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ORIGINAL ARTICLE

Trained to keep a beat: movement-related enhancements to timing perception in percussionists and non-percussionists

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Abstract Many studies demonstrate that musicians exhibit superior timing abilities compared to nonmusicians. Here, we investigated how specific musical expertise can mediate the relationship between movement and timing perception. In the present study, a group of highly trained percussionists ($n = 33$) and a group of non-percussionists ($n = 33$) were tested on their ability to detect temporal deviations of a tone presented after an isochronous sequence. Participants either tapped along with the sequence using a drumstick (movement condition) or listened without tapping (no-movement condition). Although both groups performed significantly better when moving than when listening alone, percussionists gained a greater benefit from tapping when detecting the smallest probe tone delays compared to non-percussionists. This complements both the musical expertise and timing perception literature by demonstrating that percussionists with high levels of training may further capitalize on the benefits of sensorimotor interactions. Surprisingly, percussionists and non-percussionists performed no differently when listening alone, in contrast to other studies examining the role of training in timing abilities. This raises interesting questions about the degree to which percussionists' known expertise in timing may interact with their use of motion when judging rhythmic precision.

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Introduction

Sensorimotor integration constitutes an intricate series of processes involving a combination of perception and action. These processes are crucial for achieving specific goals and making predictions about upcoming events, such as hitting a ball with a racket or stepping off a street curb. For complex activities such as playing a musical instrument or dancing, auditory–motor interactions rely on precise timing mechanisms to effectively integrate large quantities of information (Zatorre, Chen, & Penhune, 2007). Such musical activities require listeners to predict the timing of upcoming auditory events, based on previous information, and to subsequently execute movements at a particular time for movement to be synchronized with an upcoming temporal event and/or the movements of another individual. The bidirectional interplay between auditory and movement information is evident in simple tapping studies where auditory information encourages and guides motor timing (Aschersleben & Prinz, 1995, 1997; Mates, Radil, & Pöppel, 1992). Similarly, recent studies show that movement can influence subjective percepts of temporal information (Phillips-Silver & Trainor, 2007; Su & Pöppel, 2012) and even improve timing judgments (Iordanescu, Grabowecky, & Suzuki, 2013; Manning & Schutz, 2013, 2015). Typically, studies investigating sensorimotor integration implement tasks that measure timing change detection and/or simple movement synchronization (frequently finger tapping) with an external stimulus (reviewed in Repp, 2005). Simple tapping paradigms are useful for examining how movements are synchronized with a predictable auditory stimulus and can help expand our understanding of complex synchronized movements.

Although both musicians and nonmusicians can readily synchronize movements to sequences containing regularly spaced auditory events, musicians are particularly adept at timing movements with these external stimuli (Chen, Penhune, & Zatorre, 2008a; Repp, 1999). As such, musicians provide a useful view into expert temporal processing and motor timing, as well as their integration. By exploring musical training's impact on these tasks, we can gain insight into the degree that specialized training affects cross talk between movement and timing perception. Therefore, in the present study we investigate how musical expertise modulates the integration of timing information from multiple modalities.

Musical experience and timing abilities

Musicians generally show superior timing detection abilities across a broad range of tasks. For example, in duration-based timing tasks where participants compare the duration of two intervals, musicians outperform nonmusicians (Rammsayer & Altenmüller, 2006). Musicians also show lower detection thresholds (higher sensitivity) than nonmusicians for timing changes at the end of as well as within isochronous sequences (Jones, Jagacinski, Yee, Floyd, & Klapp, 1995; Jones & Yee, 1997; Lim, Bradshaw, Nicholls, & Altenmüller, 2003; Rammsayer & Altenmüller, 2006; Yee, Holleran, & Jones, 1994). This is particularly true in percussionists, who exhibit the lowest detection thresholds of all musician groups (Ehrlé & Samson, 2005). Musicians also show a greater sensitivity to structural components of temporal stimuli, including the degree of sequence isochrony (Jones & Yee, 1997; Madison & Merker, 2002; Yee et al., 1994) and changes in tempo (Drake & Botte, 1993). Musicians' enhanced sensitivity to timing may reflect their extensive experience attending to music's temporal structure. Alternatively, this may reflect a tendency for those who are adept at timing tasks to study music more extensively or successfully. Regardless, finely tuned timing abilities are crucial in coordinating movements with other musicians. However, little research on temporal discrimination in musicians explicitly explores how musicians' body movements, an integral component of musical timing, might influence their temporal discrimination abilities.

Musicians also exhibit superior motor timing abilities compared to nonmusicians. The negative mean asynchrony (NMA) prominently observed when tapping with an isochronous sequence (Aschersleben & Prinz, 1995; Aschersleben, 2002; Repp, 2000) is markedly smaller in amateur musicians compared to nonmusicians (often 10–30 vs. 20–80 ms, respectively; Aschersleben, 2002; Repp & Doggett, 2007), suggesting an expertise-driven improvement in perceived tap-tone synchrony. In professional musicians, the NMA is even smaller (sometimes approaching exact synchrony), even in sequences containing subthreshold deviations that resemble expressive timing in music (Repp, 1999). This may suggest graded improvements in synchronization abilities that arise with musical experience.

