible that movement does not facilitate temporal detection when the probe tone occurs when anticipated because detection is highly accurate in these conditions and has little room for improvement. Additionally, it is possible movement asymmetry pre- and post-tap might help explain our asymmetry in tapping's influence, as previous studies have noted that extension times—movement after a tap—are longer than flexion times—movement prior to a tap (Hove & Keller, 2010).

The motor control literature discusses how timed movements may be constricted by limited options for manipulating movements. Specifically, there is an observed redundancy in goal-oriented motor tasks, where in executing certain movements using an effector, there are multiple options for manipulating different joints to achieve the same outcome, referred to as the motor redundancy problem (Berstein, 1967), or more recently described as a motor abundance (Latash, 2012, 2014). The more options there are for manipulating movement, the greater the opportunity to select the optimal combination to minimize variability and execute better timed movements.

Here, finger movements for keystroke performance allow a restricted set of options for manipulation, whereas with other movements that include more joints we may observe a reduction in variability. The same may be true for training; with more degrees of freedom available to reduce movement variability, there may be more opportunities to also refine all degrees of freedom and develop an optimal combination of joint movements to perfect the timing of specific movements. Furthermore, training may allow for greater integration with auditory information to improve temporal prediction abilities. Here, we suggest that although finger synchronization is commonly used to examine timed movements due to its simplicity in recording (see Repp, 2005, for a review), there are limitations to these movements due to their kinematic properties. Exploring other types of musical movement will lead to a fuller understanding of the relationship between movement and timing that is so integral to musical performance.

ASSESSING SYNCHRONIZATION

In the present study, we assessed the timing of keystrokes in both pianists and non-pianists. We found no difference between groups for absolute asynchronies in the synchronization segment or the probe tone of the trials. Additionally, although we found nominally smaller signed asynchronies in keystrokes performed by pianists compared to non-pianists in the synchronization segment of the trial, we found no difference between groups for signed asynchronies at the probe tone. These findings differ from work demonstrating more precisely timed movements in musicians compared to nonmusicians (Aschersleben, 2002; Manning & Schutz, 2016; Repp, 1999; Repp & Doggett, 2007). Although in this study we compared two groups that differ only in the effector used during their music training, not with respect to the amount of music training in each group, these findings are critical to consider alongside explicit comparisons between musicians and nonmusicians to understand the source of sensorimotor improvements to timing abilities. It is possible that pianists show differences in alignment between their keystrokes and the auditory sequence compared to other musician groups if they differ in the perceived onset of their keystrokes. The perceptual center of an event is the precise moment at which that event is perceived to occur (Morton, Marcus, & Frankish, 1976). With extensive experience executing keystrokes in time with external auditory events, it is possible that pianists experience a shift in the perceptual center of these keystrokes, leading to a discrepancy when comparing our findings with other studies. However, we did observe a significant difference in keystroke variability between pianists and non-pianists. This is consistent with previous work reporting that musicians perform more consistently timed movements than do nonmusicians (Cameron & Grahn, 2014; Fujii et al., 2011; Krause et al., 2010; Repp, 2010; Repp & Doggett, 2007; Repp et al., 2013) as well as a report of musicians timing movements more accurately on their own instrument of training (Stoklasa et al., 2012). Future investigations of keystroke timing should further examine these differences using studies optimally designed to examine keystroke variability in musicians.

Finally, we observed a significant relationship between the timing of the final keystroke and the accuracy of timing judgments in both pianists and non-pianists, where the timing of the final keystroke predicted the perceptual response outcome of each trial (Figure 4). This finding might suggest that both groups of participants relied to some extent on the timing of the final keystroke as a cue to identifying their response, particularly pianists, consistent with our previous studies examining this interaction in different motor effectors and musician groups (Manning & Schutz, 2016; Manning et al., 2017). This is also consistent with literature demonstrating correlations between synchronization and perceptual timing abilities, where participants who synchronize movements more accurately with external auditory stimuli also tend to show higher performance on timing detection tasks (Krause et al., 2010). Surprisingly, the more precisely timed synchronization observed in pianists vs. non-pianists did not translate to perceptual benefits with respect to the perceptual task. Future studies should examine different musician groups to assess whether musicians that train on different motor effectors yield similar results, given previous reports of synchronization differences in musician groups using their own instruments of training (i.e., Stoklasa et al., 2012).

