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RESEARCH ARTICLE

Temporal prediction abilities are mediated by motor effector and rhythmic expertise

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Abstract Motor synchronization is a critical part of musical performance and listening. Recently, motor control research has described how movements that contain more available degrees of freedom are more accurately timed. Previously, we demonstrated that stick tapping improves perception in a timing detection task, where percussionists greatly outperformed non-percussionists only when tapping along. Since most synchronization studies implement finger tapping to examine simple motor synchronization, here we completed a similar task where percussionists and non-percussionists synchronized using finger tapping; movement with fewer degrees of freedom than stick tapping. Percussionists and non-percussionists listened to an isochronous beat sequence and identified the timing of a probe tone. On half of the trials, they tapped along with their index finger, and on the other half of the trials, they listened without moving prior to making timing judgments. We found that both groups benefited from tapping overall. Interestingly, percussionists performed only marginally better than did non-percussionists when finger tapping and no different when listening alone, differing from past studies reporting highly superior timing abilities in percussionists. Additionally, we found that percussionist finger tapping was less variable and less asynchronous than was non-percussionist tapping. Moreover, in both groups finger tapping was more variable and more asynchronous than stick tapping in our previous study. This study demonstrates that the motor effector implemented in tapping studies affects not only synchronization abilities, but also subsequent prediction abilities. We discuss these findings in light of effector-specific training and degrees of freedom in motor timing, both of which impact timing abilities to different extents.

Keywords Finger tapping · Sensorimotor integration · Movement timing · Motor effector · Musical training

Introduction

Extracting regularities from auditory sequences, predicting events in time, and synchronizing movements to those events involves a complex series of multisensory processes. This seemingly simple behavior is an automatic and often unconscious response to regularities in musical sequences. Motor synchronization requires the integration of sensory information from various modalities in order to optimally produce action-based effects on perceptual information (Hommel et al. 2001; Morillon et al. 2015; Wing et al. 2010). Since sensorimotor synchronization is multisensory in nature and includes both perception and production, many studies suggest a common timing process involved in perception and production for separately measured temporal acuity and motor timing in behavioral tasks (Cameron and Grahn 2014; Keele et al. 1985; Krause et al. 2010) and in neuroimaging studies (Bengtsson et al. 2009; Chen et al. 2008; Grahn and Brett 2007; Grahn and Rowe 2009). This is further supported by studies that explicitly examine changes to perception that arise from movement (Chemin et al. 2014; Phillips-Silver and Trainor 2007; Su and Pöppel 2012) and improvements to perceived timing due to synchronized movement (Butler and Trainor 2015; Iordanescu et al. 2013; Manning and Schutz 2013, 2015). The

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present study addresses the extent to which synchronized movement using different motor effectors (i.e., parts of the body that execute movement) interacts with movement expertise to affect subsequent perceptual abilities.

Since motor timing has substantial effects on temporal prediction, it is important to examine various types of motor synchronization used by populations that implement different amounts and types of synchronization experience. Although a subset of studies report differences between motor timing abilities in different musician groups (Cameron and Grahn 2014; Krause et al. 2010), other recent evidence documents no difference in finger tapping measures between musicians trained on different instruments (Matthews et al. 2016). Furthermore, musicians time their movements most accurately when synchronizing movements consistent with their instrument of training (Fujii et al. 2011; Stoklasa et al. 2012). Recently, we reported substantial improvements in timing detection abilities in percussionists following stick tapping movements (Manning and Schutz 2016). The present study aims to extend these findings by explicitly examining how the timing of finger tapping impacts auditory prediction abilities in percussionists and non-percussionists. We completed the present study comparing experienced percussionists with non-percussionists to address the role of movement experience in sensorimotor integration. Percussionists typically have extensive training with drumstick tapping but not necessarily with finger tapping—the type of movement typically used in motor synchronization studies. Consequently, this study will clarify whether movements executed using different motor effectors are controlled and regulated by a shared timing process in populations with and without effector-specific training, and whether this information is similarly used to inform temporal prediction.

Temporal prediction and musical experience

Temporal prediction and motor production abilities are both affected by musical experience. Musicians demonstrate superior temporal acuity compared to nonmusicians (Rammsayer and Altenmüller 2006) both in identifying global elements of musical structure (Drake and Botte 1993; Ehrlé and Samson 2005; Madison and Merker 2002; Yee et al. 1994) and in discriminating the timing of single events in a sequence (Jones et al. 1995; Jones and Yee 1997; Lim et al. 2003; Yee et al. 1994). Although any musical experience seems to play a role in refined temporal acuity (Matthews, et al. 2016), percussionists show the most sophisticated timing acuity of all musicians (Ehrlé and Samson 2005; Krause et al. 2010), which may reflect specialized training in situations that involve sensorimotor synchronization.