In addition to a lower reported NMA, musicians exhibit lower variability in tapping tasks than nonmusicians (Krause, Pollok, & Schnitzler, 2010; Repp & Doggett, 2007; Repp, London, & Keller, 2013; Repp, 2010). Since variability in movement timing is thought to reflect inaccuracies in the central timekeeper (Vorberg & Wing, 1996), this contrast in synchronization ability may represent perceptual as well as motor differences. Although it is difficult to identify whether these differences arise due to training or from selection effects, literature that examines musicians with varying types of training is consistent with the idea that musical experience does in fact drive these improvements. Movement synchronization in musicians appears to yield particularly low variability when musicians perform timing tasks using movements similar to those necessary to produce sound on their primary instrument (Keele, Pokorny, Corcos, & Ivry, 1985; Krause et al., 2010; Stoklasa, Liebermann, & Fischinger, 2012). For example, when string or wind players synchronize with a metronome, they are more accurate when using their instrument of training compared to when synchronizing through finger tapping (Stoklasa et al., 2012). Therefore, synchronization involving the movement effectors used on one's primary instrument of training may rely on complex, experience-driven sensorimotor representations (Krause et al., 2010).

Although a subset of research has focused on the relationship between enhanced movement timing and temporal processing in musically trained groups, the ways in which movement directly impacts perceived timing remain unclear. Participants (typically, musicians) demonstrating low variability in motor timing generally exhibit high sensitivity in timing discrimination tasks (Keele et al., 1985). Additionally, participants with high levels of rhythm-based musical expertise (in particular, percussionists) demonstrate superior synchronization abilities (small NMAs and low variability in tapping tasks) as well as finer temporal acuity compared to other musicians and nonmusicians (Cameron & Grahn, 2014; Krause et al., 2010). These comparisons between groups with varying levels of musical expertise indicate a relationship between perceptual and motor timing abilities, where musical expertise may act as a covariate. These behavioral studies, in addition to many neuroimaging studies (Bengtsson et al., 2009; Chen, Penhune, & Zatorre, 2008b; Grahn & Brett, 2007; Grahn & Rowe, 2009), offer evidence for a common timing mechanism that might exist for separately measured perception and movement abilities. However, further examinations of auditory–motor interactions in the same task by demonstrating the ways in which movement can modify auditory perception provide compelling support for a common source for timing abilities.

Assessing the effects of training on sensorimotor interactions

Exploring the relationship between musical expertise and timing abilities (both perceptual and motor) sheds light on broader links between perception and action. For example, if musical expertise in a specific domain (i.e., percussion) leads to improvements in associated motor abilities (i.e., tapping) and perceptual abilities (i.e., detecting the timing of rhythmic stimuli), this suggests that improvements may be specific to the focus of the musical training. Therefore, the ideal way to pursue this movement–timing relationship in a musical population is by studying participants who are not only musically trained, but trained to implement specific types of movements for synchronizing. Given previous research demonstrating short-term improvements in motor timing specific to the particular movement effector (i.e., finger, drumstick, etc.) used throughout training (Madison, Karampela, Ullén, & Holm, 2013), this is also an important issue for motor learning more generally.

To explore the role of musical expertise and associated trained movement, here we explicitly investigate how movement impacts timing perception in percussionists, a subset of musicians specializing in the use of tapping-like movements. Percussionists are ideal for this type of exploration, as they exhibit the greatest timing acuity (Ehrlé & Samson, 2005), as well as the most consistent movement synchronization (Cameron & Grahn, 2014; Krause et al., 2010) of all musicians. In the present study, a group of trained percussionists and a group of non-percussionists (with varying levels of musical experience) listened to an isochronous sequence while either tapping along with a drumstick or listening without movement, and identified temporal deviations at the end of this sequence in a two-alternative forced choice (2AFC) task. Similar studies that examine the relationship between perceived timing and movement typically use subjective tasks that report movement-related changes in pulse extraction (Su & Pöppel, 2012) and beat grouping (Phillips-Silver & Trainor, 2007). This study uses an objective measure to explore not just changes, but movement-related improvements to timing abilities.

