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The influence of visual cues on temporal anticipation and movement synchronization with musical sequences

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ABSTRACT

Music presents a complex case of movement timing, as one to several dozen musicians coordinate their actions at short time-scales. This process is often directed by a conductor who provides a visual beat and guides the ensemble through tempo changes. The current experiment tested the ways in which audio-motor coordination is influenced by visual cues from a conductor's gestures, and how this influence might manifest in two ways: movements used to produce sound related to the music, and movements of the upper-body that do not directly affect sound output. We designed a virtual conductor that was derived from morphed motion capture recordings of human conductors. Two groups of participants (29 musicians and 28 nonmusicians, to test the generalizability of visuo-motor synchronization to non-experts) were shown the virtual conductor, a simple visual metronome, or a stationary circle while completing a drumming task that required synchronization with tempo-changing musical sequences. We measured asynchronies and temporal anticipation in the drumming task, as well as participants' upper-body movement using motion capture. Drumming results suggest the conductor generally improves synchronization by facilitating anticipation of tempo changes in the music. Motion capture results showed that the conductor visual cue elicited more structured head movements than the other two visual cues for nonmusicians only. Multiple regression analysis showed that the nonmusicians with less rigid movement and high anticipation had lower asynchronies. Thus, the visual cues provided by a conductor might serve to facilitate temporal anticipation and more synchronous movement in the general population, but might also cause rigid ancillary movements in some non-experts.

1. Introduction

Integrating movement and sensory input to interact with the environment with high temporal precision is a fundamental aspect of human behavior. Such precision is exemplified in music performance, where it is aided by temporal structuring principles that include rhythms consisting of ratio-related durations and hierarchical metrical frameworks (London, 2012). Underlying such frameworks is a subjective sense of regularity known as the *beat* or *pulse* (Iversen & Patel, 2008; Large, Herrera, & Velasco, 2015; Merchant et al., 2015), which is useful for establishing a shared sense of musical time among people. Auditory-motor connections enable most people to move in time to the beat (Phillips-Silver et al., 2011; Sowinski & Dalla Bella, 2013), whether in the form of rhythmic tapping (Wing, 2002), dancing (Burger et al., 2014), or playing an instrument (Maes, Wanderley, & Palmer, 2015). In the latter two cases, timing is frequently coordinated not just intrapersonally by an individual attempting to keep a steady beat, but also interpersonally, as seen in ensemble performance (Keller, 2008; Rasch, 1979).

In a musical ensemble, several, sometimes dozens of musicians aim to coordinate their actions to produce the desired sound within a small window of temporal precision. While the presence of a beat is useful for synchronization, beat-based ensemble music rarely features a single, repeated beat interval (i.e. *isochrony*). Through expressive interpretation (Repp, 1998; Thompson & Luck, 2011) and notated tempo changes (Loehr, Large, & Palmer, 2011; Repp & Keller, 2004; van der Steen et al., 2015) the beat rate fluctuates. This leads to the general topic of our investigation: the ability of individuals to synchronize their actions with exogenous tempo-changing rhythmic signals.

Sensorimotor synchronization (SMS)—that is, the coordination of movements with rhythmic external events—is generally facilitated through perceptual monitoring and reactive error correction (Wing et al., 2014a; Wing et al., 2014b). In musical ensembles, this entails listening to oneself and others and responding to interpersonal timing

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discrepancies. Research on how people keep time has found negative serial dependencies in tap intervals, suggesting people correct successive timing errors. These errors are due to motor system nosie, and noise in an internal timekeeper (Wing & Kristofferson, 1973) suggesting that repetitively timed actions are triggered by an imperfect but adaptive cognitive control system (Torre & Balasubramaniam, 2009; Zelaznik et al., 2007). An additional strategy for synchronizing with tempo changes involves prediction, specifically *temporal anticipation* (Mills et al., 2015; Pecenka & Keller, 2009). If musicians can anticipate an upcoming beat interval, then they can minimize the error that they will need to correct, and thus achieve a more cohesive ensemble sound. Both *correction* and *anticipation* have been considered in a more recent timekeeper model (van der Steen & Keller, 2013), which can account for tempo changes by adapting to fluctuating time intervals.