Motor synchronization and musical experience

Synchronization studies that address motor timing questions typically employ simple finger tapping paradigms due to its ubiquity and simplicity in recording (see Repp 2005 for a review). Those with or without musical training can readily tap at many tempi (Madison 2001; Repp and Keller 2004; Repp 2003) and with various types of complex stimuli (Hove et al. 2013; Repp et al. 2008, 2011; Snyder et al. 2006; Ullal-Gupta et al. 2014). While synchronizing finger movements with isochronous auditory events, participants tend to show a negative mean asynchrony (NMA), tapping slightly in advance of the anticipated events, which is thought to reflect temporal prediction (Aschersleben and Prinz 1995; Aschersleben 2002; Mates et al. 1992; Repp 2000). Differences in the NMA appear to vary as a function of musical experience, where participants with greater levels of musical training show smaller tap asynchronies compared to those with little or no musical experience (Aschersleben 2002; Repp and Doggett 2007; Repp 1999). Musicians also tap with lower variability than do nonmusicians (Repp and Doggett 2007; Repp et al. 2013; Repp 2010), reflecting greater consistency in motor production. This is especially true for percussionists who show extremely low variability in tapping (Cameron and Grahn 2014; Fujii et al. 2011; Krause et al. 2010; Manning and Schutz 2016) and for musicians who synchronize using movements most similar to those used while playing their instrument of training (Stoklasa, et al. 2012; Manning and Schutz 2016). While it is difficult to distinguish whether explicit training is causing these improvements, or whether a propensity for well-timed movements leads individuals to pursue musical training, it is clear that short-term practice leads to considerable improvements in tapping variability (Madison et al. 2013), which offers further support for the idea that training is a possible source of these abilities.

Motor effector comparisons in sensorimotor synchronization research

Although finger tapping is most commonly used to examine motor timing, some studies have compared timing across various motor effectors. Movements reflect patterns in auditory structure, where larger motor effectors tend to synchronize with higher levels of a metrical hierarchy (i.e., at a slower rate) than do smaller motor effectors (Toiviainen et al. 2010). There is some evidence that synchronization ability is correlated across effectors (Fujii et al. 2011; Keele et al. 1985), suggesting a common mechanism for timed movements. However, different effectors synchronize with varying degrees of success, where, for example, foot tapping shows greater asynchronies than hand tapping (Aschersleben and Prinz 1995; Fraisse 1982; Fujii et al. 2011). Interestingly, while variability decreases with practice across both effectors (Madison et al. 2013), finger tapping is significantly more variable (Collier and Ogden 2004; Madison 2001) than tapping using a drumstick (Fujii and Oda 2009; Madison and Delignières 2009). There are many differences between finger tapping and stick tapping that could explain these differences in timing including the weight of the object in stick tapping, the amount of experience executing each type of movement and the trajectory of the movements. Additionally, the amount and integration of auditory and tactile feedback produced by each movement impacts synchronization (Finney 1997; Maduell and Wing 2007; Wing 1977), where the timing of movements is more precise when multiple sources of sensory information are integrated (Wing et al. 2010). Furthermore, experience with a specific effector leads to more accurate motor timing using that effector, but this may not generalize to other effectors (Stoklasa et al. 2012).

The motor control literature often describes differences between movements based on many features. This includes descriptions of the motor redundancy for movements, which suggest that in order to execute a movement the system must eliminate redundant degrees of freedom—factors that are independently varied (Bernstein 1967). More recently, this has been described instead as an abundance of options for movement manipulation (Latash 2000, 2012, 2014; Todorov and Jordan 2002), such as the use of different joints or combinations of joints available to be varied to accomplish goal-oriented action. Movements containing more available degrees of freedom are more accurately timed than movements that contain fewer available degrees of freedom (Verrel et al. 2013; Winold et al. 1994). This is an important consideration for comparing synchronization in different motor effectors and examining how their timing leads to perceptual differences. In the current study, we consider this view by examining the timing of finger tapping using the metacarpophalangeal joint (i.e., the knuckle), which depends on only one degree of freedom. This synchronization study is conducted with percussionists, who are trained extensively with stick tapping motions, and non-percussionists.

Current study

The present study explicitly examines the extent to which motor timing abilities are generalized from one effector to another and similarly integrated with auditory information. Previously, we found that participants are better at identifying timing changes after tapping along with the sequence using a drumstick compared to when listening alone, regardless of their level of musical training (Manning and Schutz 2013). When we examined percussionists, musicians that are familiar with drumstick tapping, we found that percussionists received a greater perceptual benefit from movement, but perform no different to non-percussionists when completing the same task without movement (Manning and Schutz 2016). This suggests that percussionists may rely on movement for their superior abilities in temporal prediction. However, this calls into question whether percussionists' improvements are restricted to the movements used while playing and practicing, reflecting task-specific motor abilities. Alternatively, these improvements may extend to all timed movements, demonstrating a general refinement in motor proficiency.