Here, we assessed the effect of musical expertise on sensorimotor integration by asking participants to make judgments about a rhythmic sequence while either tapping along or listening without moving. We found previously that participants (with or without musical training) were better able to detect timing changes at the end of a sequence when tapping with the sequence, particularly when the probe tone occurred later than expected (Manning & Schutz, 2013). Additionally, in a follow-up study where we masked the sound of taps using white noise, we found that this improvement in perceived timing was not due to auditory feedback from the synchronized movement, but instead due to the movement itself (Manning & Schutz, 2015). Due to musicians' superior sensitivity in timing perception tasks (Madison & Merker, 2002; Rammsayer & Altenmüller, 2006), in particular percussionists (Ehrlé & Samson, 2005), here we expected percussionists to perform better than non-percussionists. Because musicians tend to exhibit more accurate motor timing (Krause et al., 2010; Repp et al., 2013; Repp, 2010), particularly when implementing movements pertaining to their instrument of training (Keele et al., 1985; Stoklasa et al., 2012), we predicted that percussionists would also exhibit lower tapping variability and smaller NMAs than nonpercussionists. Due to the amount of movement inherently required for playing percussion instruments (i.e., striking a drum), we expected that percussionists would more accurately detect temporal deviations than non-percussionists when tapping along with the sequence. If more accurate movement timing in musicians leads to more accurate timing discrimination in this task due to a common timing mechanism for movement and perception (as proposed in correlational studies by Keele et al., 1985 and Krause et al., 2010), we expected that percussionists would benefit more from movement than non-percussionists (i.e., observe a greater perceptual timing advantage). By directly comparing performance in a timing detection task that involves either moving along or listening without movement, these findings contribute to our understanding of the overlap in perceptual timing enhancements and accuracy of motor timing reported in musicians, specifically in percussionists. These findings will also shed light on the degree to which percussionists rely on movement as a cue for timing in musical performance.

Method

Participants

Two groups of participants completed this experiment. The first group (hereafter "percussionists") consisted of 33 (24 male, 9 female) participants, ranging in age from

17–42 years ($M = 24.33$, SD = 7.19). All members of this group currently played in a percussion ensemble, had between 1 and 24 years of formal percussion training ($M = 9.18$, SD = 5.62), and had been playing percussion instruments for 5–33 years ($M = 13.36$, SD = 8.07). These participants either played in percussion ensembles at McMaster University, University of Toronto, or Western University, were members of a professional percussion quartet, or were percussionists attending the Percussive Arts Society International Convention (PASIC) in November 2013 and volunteered to participate. All but two percussionists had some musical training in other instruments (0–18 years; $M = 6.48$, SD = 4.66).

The second group consisted of 33 participants (18 female, 15 male) ranging in age from 17 to 25 years ($M = 18.73$, SD = 1.51) who were recruited from the McMaster University psychology participant pool in exchange for course credit. These participants (hereafter "non-percussionists") had varying degrees of musical training (0–15 years; $M = 6.79$, SD = 4.39); all but four non-percussionists had some musical training and none had percussion training. Percussionist and non-percussionist groups did not differ in years of training on instruments other than percussion ($t(64) = 0.27$, $p = .788$); however, the percussionist group included more males than the non-percussionist group, due to a gender imbalance in instrument choice in the population. Both groups reported normal hearing and normal or corrected-to-normal vision and tapped with their dominant hand. We excluded four of the original 37 participants from the percussionist group and three of the original 36 participants from the non-percussionist group based on our exclusion criteria described below in the "Design and procedure". This experiment met ethics standards according to the McMaster University Research Ethics Board.

Stimuli and apparatus

We conducted the experiment using a software package developed specifically for this paradigm (Manning & Schutz, 2013). Each trial began with a MIDI sequence consisting of 13 woodblock sounds (gmBank = 115) presented at an inter-onset interval (IOI) of 500 ms (120 beats-per-minute). Since imposing meter on a sequence of beats affords enhancements in temporal encoding and attention (Essens & Povel, 1985; Grube & Griffiths, 2009; Jones et al., 1995), we divided the tones into four groups (see Fig. 1), with the first tone of each group higher in pitch (C5; 523 Hz) than the remaining three (G4; 392 Hz) to evoke a 4/4 m. In the last group of tones (the "timekeeping" segment), the second, third and fourth "beats" were silent. A single additional woodblock sound (hereafter, "probe tone") followed this timekeeping segment; on half of the trials, the probe tone followed consistent timing with the sequence, and in the other half of the trials the probe tone occurred slightly late. Participants listened to the sequences through Sennheiser HDA200 headphones. An Alesis Trigger i/O Trigger-to-MIDI USB Interface converted signals from an electronic drum pad (Roland PDX-85 or PDX-100) into MIDI messages sent to an iMac computer.[1]

Design and procedure

Participants completed 64 trials grouped into eight blocks. Participants tapped along with the sequence on half of the blocks (movement condition) and listened without moving during the other blocks (no-movement condition). For half of the trials in each block, the probe tone occurred "on-time" (i.e., at an offset of 0 ms), while for the other half of the trials the probe tone occurred late at an offset of 15 % (75 ms) or 30 % (150 ms) of the IOI, and participants were aware of these potential probe tone alternatives. In a previous series of experiments we used a similar paradigm, where the probe tone fell on-time, early (15 and 30 % of the IOI) or late (15 and 30 % of the IOI) in movement and no-movement conditions (Manning & Schutz, 2013). These participants more accurately detected probe tone changes in the movement (relative to no-movement) condition only when the probe tone occurred late. Here, we include only on-time and late offsets in each movement condition as we did in a follow-up study (Manning & Schutz, 2015) to examine these differences with more granularity. Participants performed five warm-up trials and then completed the full experiment (four blocks of the movement condition and four blocks of the no-movement condition). We randomized the order of the experimental blocks and the order of the trials within each block for each participant.