From numerous SMS experiments (Repp & Su, 2013)—in which participants tap a finger in time to a pacing signal or other auditory stimulus—we know that there is a tendency for individuals to predict upcoming time intervals. Although people vary in their ability to predict (Colley, Keller, & Halpern, 2017; Mills et al., 2015), temporal anticipation is not a static skill. Instead, it can be improved by partnering with another individual who is a good predictor (Pecenka & Keller, 2011), and by observing visual cues that are informative about event timing (Maruta et al., 2013; Repp & Moseley, 2012). These strategies—partnering and visual cues—are relevant in musical ensemble performance, especially in large ensembles (e.g., symphony orchestras) where individuals rarely play alone but rather in a section (e.g., a group of violinists all playing the same part), and musicians can see each other as well as a conductor. The present study will focus on the role of visual cues such as those provided by the conductor, and how these cues influence musical synchronization.

The conductor is typically responsible for interpreting expressive aspects of the music, and also directing the musical timing. Thus, he or she provides a temporally relevant visual cue in the form a gesture made with a handheld baton. Musical beat locations are usually marked by a rapid downward trajectory of the baton, thus providing a common source of continuous visual information to the ensemble musicians (see Fig. 1C).

Fundamental research on visuo-motor coordination suggests that marked deceleration towards the endpoint of a moving object's trajectory makes the timing of the endpoint more salient, thereby facilitating synchronization with that object (Varlet et al., 2014a; Zelic et al., 2016). Consistent with this, studies on synchronizing with conducting gestures have shown advantages for specific types of motion trajectory. For example, musicians were able to synchronize better with a “morphed” virtual conductor that was made by averaging the movements of multiple conductors, than with individual conductors (Wöllner et al., 2012). Presumably, this is because the morphed conductor

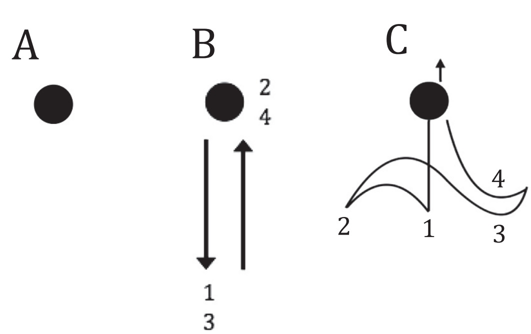

Fig. 1. Diagrams of our visual cue conditions. Panel A depicts the stationary circle, which did not move during trials. Panel B depicts the no-acceleration cue, which reached its lowest point at beats 1 and 3, and its highest point at beats 2 and 4. Panel C depicts a common conductor gesture, which was performed by our conductors when making the virtual conductor. Each number correspond to a musical beat, and after every fourth beat, the gesture repeats.

provided a prototypical gesture with minimal noise (i.e., minimal variability along the trajectory), so the target timing could be readily predicted. In the same study, the reported quality of the virtual conductors correlated with the vertical velocity of the gestures, suggesting that people are sensitive to subtle differences in visual cues, and that fast vertical motion between beat locations is important for conveying time. Similarly, a study of an ensemble rehearsal found that moments of maximal synchrony in the orchestra correlated with the vertical velocity of the conductor's baton (Luck & Nte, 2008; Luck & Toiviainen, 2006).

However, none of these studies have looked explicitly at whether such visual cues specifically affect the process of temporal anticipation by quantifying the degree to which movements are aligned with tempo-varing beat intervals. This has been considered outside of the music domain in a study that had participants anticipate the action timing of a human or robot (Saygin & Stadler, 2012), but the kinematics were kept constant and only the appearance of the stimulus changed. Given the role of kinematics in synchronization (D'Ausilio et al., 2012; Luck & Nte, 2008; Varlet et al., 2014a) and the apparent effects of visual cues on anticipation (Knoblich & Flach, 2001; Koul et al., 2016; Schubotz, 2007; Wollner & Canal-Bruland, 2010), we investigated whether continuous visual information with a dynamic velocity profile can facilitate predictions of upcoming beat intervals, thereby improving synchronization performance. Furthermore, these beneficial effects of visual information could arise directly by influencing estimates of the timing of upcoming sounds or indirectly by entraining the body movements of the individual.

Studies on visuo-motor entrainment in the field of ecological psychology have shown that individuals entrain their movements to visual rhythms in the environment, sometimes even unintentionally (Richardson et al., 2007; Schmidt et al., 2007; Varlet et al., 2015a). In studies of body motion during music performance, a distinction has been drawn between instrumental movements, which are directly related to the production of musical sounds (e.g., the keystrokes of pianists), and ancillary movements, which are not causally linked to sound production (e.g., head nods or body sway) (Nusseck & Wanderley, 2009). The functions of ancillary movements may be related to expressive aspects of the music (Castellano et al., 2008) and also to the control and communication of performance timing (Ginsborg & King, 2009; Goebl & Palmer, 2013).