Since finger tapping is widely used in sensorimotor synchronization research to index motor timing (Repp 2005), here we examine whether documented improvement to perception following movements also exists for finger tapping. If percussionists gain larger movement-related enhancements to perception compared to non-percussionists while *finger tapping*, this might suggest a common motor representation for multiple effectors (consistent with Fujii et al. 2011; Keele et al. 1985) that leads to these motor and perceptual benefits. However, if percussionists do not receive the same perceptual benefit while finger tapping as previously observed when stick tapping (Manning and Schutz 2016), this would suggest that these benefits arise at least in part from experience with a specific motor effector and may not generalize to movements of all effectors. We expect that finger tapping will lead to perceptual improvements for both percussionists and non-percussionists. In light of recent evidence reporting no differences between musician groups for finger tapping performance or perceptual abilities (Matthews et al. 2016), we do not expect to observe large differences between percussionists and non-percussionists perceptual timing judgments as observed following stick tapping (Manning and Schutz 2016). We predict that this will arise from more variable (and perhaps less reliable) motor timing information, since timed finger tapping movements are less consistent than stick tapping movements (Madison et al. 2013). This would demonstrate how strongly the quality of motor timing directly influences temporal prediction abilities. Additionally, this would suggest that rhythmic motor training does not impact general listening abilities, but instead may depend on specific motor training.

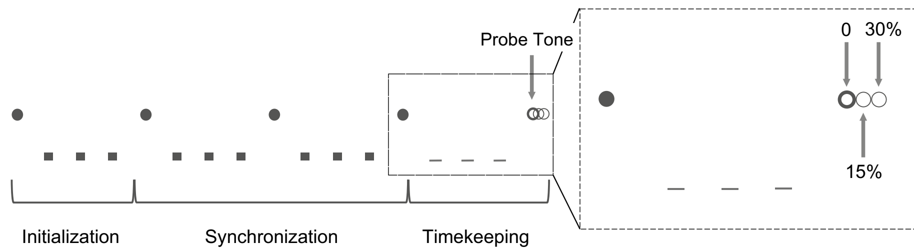

Fig. 1 Single trial depicted with labeled segments. The *circles* represent accented beats, while the *squares* represent unaccented beats. The final grouping is enlarged to highlight silent "beats" (*black lines*) and possible probe tone offsets (*unfilled circles*)

Method

Participants

Participants consisted of two groups. The first group included 28 trained percussionist volunteers, hereafter "percussionists," (21 males and 7 females; 17–65 years of age, $M = 30.50$, SD = 12.31) with varying degrees of percussion training (2–20 years, $M = 10.46$, SD = 5.54), who attended the Percussion Arts Society International Convention (PASIC) in November 2013. The second group included 29 undergraduate "non-percussionists" (6 males and 23 females; 17–24 years of age, $M = 19.00$, SD = 1.32), who were students from the McMaster University psychology participant pool who received course credit for participating in this experiment. Non-percussionists had varying degrees of formal musical training (0–13 years, $M = 5.24$, SD = 4.10), but none were expert musicians nor did any play percussion instruments. Participant groups did not differ in years of musical training on instruments other than percussion ($t(55) = 0.541$, $p = .591$). All participants reported normal hearing and tapped with their dominant hand. Participants gave written informed consent prior to the study in accordance with the McMaster University Research Ethics Board.

Stimuli and apparatus

Stimuli were identical to those used in a previous study (Manning and Schutz 2016) and presented with customized software that played MIDI "woodblock" sounds (gmBank = 115) through Sennheiser HDA200 headphones. The stimuli consisted of a sequence of beats presented at an inter-onset interval (IOI) of 500 ms (120 bpm). The beats were grouped together with four beats per grouping and each grouping repeated four times within one trial (see Fig. 1). The first beat of each grouping was of higher relative pitch (C5; 523 Hz) than the three subsequent beats (G4; 392 Hz) to induce a sense of meter and to orient attention through the trial. In the fourth repetition of the grouping, the unaccented beats were silent. After the silent segment of the trial, one final probe tone occurred. On half of the trials, this probe tone occurred on-time with the previous sequence (at an offset of 0 ms), and on the other half of the trials, the probe tone occurred later than anticipated at one of two offsets; 15% of the IOI late (+75 ms) or 30% of the IOI late (+150 ms). An electronic hand percussion pad (Roland Handsonic 10) connected to an Alesis Trigger i/O Trigger-to-MIDI USB Interface converted finger tapping into MIDI messages sent to a MacBook Pro.[1]

Design and procedure

Participants completed 64 trials separated into eight blocks. On half of the trials (movement condition), participants tapped along with the sequence using the index finger (metacarpophalangeal joint movement) of their dominant hand throughout all segments up to and including the probe tone (see Fig. 1). On the other half of the trials (no-movement condition), participants were instructed to remain completely still (e.g., no foot tapping or head bobbing). Blocks randomly alternated between movement/no-movement conditions, and within each block, four trials contained a probe tone that was on-time, and four trials contained a late probe tone at one of two offsets. Participants listened to each trial and, in a two-choice task, identified whether the probe tone was consistent with the timing of the sequence ("on-time") or not and indicated their confidence on a scale from 1 (not at all confident) to 5 (very confident). Participants received feedback on the correctness of their responses to retain attention and motivation. Participants completed five warm-up trails to ensure task understanding before proceeding with the rest of the experiment. The order of trials within each block was randomized for each participant.