Throughout the movement blocks participants tapped on each beat of the stimulus in all three segments (through the silence and including the probe tone; see Fig. 1) using an innovative percussion (IP-1) drumstick or equivalent on the electronic drum pad that recorded the timing of each tap. Throughout the no-movement blocks, we asked participants to remain as still as possible (i.e., refrain from foot tapping, head bobbing, etc.). In a 2AFC task, participants identified whether the probe tone in each trial was "on-time" (consistent with the timing of the repeated sequence of beats) or not, and indicated their confidence on a scale from 1 (not at all confident) through 5 (very confident). Participants were aware that the probe tone would occur either on-time or late (but never early). To help retain attention, participants received feedback on the correctness of these judgments.

[1] Accuracy of tap recording was verified in the experimental setup and tapping measurements were corrected for a constant latency in recording.

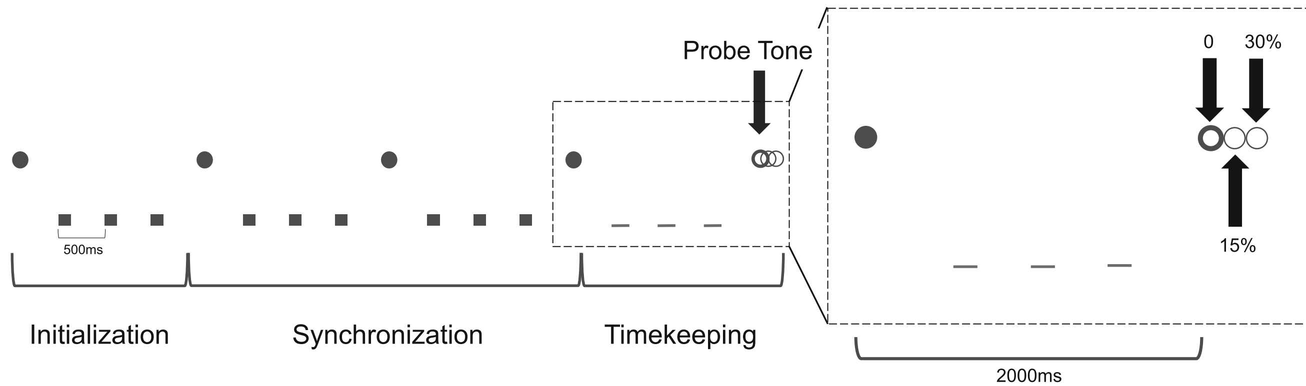

Fig. 1 Trial structure depicting the number of stimuli with initialization, synchronization, and timekeeping segments labeled. *Filled circles* represent the accented tones and *squares* represent unaccented tones in the initialization and synchronization segments. *Lines* indicate silent "beats" and empty circles are possible probe tone positions. The timekeeping segment is enlarged on the right to *highlight* probe tone offsets, and beats are spaced in 500 ms inter-onset intervals (IOIs)

Some participants were excluded from the original sample based on criteria set prior to the experiment. Consistent our previous criteria (Manning & Schutz, 2013), we excluded participants for tapping in more than 25 % of no-movement trials, failing to tap as instructed in more than 25 % of movement trials, or failing to tap on the probe tone for more than 25 % of trials. This led us to exclude four percussionists; one moved excessively during the no-movement condition (finger tapped on their leg), two tapped not only on each beat, but also between these beats (i.e., every 250 ms) in the movement condition, and one failed to tap in more than 25 % of beats in the movement trials. In the non-percussionist group, we excluded three participants: two for tapping throughout the no-movement condition on more than 25 % of trials and one for failing to tap on the probe tone for more than 25 % of trials.