OTHER FACTORS TO CONSIDER IN INTERPRETING THESE RESULTS

There are some alternative interpretations of the lack of difference between participant groups in the study. For example, we make the assumption that pianists are well-practiced at conducting repetitive, isochronous keystrokes. However, pianists typically perform movements with multiple, often alternating fingers. It is also possible that experience with typing improves motor timing abilities and impacts perception in both groups, or that short-term training in the task allowed participants enough exposure to the task to improve synchronization and perception. Additionally, it is possible that since the non-pianist group's amount of overall music training was no different than pianists' training on instruments other than piano, this training might have been sufficient to enhance timing judgments overall in both groups. Although future studies could independently assess the role of piano vs. music training on another instrument, here we intentionally matched music training in order to isolate the role of training on piano-specific (i.e., finger) movements. Since we did not observe differences between groups in this study, these findings may suggest that general music training is sufficient to observe additional movement-related enhancements to timing abilities.

A growing number of studies describe benefits to listening abilities acquired merely through listening (Bigand, 2003; Honing & Ladinig, 2009). As such, it is possible that differences in music listening or interacting with music in ways other than explicit sensorimotor synchronization can enhance perceptual timing abilities, and it is possible that participant categories in the present study failed to capture these differences. It is possible that in these groups, listening abilities might have reached comparable levels, making it difficult to identify group differences (Bigand & Poulin-Charronnat, 2006). Similarly, DJs who engage with rhythmic information acquire refined sensorimotor abilities compared to non-DJs (Butler & Trainor, 2015) likely due to a high degree of exposure to musical stimuli and actively interacting with the rhythmic content. In general, broader training benefits to sensorimotor abilities may create challenges in distinguishing effects related to the trained effector. Future work should examine differences between musicians and nonmusicians in a similar task to clarify this possible interpretation.

IMPLICATIONS AND CLOSING THOUGHTS

This study has important implications for literature describing interactions between action and perception (Hommel et al., 2001; Prinz, 1997), by highlighting critical interactions between motor effector synchronization and musical expertise. Recent forward models of sensorimotor integration describe an embodied account of action and perception interactions (Maes, Leman, Palmer, & Wanderley, 2014) and suggest that "active sensing" allows us to use rhythmic motor information to refine temporal representations of external sensory inputs through sensorimotor coupling (Morillon et al., 2015; Schroeder et al., 2010). This occurs by enhancing the signal based on movement information and suppressing irrelevant information that would interfere with its processing (Morillon et al., 2014). This is further supported by functional imaging studies that report motor recruitment during passive listening tasks (Bengtsson et al., 2009; Chen et al., 2008; Grahn & Brett, 2007). By attributing differences in movement-related improvements to temporal prediction abilities in the present study to a combination of music training and movement effectors (see also Manning & Schutz, 2016; Manning et al., 2017), the present study suggests that interactions between motor kinematics and expertise play a critical role in sensorimotor integration studies and must be further considered in these models. Additionally, the finding that movement influences auditory perception provides a useful counterpart to previous documentation of auditory information affecting movement. For example, Keller, Dalla Bella, and Koch (2010) found that taps following pacing signals exhibited more acceleration, greater amplitude, and shorter IOIs when pacing signals contained congruent auditory (as well as visual) information, compared to those that did not.

In summary, this study demonstrates that keystrokes performed by pianists and non-pianists facilitate perceptual timing judgments for both groups. This observation offers further support for the perceptual benefits that may arise from timed movements, highlighting interactions between motor synchronization and perceptual timing abilities (Chemin, et al., 2014; Manning & Schutz, 2013; Su & Pöppel, 2012). This benefit to performance was no different between groups, showing that although finger movements are highly trained in pianists, the perceptual benefits of these movements with respect to timing may be limited due to the constraints of finger kinematics. Due to the large amount of variability in synchronized finger movements (Madison, et al., 2013; Stoklasa et al., 2012), finger tapping as a mode of synchronization may not serve as a reliable cue for timing information, despite its ubiquitous use in the synchronization literature. Overall, we suggest that future synchronization studies should make use of different modes of recording timed movements based on the kinematics involved in movement execution, while considering possible interactions with musical expertise.