Results

Timing judgments

First, we identified the proportion of "on-time" responses for visualization (see Fig. 2c). Next, we computed the

[1] The accuracy of tap recording was verified in the experimental setup and tap onset recordings were corrected for using a consistent latency value through the recording.

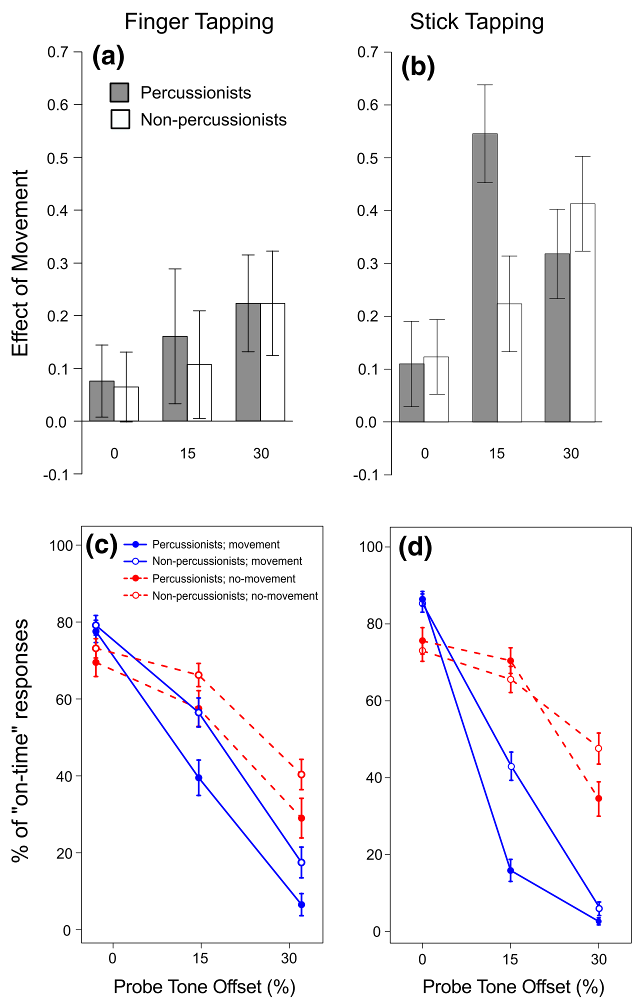

Fig. 2 **a**, **b** Depict the effect of movement (movement task score–no-movement task score) on timing judgments at each probe tone offset for each group. **c**, **d** Display the percentage of "on-time" responses at each offset for each movement condition and group. **a**, **c** Contain data from the current study and **b**, **d** contain data from our previous study (Manning and Schutz 2016). *Error bars* indicate the standard error of the mean

response accuracy for each participant in the movement and no-movement conditions by calculating the proportion of correct identifications of the probe tone timing for each trial in the task. We computed a 2 (movement condition) × 3 (probe tone offset) × 2 (participant group) mixed-model ANOVA to assess differences. We observed a two-way interaction between movement condition and probe tone offset ($F(2,110) = 23.61$, $p < .001$, $\eta^2 = 0.081$), but no three-way interaction and no other two-way interactions. We also observed a main effect of group ($F(1,55) = 16.27$, $p < .001$, $\eta^2 = 0.059$), a main effect of movement condition ($F(1,55) = 20.34$, $p < .001$, $\eta^2 = 0.051$), and a main effect of probe tone offset ($F(2,110) = 119.90$, $p < .001$, $\eta^2 = 0.487$). Pairwise comparisons between group performance with Bonferroni correction ($\alpha = .0167$) in the movement condition showed a significant difference between groups at the 15% late probe tone ($t(55) = 2.801$, $p = .007$) and the 30 percent offset ($t(55) = 2.607$, $p = .012$), but showed no difference between groups in the different offsets of the no-movement condition.