Results

Perception

We examined the percentage of "on-time" responses for each movement condition and probe tone offset in both participant groups (see Fig. 2b) to visualize responses. Next, we computed a score (% of correct responses) in each of the movement (movement/no-movement) and offset (on-time, 15, 30 % late) conditions for each participant. Group performance (task score) differed in the movement trials ($t(64) = 4.06$, $p < .001$; two-tailed, independent samples t test; $d = 1.00$); however, there was no difference between group performance in the no-movement trials ($t(64) = 0.95$, $p = .344$). Pairwise comparisons with Bonferroni correction showed no difference in performance between groups in the different offsets of no-movement condition ($\alpha = 0.0167$); however, the difference between groups in the 30 % late probe tone offset condition approached significance ($t(64) = 2.11$, $p = .039$). We calculated the difference score (movement − no-movement score) to obtain a measure of the effect of movement on task performance (see Fig. 2a). Higher values for the effect of movement indicate a greater benefit for the movement condition than for the no-movement condition. We assessed the effect of movement using a mixed-model ANOVA with "group" as a between-subjects factor (2 levels: percussionist, non-percussionist) and "offset" as a within-subjects factor (3 levels: 0, 15, 30 % late). We found a significant interaction between group and offset ($F(2,128) = 17.87$, $p < .001$, $\eta^2 = 0.13$), indicating that the effect of movement for each group differed at one or more levels of the offset (see Fig. 2a). There was also a main effect of offset ($F(2,128) = 32.79$, $p < .001$, $\eta^2 = 0.21$), but the main effect of group did not reach significance ($F(1,64) = 3.05$, $p = .086$, $\eta^2 = 0.02$). Post hoc comparisons (Tukey HSD, $\alpha = 0.05$) showed significant differences between percussionists and non-percussionists in the effect of movement at the 15 % probe tone offset ($p < .001$; see Fig. 2b), where the timing judgment task was more difficult. Group differences between the effect of movement at the 30 % probe tone offset may be obscured due to a ceiling effect for the movement trials (see Fig. 2b), since accuracy is above 90 % for both groups in the movement trials only. Additionally, heteroscedasticity is violated for both percussionists (Levene's test; $F(1,64) = 52.34$, $p < .001$) and non-percussionists ($F(1,64) = 14.55$, $p < .001$) in these movement trials compared to the no-movement trials when the probe tone is 30 % late, further suggesting a ceiling effect for both groups for these conditions.

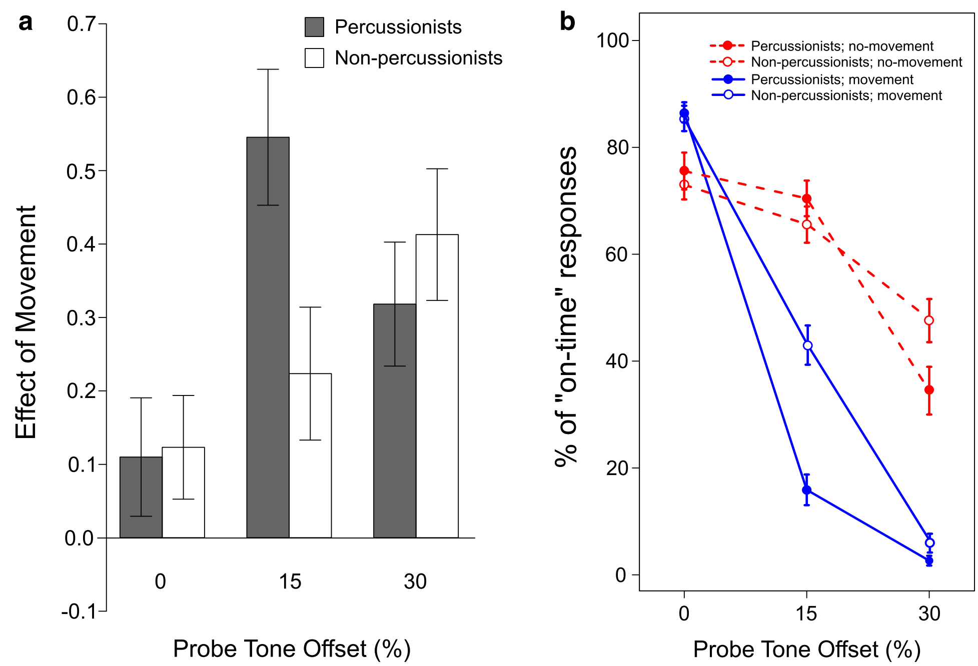

Fig. 2 Timing detection performance for percussionists and non-percussionists. **a** The effect of movement (movement score − no-movement task score) on timing judgments at each probe tone offset. **b** The proportion of "on-time" responses at each offset for each movement condition and group. *Error bars* indicate the standard error of the mean

Production

To quantify motor synchronization ability, we measured the signed tap asynchrony and the coefficient of variation (CV) of tapping for the synchronization segment of each movement trial (see Fig. 1). We also measured the signed tap asynchrony at the probe tone. Tap asynchronies for the synchronization segment were calculated by subtracting the tone onset time from the tap recorded by the electronic drum pad. The tap asynchrony for the probe tone was calculated by subtracting the expected probe tone onset from the recorded tap. Positive asynchronies indicate that taps fall after the sounded or expected tone, whereas negative asynchronies indicate that taps precede the tone. Asynchronies differed between percussionists and non-percussionists in both the synchronization ($t(64) = 6.03$, $p < .001$); two-tailed independent samples t test) and at the probe tone segments ($t(64) = 4.43$, $p < .001$) where percussionists showed smaller mean tap asynchronies compared to non-percussionists (see Fig. 3). We calculated the CV as a measure of tap variability by dividing the standard deviation of the inter-tap interval (ITI) by the mean ITI in each movement trial throughout the synchronization segment (see Fig. 4). Percussionists tapped significantly less variably than non-percussionists in the synchronization segment ($t(64) = 8.16$, $p < .001$).