Author Note

We would like to thank Alisia Palermo, Sarah McGrath, Kirandeep Matharu, Shanthika Ravindran, and Nicole Divincenzo for their assistance with data collection. This work was supported by grants from the Natural Sciences and Engineering Research Council of Canada (NSERC RGPIN/386603-2010), Ontario Early Researcher Award (ER10-07-195), and Canadian Foundation for Innovation (CFI-LOF 30101) to Michael Schutz, PI. This work was also supported by a Joseph-Armand Bombardier CGS to the lead author.

Correspondence concerning this article should be addressed to Fiona Manning, Department of Psychology, Neuroscience and Behaviour, Psychology Building (PC), Room 102, McMaster University, 1280 Main St. West, Hamilton, ON, Canada L8S 4K1. E-mail: fiona.c.manning@gmail.com

References

Aschersleben, G. (2002). Temporal control of movements in sensorimotor synchronization. *Brain and Cognition*, *48*, 66–79.

Aschersleben, G., & Prinz, W. (1995). Synchronizing actions with events: The role of sensory information. *Perception and Psychophysics*, *57*, 305–317.

Barnes, R., & Jones, M. R. (2000). Expectancy, attention, and time. *Cognitive Psychology*, *41*, 254–311.

Bengtsson, S. L., Ullén, F., Ehrsson, H. H., Hashimoto, T., Kito, T., Naito, E., et al. (2009). Listening to rhythms activates motor and premotor cortices. *Cortex*, *45*, 62–71.

Bernstein, N. A. (1967). *The co-ordination and regulation of movements*. Oxford, UK: Pergamon Press.

Bigand, E. (2003). More about the musical expertise of musically untrained listeners. *Annals of the New York Academy of Sciences*, *999*, 304–312.

Bigand, E., & Poulin-Charronnat, B. (2006). Are we "experienced listeners"? A review of the musical capacities that do not depend on formal musical training. *Cognition*, *100*, 100–130.

Billon, M., Bard, C., Fleury, M., Blouin, J., & Teasdale N. (1996). Simultaneity of two effectors in synchronization with a periodic external signal. *Human Movement Science*, *15*, 25–38.

Butler, B. E., & Trainor, L. J. (2015) The musician redefined: A behavioral assessment of rhythm perception in professional club DJs. *Timing and Time Perception*, *3*, 116–132.

Cameron, D. J., & Grahn, J. A. (2014). Enhanced timing abilities in percussionists generalize to rhythms without a musical beat. *Frontiers in Human Neuroscience*, *8*.

Chemin, B., Mouraux, A., & Nozaradan, S. (2014). Body movement selectively shapes the neural representation of musical rhythms. *Psychological Science*, *25*, 2147–2159.

Chen, J. L., Penhune, V. B., & Zatorre, R. J. (2008). Listening to musical rhythms recruits motor regions of the brain. *Cerebral Cortex*, *18*, 2844–2854.

Collier, G. L., & Ogden, R. T. (2004). Adding drift to the decomposition of simple isochronous tapping: An extension of the Wing-Kristofferson model. *Journal of Experimental Psychology: Human Perception and Performance*, *30*, 853–872.

Doumas, M., & Wing, A. M. (2007). Timing and trajectory in rhythm production. *Journal of Experimental Psychology: Human Perception and Performance*, *33*, 442–455.

Dounskaia, N., & Wang, W. (2014). A preferred pattern of joint coordination during arm movements with redundant degrees of freedom. *Journal of Neurophysiology*, *112*, 1040–1053.

Finney, S. A. (1997). Auditory feedback and musical keyboard performance. *Music Perception*, *15*, 153–174.