Next, we subtracted the no-movement accuracy from the movement accuracy values for each participant at each probe tone offset to assess an effect of movement on task performance, which represents the degree to which finger tapping improved timing detection abilities (Fig. 2a). We conducted an ANOVA on the effect of movement on task performance against zero. These values were significantly greater than 0 in non-percussionists ($F(2,54) = 3.54$, $p = .036$, $\eta^2 = 0.079$) and approached significance in percussionists ($F(2,54) = 2.82$, $p = .068$, $\eta^2 = 0.055$),[2] indicating that finger tapping facilitated task performance in both groups. We conducted a 2 (group) × 3 (offset) mixed-model ANOVA on the effect of movement difference scores as the dependent measure to index the degree to which the benefit of tapping changed as a function of group and probe tone offset. We did not find a main effect of group ($F(1,55) = 0.470$, $p = .496$), nor did we find an interaction between group and offset ($F(2,110) = 0.385$, $p = .681$), showing no difference between the percussionist and non-percussionist effects of movement difference scores when finger tapping. We did find a main effect of probe tone offset ($F(2,110) = 6.843$, $p = .002$, $\eta^2 = .069$), demonstrating that movement affected performance differently for different offsets.

Tapping

We examined finger tapping in two ways. First we quantified the variance associated with taps by computing the coefficient of variation (CV) of tapping in the synchronization segment of the trials for each group (see Fig. 1). To obtain the CV, we first calculated the inter-tap intervals (i.e., the time elapsed between two subsequent taps) in each trial for each subject. We computed the standard deviation of the inter-tap intervals of each trial and divided by the mean inter-tap interval to obtain the CV, indexing the tapping variability in each sequence. We conducted subsequent analyses using the mean CV for each participant to assess differences in tapping variability between groups. Non-percussionists tapped with slightly more variability than did percussionists ($t(55) = 1.908$, $p = .062$) in the synchronization segment of the trial (see Fig. 3a).

[2] Figure 2a visually appears to contradict this statement, however the variance for percussionists is slightly greater than that of non-percussionists, which might explain the marginally significant effect observed for non-percussionists only. We performed a Levene's test to identify whether variances were homogeneous and found no difference between variances in the groups ($F = 0.94$, $p = .513$).

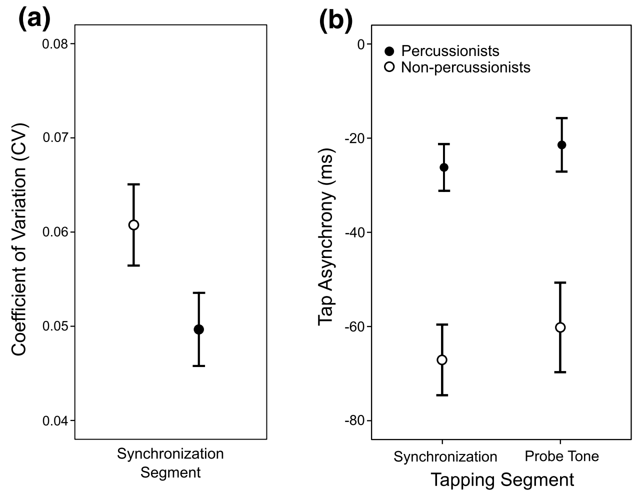

Fig. 3 Coefficient of variation in the synchronization segment of the beat sequence (**a**) and mean finger tap asynchronies in the synchronization and probe tone segments of the sequence (**b**) for percussionists and non-percussionists. *Error bars* indicate the standard error of the mean

We also assessed the signed tap asynchrony by subtracting the timing of the onset of each beat to the onset of the corresponding tap. A negative asynchrony indicates that taps preceded tone onset, while a positive asynchrony indicates that taps followed tone onset. We measured the tap asynchrony both throughout the synchronization segment of the trials and at the expected probe tone position. While both groups showed a NMA (see Fig. 3b), the asynchrony was significantly smaller for percussionists compared to non-percussionists both through the synchronization segment ($t(55) = 4.511$, $p < .0001$) and at the expected probe tone position ($t(55) = 3.470$, $p = .001$). This indicated that finger tapping was more aligned with the beat sequence for percussionists compared to non-percussionists.

Comparison between stick tapping and finger tapping

In a previous study, we examined perceptual and motor timing abilities in percussionists and non-percussionists with stick tapping in a similar task (Manning and Schutz 2016). There we found that percussionists outperformed non-percussionists in the movement trials, but performed no differently from non-percussionists in the no-movement trials. This raised questions surrounding whether it was percussionists' experience using a drumstick led to superior movement timing and therefore improvements in task performance while stick tapping. Here, we compare task performance while finger tapping to our previous study with stick tapping. We conducted a 2(motor effector) × 2(participant group) factorial ANOVA on the effect of movement on task performance (i.e., difference in response accuracy between movement and no-movement trials) to assess differences across percussionists and non-percussionists across different motor effectors. We found a significant interaction between motor effector and participant group ($F(3,362) = 10.29$, $p < .001$, $\eta^2 = 0.064$) demonstrating differences in the effect of movement on perception in each condition. This suggests a difference in the effect of movement on performance based on the motor effector used for synchronization as a function of participant group. We also observed a main effect of motor effector ($F(1,362) = 27.10$, $p < .001$, $\eta^2 = 0.073$), but no main effect of participant group ($F(2,362) = 1.89$, $p = .153$).