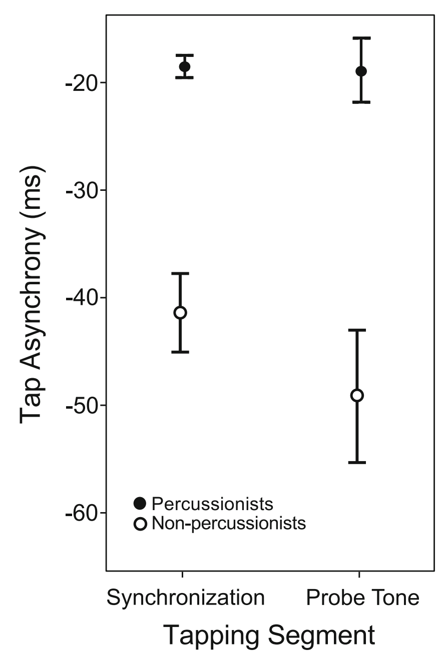

Fig. 3 The mean signed tap asynchrony in the synchronization and probe tone segments of trials plotted for percussionists and non-percussionists. *Error bars* represent the standard error of the mean

Perception and production interactions

Since we observed more accurate and consistent tapping and a greater effect of movement for percussionists compared to non-percussionists when the probe tone occurs slightly (15 %) late, we examined whether the differences varied systematically using Pearson's correlations between task performance and measures of tapping ability. Percussionists exhibited a significant correlation between task performance in the movement condition and mean tap asynchrony at the probe tone ($r(31) = -0.40$, $p = .020$),

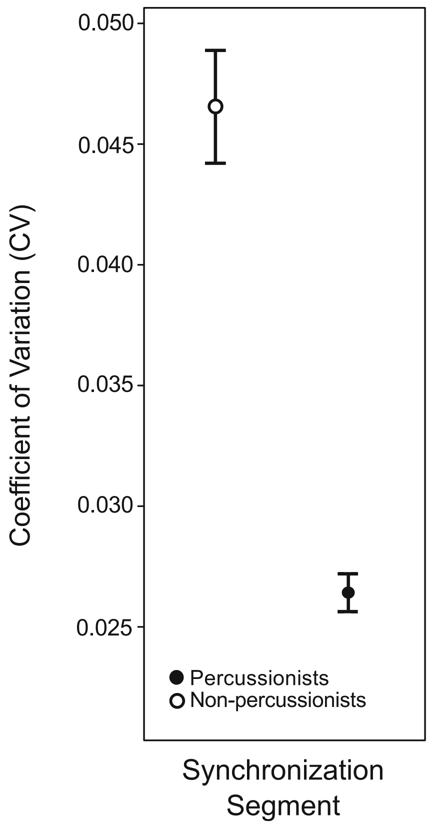

Fig. 4 The coefficient of variation (CV) during the synchronization segment of the trials for percussionists and non-percussionists. *Error bars* represent the standard error of the mean

indicating percussionists with lower tap asynchronies at the probe tone performed better on the movement trials. However, non-percussionists did not show this pattern ($r(31) = 0.01$, $p = .958$).[2] We also examined the relationship between the CV of tapping through the synchronization segment and performance in the movement trials and found a significant negative correlation for non-percussionists ($r(31) = -0.36$, $p = .038$), but no correlation for percussionists ($r(31) = -0.25$, $p = .162$). This indicates that non-percussionists who showed lower tapping variability (i.e., tapped more consistently) throughout the movement trials performed better on the probe tone discrimination task.

Additionally, we conducted a binary logistic regression analysis to determine whether timing of the final tap (adjacent to the probe tone) predicts the response outcome for each trial (either correct or incorrect). In the percussionist group, as tap asynchrony increased by 1 ms, the odds of correctly identifying the timing of the probe tone decreased by 1.64 % [$\chi^2 = 28.54$, $p < .001$; odds ratio (OR) = 0.984]. A similar pattern emerged for non-percussionists, where the odds of correctly identifying the timing of the probe tone decreased by 0.62 % [$\chi^2 = 42.60$, $p < .001$; odds ratio (OR) = 0.994] for every 1 ms increase of the tap asynchrony at the probe tone. This relationship suggests that the timing of the tap at the probe tone might be used to predict the response outcome of the trial, where more accurate tapping increases the probability of a correct timing judgment, particularly for percussionists.

Musical experience and task performance

We were also interested in exploring the relationship between task performance and measures of musical experience. Percussionists exhibited a significant correlation between years of experience playing percussion instruments and performance in the movement condition ($r(31) = 0.36$, $p = .042$). This relationship may indicate that those who are more experienced in playing percussion instruments perform better than those with less playing experience when tapping with the sequence, possibly due to experience synchronizing this type of movement with an external stimulus. However, there was no significant correlation between performance in the no-movement condition and years of formal percussion training ($r(31) = 0.01$, $p = .950$). In the non-percussionist group, we did not find a correlation between years of formal musical training and performance in the movement trials ($r(31) = -0.09$, $p = .610$) and the correlation between years of formal musical training and performance in the no-movement trials approached but did not reach significance ($r(31) = 0.32$, $p = .071$), showing little relationship between musical experience and task performance, perhaps due to a significant proportion of these non-percussionists having little or no formal musical training.