Flash, T., & Hogan, N. (1985). The coordination of arm movements: An experimentally confirmed mathematical model. *Journal of Neuroscience*, *158*, 50–57.

Fraisse, P. (1982). Rhythm and tempo. In D. Deutsch (Ed.), *Psychology of music* (pp. 149–180). Orlando, FL: Academic Press.

Fujii, S., Hirashima, M., Kudo, K., Ohtsuki, T., Nakajima, Y., & Oda, S. (2011). Synchronization error of drum kit playing with a metronome at different tempi by professional drummers. *Music Perception*, *28*, 491–503.

Fujii, S., & Oda, S. (2009). Effect of stick use on rapid unimanual tapping in drummers. *Perceptual and Motor Skills*, *108*, 962–970.

Goble, J., Zhang, Y., Shimansky, Y., Sharma, S., & Dounskaia, N. (2007). Directional biases reveal utilization of arm's biomechanical properties for optimization of motor behavior. *Journal of Neurophysiology*, *98*, 1240–1252.

Grahn, J. A., & Brett, M. (2007). Rhythm and beat perception in motor areas of the brain. *Journal of Cognitive Neuroscience*, *19*, 893–906.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *The Behavioral and Brain Sciences*, *24*, 849–937.

Honing, H., & Ladinig, O. (2009). Exposure influences expressive timing judgments in music. *Journal of Experimental Psychology: Human Perception and Performance*, *35*, 281–288.

Hove, M. J., & Keller, P. E. (2010). Spatiotemporal relations and movement trajectories in visuomotor synchronization. *Music Perception, 28*, 15–26.

Keele, S. W., Pokorny, R. A., Corcos, D. M., & Ivry, R. (1985). Do perception and motor production share common timing mechanisms: A correlational study. *Acta Psychologica*, *60*, 173–191.

Keller, P. E., Dalla Bella, S., & Koch, I. (2010). Auditory imagery shapes movement timing and kinematics: Evidence from a musical task. *Journal of Experimental Psychology: Human Perception and Performance, 36,* 508–513.

Krause, V., Pollok, B., & Schnitzler, A. (2010). Perception in action: The impact of sensory information on sensorimotor synchronization in musicians and non-musicians. *Acta Psychologica*, *133*, 28–37.

Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychological Review*, *106*, 119–159.

Latash, M. L. (2012). The bliss (not the problem) of motor abundance (not redundancy). *Experimental Brain Research*, *217*, 1–5.

Latash, M. L. (2014). Motor control: On the way to physics of living systems. In M. F. Levin (Ed.), *Progress in motor control* (pp. 1–14). New York: Springer.

Loehr, J. D., Large, E. W., & Palmer, C. (2011). Temporal coordination and adaptation to rate change in music performance. *Journal of Experimental Psychology: Human Perception and Performance*, *37*, 1292–1309. DOI: 10.1037/a0023102

Madison, G. (2001). Variability in isochronous tapping: Higher order dependencies as a function of intertap interval. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 411–422.

Madison, G., & Delignières, D. (2009). Auditory feedback affects the long-range correlation of isochronous serial interval production: Support for a closed-loop or memory model of timing. *Experimental Brain Research*, *193*, 519–527.

Madison, G., Karampela, O., Ullén, F., & Holm, L. (2013). Effects of practice on variability in an isochronous serial interval production task: Asymptotical levels of tapping variability after training are similar to those of musicians. *Acta Psychologica*, *143*, 119–128.

Maduell, M., & Wing, A. M. (2007). The dynamics of ensemble: The case for flamenco. *Psychology of Music*, *35*, 591–627.

Maes, P.-J., Leman, M., Palmer, C., & Wanderley, M. M. (2014). Action-based effects on music perception. *Frontiers in Psychology*, *4*(January), 1–14. DOI: 10.3389/fpsyg.2013.01008

Manning, F., & Schutz, M. (2013). "Moving to the beat" improves timing perception. *Psychonomic Bulletin and Review*, *20*, 1133–1139.