When we examined the quality of tapping between studies, there was significantly greater variability in the CV measures for finger tapping compared to stick tapping for percussionists ($t(68) = 3.27$, $p < .001$) and non-percussionists ($t(68) = 4.17$, $p < .001$) (Manning and Schutz 2016). We also found significantly greater tap asynchronies for finger tapping compared to stick tapping in percussionists ($t(68) = 2.91$, $p = .009$) and non-percussionists ($t(68) = 2.51$, $p = .014$). This shows that finger tapping is more variable and less accurate in both percussionists and non-percussionists compared to stick tapping.

Interactions between perception and tapping

Since the effect of movement in both groups indicated that movement significantly improved timing judgments, we conducted Pearson's correlations between finger tapping measures and detection abilities in each group (see Fig. 4). Similar to previous findings showing a relationship between different measures of stick tapping in percussionists and non-percussionists (Manning and Schutz 2016), we found a small relationship between finger tapping CV in the synchronization segment and task performance in non-percussionists ($r(27) = -.342$, $p = .069$), indicating those with lower variability of tapping performed better on the task, but we did not observe the same pattern for percussionists ($r(26) = -.144$, $p = .463$). We also observed a relationship between tap asynchronies measured in the synchronization segment of the trial and task score for non-percussionists ($r(27) = .397$, $p = .033$), but this was not the case for percussionists ($r(26) = .228$, $p = .243$).

Next, we conducted a binary logistic regression to determine the degree to which the timing of the final tap adjacent to the probe tone predicted the correctness of responses in the perceptual task (see Fig. 5). In the percussionist group as tap asynchrony increased by 1 ms, the odds of correctly identifying the timing of the probe tone decreased by 1.12% ($\chi^2 = 15.74$, $p < .001$; odds ratio