Discussion

In this study, we examined how movement facilitates timing perception in percussionists and non-percussionists. Both groups listened to a sequence of beats and identified the timing of an additional beat after a short period of silence having either tapped along using a drumstick or listened without moving. Consistent with our previous findings (Manning & Schutz, 2013, 2015), both groups performed better when tapping with the sequence compared to listening alone. However, here we extend our previous work in two important ways. First, our data demonstrate that percussionists benefit more from tapping than do non-percussionists, particularly when the task is more difficult (i.e., the 15 % offset condition, see Fig. 2). We suspect they would also have benefited more at the 30 % offset condition were it not for the ceiling effect

[2] Additional correlations are given in Online Resource 1.

(however, to preserve consistency with previous work we retained the same offset values). Future testing of intermediate offsets would help clarify the temporal window within which movement-related perceptual benefits differ between the groups. Our second and more surprising finding is that although percussionists demonstrated superior performance in the movement conditions, they did not outperform non-percussionists in the no-movement conditions, raising interesting questions regarding the degree to which percussionists depend on movement for timing. Our findings therefore complement previous perception-only experiments in which percussionists typically show greater sensitivity to timing changes (Ehrlé & Samson, 2005; Krause et al., 2010), but we observe this pattern only when percussionists are moving with the stimulus.

Additional interpretations

There are a few additional explanations for the greater movement-related improvements to temporal processing in percussionists compared to non-percussionists. First, we find that moving with an external beat facilitates perceived timing of subsequent temporal events. This may be due to movement enabling beat maintenance throughout the silent portion of the trial, where the pacing signal is not available, clearly demonstrating the supportive role movement plays in temporal processing (Iordanescu et al., 2013; Manning & Schutz, 2013; Su & Pöppel, 2012). However, here we find that percussionists receive a greater benefit from movement compared to non-percussionists. This may suggest that percussionists rely on movement information for timing more than non-percussionists, perhaps due to the reliability of their movement demonstrated through more consistent and accurate tapping that is thought to arise with training (see Figs. 3, 4; Aschersleben, 2002; Krause et al., 2010; Madison et al., 2013; Repp & Doggett, 2007). Anecdotally, percussionists reported difficulty in inhibiting movement slightly more than non-percussionists, an observation that supports this notion. Surprisingly, we did not observe a difference between percussionists and non-percussionists in the no-movement conditions, in contrast to studies reporting that percussionists perform significantly better than non-percussionists in listening-only timing tasks (Cicchini, Arrighi, Cecchetti, Giusti, & Burr, 2012; Ehrlé & Samson, 2005; Krause et al., 2010). This may be in part due to percussionists actively inhibiting movement in the no-movement trials, perhaps allocating more cognitive resources to avoid movement. We recognize that this could lead to worsened performance in no-movement conditions for the percussionists; however, it might also be the case for the non-percussionists who similarly reported some trouble with remaining still. Interestingly, this highlights the close relationship between movement and auditory timing abilities, and future studies should aim at identifying the importance of allocating attentional resources to movement inhibition through a similar task.

Another possible explanation for these findings is that the reported improvement in perceived timing with movement may be a product of effector-specific training (i.e., stick tapping in percussionists). Non-percussionists show higher consistency when tapping with a stick compared to a finger (Madison et al., 2013) and in our previous work benefited from stick-tapping movements even without prior training (Manning & Schutz, 2013, 2015). However, it is possible that percussionists' extensive training with stick tapping might have led to a greater advantage in terms of both tapping accuracy and the magnitude of the perceptual benefit. We plan to further explore the use of effectors and relative amounts of motor training in future experiments.

Additionally, the amount of movement-related sensory feedback present in each group might differ and this may contribute to performance differences. Our technical setup allowed only limited capture of participants' tapping force to the degree of sensory feedback, given that participants tapped quite forcefully, but percussionists did appear to tap with more force in general, perhaps due to experience playing instruments requiring a fair amount of movement to produce sound. This might lead to differences in sensory feedback, particularly in auditory and tactile feedback. Although we know that auditory feedback is helpful in guiding movement timing, its presence is not essential for movement to benefit perceived timing (Manning & Schutz, 2015). However, with more forceful tapping participants would also receive more tactile feedback, which facilitates motor timing (Wing, Doumas, & Welchman, 2010) and this additional sensory information may enhance subsequent perceptual abilities.

We note finally that percussionists in our study volunteered their time to participate in the experiment, whereas non-percussionists received course credit. Although this might lead to differences in motivation between the groups, it is important to note that we did not find differences between group performance in the no-movement trials. Moreover, as we were primarily interested in the effect of movement, a within-subjects variable, a difference in motivation would not undermine our primary question of interest (i.e., the effect of movement on task performance in percussionists vs. non-percussionists).