Manning, F. C., & Schutz, M. (2016). Trained to keep a beat: Movement-related enhancements to timing perception in percussionists and non-percussionists. *Psychological Research*, *80*, 532–542.

Manning, F. C., Harris, J., Schutz, M. (2017). Temporal prediction abilities are mediated by motor effector and rhythmic expertise. *Experimental Brain Research*, *235*, 861–871.

Matthews, T. E., Thibodeau, J. N. L., Gunther, B. P., & Penhune, V. B. (2016). The impact of instrument-specific musical training on rhythm perception and production. *Frontiers in Psychology, 7*(February). DOI: 10.3389/fpsyg.2016.00069.

McAuley, J. D., & Jones, M. R. (2003). Modeling effects of rhythmic context on perceived duration: A comparison of interval and entrainment approaches to short-interval timing. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 1102–1125.

McAuley, J. D., & Kidd, G. R. (1998). Effect of deviations from temporal expectations on tempo discrimination of isochronous tone sequences. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1786–1800.Morillon, B., Hackett, T. A., Kajikawa, Y., & Schroeder, C. E. (2015). Predictive motor control of sensory dynamics in auditory active sensing. *Current Opinion in Neurobiology, 31*, 230–238.

Morillon, B., Schroeder, C. C., & Wyart, V. (2014). Motor contributions to the temporal precision of auditory attention. *Nature Communications*, *5*, 5255.

Morton, J., Marcus, S., & Frankish, C., (1976). Perceptual centers (P-centers). *Psychological Review*, *83*, 405–408.

Palmer, C., & Krumhansl, C. L. (1990). Mental representations for musical meter. *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 728–741.

Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology*, *9*, 129–154.

Repp, B. H. (1998). Obligatory "expectations" of expressive timing induced by perception of musical structure. *Psychological Research*, *61*, 33–43.

Repp, B. H. (1999). Control of expressive and metronomic timing in pianists. *Journal of Motor Behavior*, *31*, 145–164.

Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin and Review*, *12*, 969–992.

REPP, B. H. (2010). Sensorimotor synchronization and perception of timing: Effects of music training and task experience. *Human Movement Science*, *29*, 200–213.

REPP, B. H., & DOGGETT, R. (2007). Tapping to a very slow beat: A comparison of musicians and nonmusicians. *Music Perception*, *24*, 367–376.

REPP, B. H., LONDON, J., & KELLER, P. E. (2013). Systematic distortions in musicians' reproduction of cyclic three-interval rhythms. *Music Perception*, *30*, 291–305.

SCHROEDER, C. E., WILSON, D. A., RADMAN, R., SCHARFMAN, H., & LAKATOS, P. (2010). Dynamics of active sensing and perceptual selection. *Current Opinion in Neurobiology*, *20*, 172–176.

STOKLASA, J., LIEBERMANN, C., & FISCHINGER, T. (2012). *Timing and synchronization of professional musicians: A comparison between orchestral brass and string players*. Paper presented at the 12th International Conference on Music Perception and Cognition, Thessaloniki, Greece.

SU, Y.-H., & PÖPPEL, E. (2012). Body movement enhances the extraction of temporal structures in auditory sequences. *Psychological Research*, *76*, 373–382.

TOIVIAINEN, P., LUCK, G., & THOMPSON, M. R. (2010). Embodied meter: Hierarchical eigenmodes in music-induced movement. *Music Perception*, *28*, 59–70.

TODOROV, E., & JORDAN, M. I. (2002). Optimal feedback control as a theory of motor coordination. *Nature Neuroscience*, *5*, 1226–1235.

WING, A. M. (1977). Perturbations of auditory feedback delay and the timing of movement. *Journal of Experimental Psychology: Human Perception and Performance*, *3*, 175–186.

WING, A. M., & KRISTOFFERSON, A. B. (1973). Response delays and the timing of discrete motor responses. *Perception and Psychophysics*, *14*, 5–12.

WINOLD, H., THELEN, E., & ULRICH, B. D. (1994). Coordination and control in the bow arm movements of highly skilled cellists. *Ecological Psychology*, *6*, 1–31.