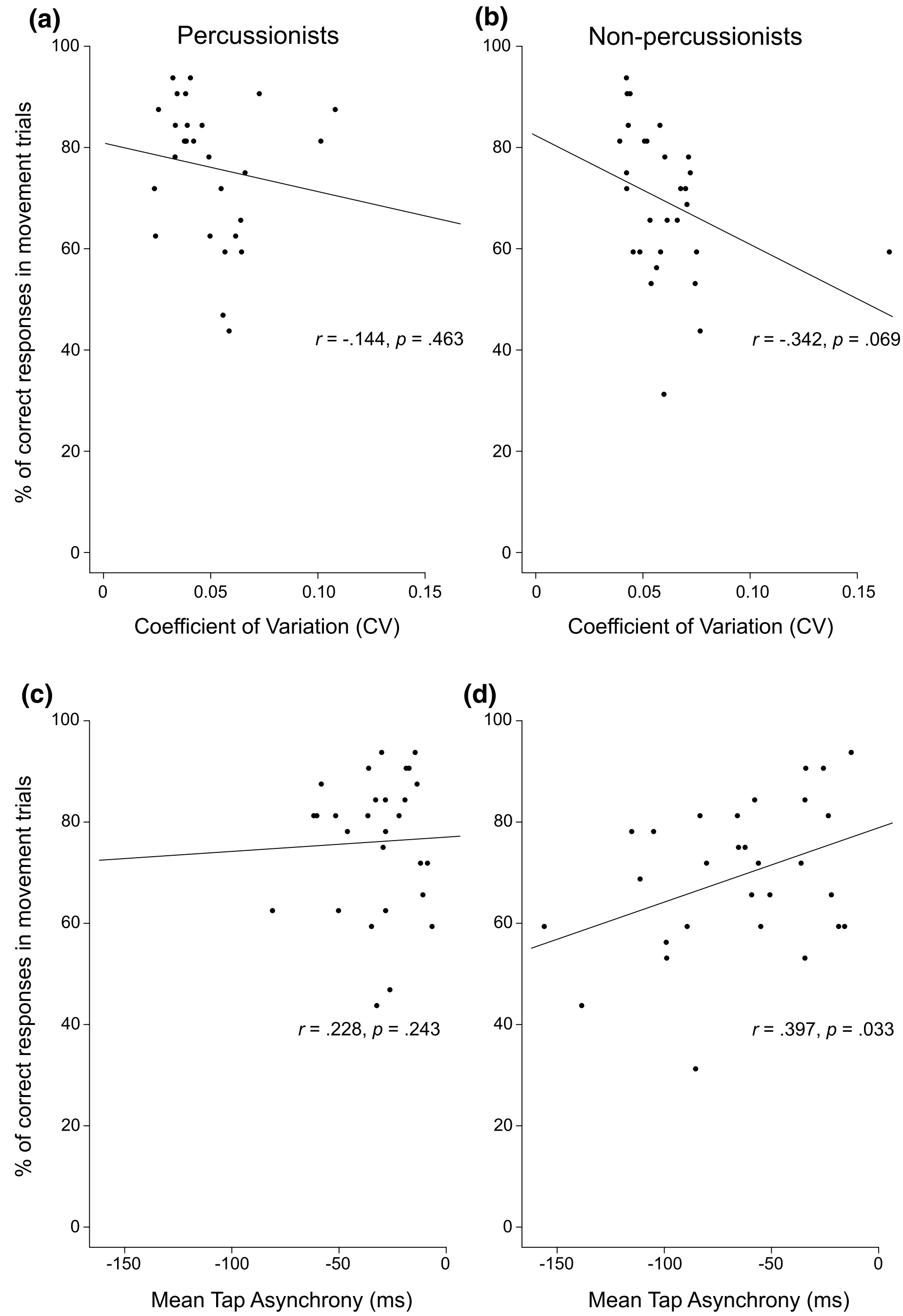

Fig. 4 Pearson's correlations between the percentage of correct responses in movement trials and two measures of tapping data in the synchronization segment of the trials; the coefficient of variation (CV) of tapping (**a**, **b**) and the mean tap asynchrony (**c**, **d**)

(OR) = 0.943). Similarly, the timing of the final tap in non-percussionists significantly predicted the correctness of responses, where as tap asynchrony increased by 1 ms, the odds of correctly identifying the timing of the probe tone decreased by 1.08% ($\chi^2 = 16.51$, $p < .001$; odds ratio (OR) = 0.954). This relationship suggests that the timing of taps adjacent to the probe tone can be used to predict the response outcome of the trial, where more accurate tapping increases the probability of a correct timing judgment for both percussionists and non-percussionists.

Discussion

The present study examined the perceptual consequences of finger tapping with auditory sequences in percussionists and non-percussionists. We found that percussionists and non-percussionists perform no differently in the no-movement trials of the task, similar to our previous findings using this paradigm (Manning and Schutz 2016). In the present study, percussionists showed only a slight perceptual advantage in the movement trials compared to

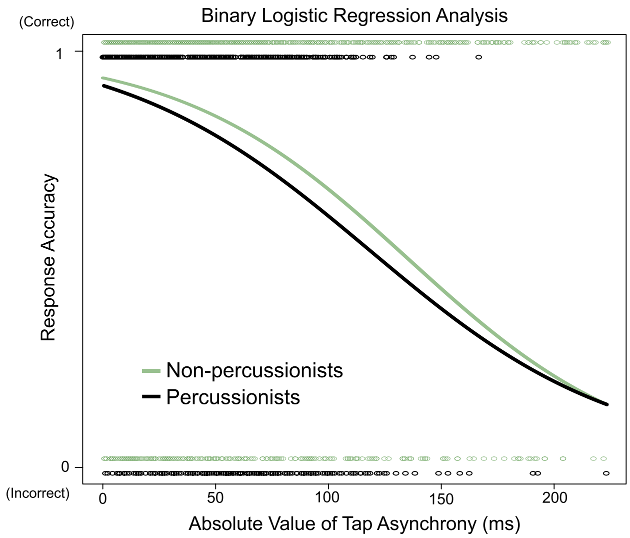

Fig. 5 Binary logistic regression analysis comparing the absolute tap asynchronies from the expected onset of the probe tone to the response accuracy on a trial-by-trial basis for both percussionists and non-percussionists

non-percussionists when finger tapping with the auditory sequence. This important finding corroborates our previous stick tapping study that showed perceptual benefits of movement in both percussionists and non-percussionists, where percussionists showed a much greater benefit from this movement. However, percussionists receive a much greater perceptual benefit than non-percussionists from stick tapping compared to finger tapping, and this suggests that although percussionists might rely on movement more for timing judgments, movement consistent with their training yields an even greater benefit. This perceptual difference is based on the type of movement used to synchronize with external auditory stimuli and comments on the role of effector-specific training in percussionists, complementary to other studies that report superior synchronization using explicitly trained movement (Stoklasa et al. 2012). The small difference observed here might clarify conflicting evidence for musician differences in timing abilities (Butler and Trainor 2015; Cameron and Grahn 2014; Krause et al. 2010; Matthews et al. 2016).

The finger tapping data in this study showed lower tapping variability and smaller NMAs in percussionists compared to non-percussionists. This is consistent with studies demonstrating that musicians exhibit highly accurate tapping compared to nonmusicians (Aschersleben 2002; Repp and Doggett 2007; Repp 1999) as well as very low tapping variability (Repp and Doggett 2007; Repp et al. 2013; Repp 2010), particularly percussionists (Cameron and Grahn 2014; Fujii et al. 2011; Krause et al. 2010; Manning and Schutz 2016). Previous studies show a relationship between the qualities of motor output between various effectors suggesting a common mechanism for timed movements (Fujii et al. 2011; Keele et al. 1985). Here, we note that although percussionists display more consistent and precise synchronization than do non-percussionists while finger tapping, this group difference is much smaller than the observed group difference in synchronization measures while stick tapping (Manning and Schutz 2016), suggesting the transfer of training benefits from one effector to another may be minimal.