Production and perception interactions

Consistent with research on tapping and musical training, the present data demonstrate that percussionists exhibit tapping that is more accurate (denoted by smaller tap asynchronies) and less variable (lower CVs) compared to non-percussionists. This finding complements literature showing smaller NMAs produced by musicians compared to non-musicians (Aschersleben & Prinz, 1995; Repp, 1999) and less variable tapping for musicians compared to nonmusicians (Krause et al., 2010; Repp & Doggett, 2007; Repp et al., 2013), particularly for percussionists (Krause et al., 2010). Interestingly, this is especially true when musicians implement movements pertaining to their instrument of training (Keele et al., 1985; Stoklasa et al., 2012). Here, we measure motor timing using a tapping task, which is most like movements executed by percussionists. Although these tapping movements improve timing perception for both groups, they provide greater benefit to the group for whom they are consistent with their extensive training.

In percussionists and non-percussionists, tap asynchrony at the probe tone predicted response accuracy, suggesting a dependence on the timing of movement proximal to the probe tone (response target) for timing judgments. Previously, we demonstrated that movement improves timing abilities (Manning & Schutz, 2013, 2015); here, we build on this by showing that movement timing further improves timing detection, where more accurate motor timing prior to the response (such as that observed in percussionists) leads to greater accuracy in the timing detection task. We also found a correlation between performance in the movement condition and tapping variability in non-percussionists, where less variable tapping may have led to better task performance. Contrary to non-percussionists, there was no correlation between task performance in the movement conditions and tapping variability in percussionists, a correlation that was observed between tapping measures and performance in a timing perception task with musicians and nonmusicians (Keele et al., 1985; Krause et al., 2010). This may be due to percussionists' very low measures of tapping variability (Fig. 4) or exceptional performance on the probe tone task in the movement condition, but further investigation is necessary to determine if these measures of tapping quality and perceptual abilities are related in percussionists.

Interactions with musical experience

We examined musical experience both as a function of years of formal lessons and years of playing a given instrument to index the amount of practice participants have not only with musical practice, but also with executing movements in musical situations. The analyses between musical experience and task performance yielded a correlation between performance in the movement condition and years of percussion playing in percussionists, but no correlation between score in the no-movement condition and years of playing. This lends further support to the notion that percussionists gain a greater timing benefit when moving, and their capacity for precise timing may to some extent require movement. This finding complements literature that reports musicians' superior timing detection abilities compared to nonmusicians (Ehrlé & Samson, 2005; Madison & Merker, 2002; Rammsayer & Altenmüller, 2006) and suggests a complex interaction between musical training, movement, and timing abilities. It is possible that these differences are due to explicit training; however, it is important to note that pre-existing differences between movement abilities and musical proficiency or instrument choice can also play a role in these assessments. Here, we contribute to this literature by demonstrating that improved task performance may be specific to conditions that employ movement for keeping time, particularly practiced movement.

Contributions to theories of perception and action

More broadly, our study contributes to common coding theories of perception and action (Hommel, Müsseler, Aschersleben, & Prinz, 2001; Prinz, 1997; Repp, London, & Keller, 2011) as well as neural accounts describing overlapping cortical regions for motor planning and execution and beat perception (Grahn & Brett, 2007) in addition to more pronounced auditory–motor neural coupling in musically trained participants (Baumann et al., 2007; Chen et al., 2008b; Grahn & Rowe, 2009; Haueisen & Knösche, 2001). Additionally, these findings are in line with the embodied account of a forward internal model of action describing how action influences perception (Maes, Leman, Palmer, & Wanderley, 2014). Here, we also provide further evidence for the notion that when movements synchronize periodically with an external beat this may set up expectations for upcoming temporal events through auditory–motor interactions (Iversen, Repp, & Patel, 2009; Patel & Iversen, 2014). In conjunction with these accounts of action influencing perception, we argue that movement sharpens the perception of periodic auditory events, and extensive training with task-consistent movements enhances this interaction.

Conclusion

As a whole, this study shows that movement improves timing detection abilities and this improvement is mediated by musical expertise. Additionally, it presents the possibility that percussionists' superior timing abilities might to some degree be dependent upon movement, as they outperformed non-percussionists when moving with the stimulus, but did not perform any better than non-percussionists when completing the detection task without movement. Although it is possible that actively inhibiting movement plays a role in this finding, future studies should address the degree to which this might divert attention from the timing task. Percussionists tapped more accurately and consistently, which likely both reflects and enhances their internal representation of timing. Superior motor timing and improvements in timing judgments in percussionists while tapping with a drumstick may be a product of effector-specific training, and future research should address whether musicians with expertise using different types of motor synchronization experience similar movement-related improvements in perception. This finding extends literature on links between perception and action in addition to training-specific movements by showing that high levels of training might lead percussionists to acquire greater timing benefits from auditory–motor interactions.

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