Both percussionists and non-percussionists in this study relied on the timing of their final tap to make perceptual judgments about the probe tone, suggested by our regression analysis comparing perceptual and tapping data. Since we observed differences in synchronization abilities between stick tapping and finger tapping for both percussionists and non-percussionists, as well as differences in perceptual data, this might indicate that percussionists may use finger tapping information less in their perceptual timing decisions due to the lower quality of this information. This supports the notion that tapping offers an additional cue for temporal detection, and the quality of synchronization allows this information to be weighted accordingly, where more consistent stick tapping (Fujii and Oda 2009; Madison and Delignières 2009; Madison et al. 2013) is a better cue for identifying timing of external information compared to finger tapping, which is less reliable (Collier and Ogden 2004; Madison 2001).

There are several differences between finger tapping and stick tapping movements that may lead to synchronization differences and therefore to perceptual differences. In the present study, finger tapping involved the movement of the index finger of the dominant hand, which allows only movement of the metacarpophalangeal joint similar to studies examining finger tapping trajectories (Balasubramaniam et al. 2004; Doumas and Wing 2007; Hove and Keller 2010). Stick tapping, however, consists of larger movements than finger tapping, involving the wrist and perhaps forearm, depending on how a participant chooses to manipulate the stick. Research in motor control discusses how the number of degrees of freedom in goal-oriented movement might contribute to optimal control of movement (Latash 2014; Todorov and Jordan 2002). The kinematics involved in timed movements might explain differences in synchronization ability, where, for example, in skilled musicians, movements that allow a performer to vary more than one degree of freedom show more tightly controlled timing (Winold et al. 1994). For the present study, this may suggest that using a stick allows for more control over the movement trajectory than does finger tapping and this might lead to more precise synchronization, since the finger tapping allows only one joint to be varied while stick tapping may allow many joints to be varied. We observe differences in the tapping that support this notion, where stick tapping is more consistent than is finger tapping (see also Madison et al. 2013), which also has perceptual consequences. Additionally, those with more experience manipulating an object for movements, namely percussionists with a drumstick, might have even more control and therefore time motions more accurately. This improvement in synchronization due to experience may not extend fully to finger tapping since only one joint is used, compared to two or more joints involved in stick wielding using the wrist and/or forearm. It is also important to note that these effectors are different in size and we compared synchronization at a single tempo. Previous work examining music-induced movement reports that larger motor effectors, such as the torso and legs, have a tendency to spontaneously synchronize with higher levels of a metrical hierarchy in music (i.e., half the rate of the beat), whereas smaller motor effectors tend to synchronize with lower levels of the metrical hierarchy (i.e., the beat rate). Future work should address this notion by assessing these effectors at various tempi to examine whether this accounts for some of the observed differences between synchronization and perception data.

Recently, a dual-route model for rhythm processing has emerged that describes two separate cognitive approaches for tracking and synchronizing with rhythm (Fischinger 2011). In this model, two synchronization approaches may be used: one for the automatic processing of temporal events and the other for explicit monitoring (Miyake et al. 2004). We can determine the approach that is used by diverting attention and examining subsequent synchronization performance. Percussionists are thought to typically depend on precise monitoring processes for highly accurate synchronizing and error correction (Fischinger 2011). Since percussionists are primarily trained on executing stick tapping movements and therefore exhibit more precise synchronization (Cameron and Grahn 2014) and greater perceptual benefits as a result of stick tapping (Manning and Schutz 2016), the motor effector involved in synchronization might require different amounts of attention. In the present study, when percussionists synchronize using finger tapping, they might return to an automatic approach to timing, similar to the non-percussionists, since this movement is not specific to their method of training. This may explain differences between stick tapping and finger tapping in percussionists and non-percussionists and suggest that percussionists' extensive training in synchronization might be somewhat experience-dependent and not generalize to the synchronization ability of other motor effectors.

Conclusion

Overall this study shows that finger tapping leads to perceptual improvements for both percussionists and non-percussionists. This improvement is significantly smaller than in our previous study with stick tapping (Manning and Schutz 2016), suggesting that less reliable finger tapping information provides a less reliable cue for perceived timing. This finding further supports interactions between motor information and timing abilities (Chemin et al. 2014; Manning and Schutz 2013, 2015; Su and Pöppel 2012), since differences in tapping information are reflected in perceptual judgments. More generally, this support recent hypotheses describing auditory–motor interactions in beat perception (Patel and Iversen 2014) and a forward model of embodied action and its effects on perception (Maes et al. 2014). More broadly, these findings support the active sensing framework that discusses how synchronized movements assist in refining attention surrounding relevant sensory information (Morillon et al. 2014, 2015). Although motor synchronization leads to improvements in perception, this interaction is mediated by musical abilities and experience with specific movements.

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