In line with their functional distinction, instrumental and ancillary movements may be linked to different levels of musical structure. Music typically has hierarchical time scale structure, such that rapid events unfolding at short time scales are embedded within slower, less frequent events at longer time scales. Instrumental movements often account for the fastest events (beats, or beat divisions), and ancillary movements may relate to larger time scales, such as bars formed from multiple beats, or phrases formed from multiple bars (MacRitchie, Buck, & Bailey, 2013; Thompson & Luck, 2011).

Ancillary movements may also be communicative, conveying timing cues to co-performers when auditory information is degraded or reduced (Goebl & Palmer, 2009). Consistent with communicative functions, it has been found that co-performers make more eye contact during irregularly timed musical passages, suggesting that visual information is especially beneficial when interpersonal coordination demands are high (Kawase, 2014). Thus, in addition to the conductor, musicians rely to some degree on seeing each other to maintain a shared sense of time, and may capitalize on this by moving rhythmically. Furthermore, movement kinematics in orchestral musicians were found to relate to leadership in the orchestra (D'Ausilio et al., 2012), again pointing towards the importance of body movement in musical synchronization.

While the majority of studies on sensorimotor synchronization have focused on sound-producing instrumental movements, there is evidence that ancillary movements can also play an important role in timekeeping. Performers may use ancillary movements to act as a "coordination smoother" (Vesper et al., 2010) to make their actions more regular, and thus predictable, as seen in a study where pianists in duos increased the amplitude of their body sway when they could not see each other (Keller & Appel, 2010). The effects of increased body sway on timing regularity may be related to increased head movement, which may facilitate timing by reinforcing one's sense of rhythm through the stimulation of vestibular networks (Phillips-Silver & Trainor, 2008; Todd & Lee, 2015; Trainor et al., 2009).

However, despite evidence that whole-body movements may be related to time-keeping, it is not conventional to measure ancillary movements during basic SMS tasks, and those that examine ancillary movements in skilled music performance (Goebl & Palmer, 2009) necessarily exclude nonmusicians, despite the fact that musical synchronization is a widespread phenomenon (e.g. audience members tap or nod with the music). The aim of the present study was to investigate the effects of continuous information in visual cues provided by conducting gestures on synchronization with musical sequences containing tempo changes. We assumed that in addition to influencing instrumental movement by improving temporal anticipation of musical beat locations (relative to no visual stimulus, or a simple moving stimulus), continuous visual cues provided by rhythmic conducting gestures might also entrain rhythmic ancillary movements. This could in turn enhance an individual's SMS ability by improving the stability of one's embodied sense of time.

The task used to assess the role of visual cues in motor coordination was an SMS tapping task. We tested both highly trained ensemble musicians, and people with no formal musical training, to test the generalizability of visual cues in music synchronization beyond people with relevant experience. Typical synchronization studies use click tracks devoid of pitch variation and harmony (Keller & Repp, 2008; Repp, 2008; Zelaznik et al., 2005). This is effective for studying timing outside the music domain, but we were specifically interested in musical timing. Therefore, our stimuli were designed with harmonies and multiple instruments to simulate a musical context with tempo changes, in which a conductor is typically considered to be helpful. Previous studies have found that individual differenes in auditory imagery predict anticipatory timing abilities, and that people synchronize more accurately with isochronous (or nearly isochronous) pacing signals and music excerpts than with tempo changing pacing signals (Pecenka & Keller, 2009) or expressively timed music excerpts (Colley et al., 2017). Knowing this, we wanted to focus on how anticipatory timing can be influenced or improved across long musical sequences with alternations between steady phases and tempo-change phases. Therefore, participants were instructed to drum in synchrony with the beat of rhythmically simple, but tempo-changing, multi-part music, for 3 m 22 s per trial. Concurrently, in separate conditions, participants observed a virtual conductor, a simple visual metronome that moved without acceleration (within each cycle) on the vertical axis only, or a stationary circle. We hypothesized that the virtual conductor would reduce asynchronies and improve temporal anticipation relative to both the non-moving stimulus and the simple visual metronome, due to the virtual conductor's informative velocity profile (Luck & Toiviainen, 2006; Varlet et al., 2014a), which clearly marks beat locations. We also expected the degree of temporal anticipation to correlate negatively with asynchrony, as increase in the ability to predict the timing of beats due to the conductor should supplemet the general tendency for greater prediction to result in lower asynchronies (Colley et al., 2017). Furthermore, we expected these effects to apply to both experts (ensemble musicians) and nonexperts (nonmusicians) as the underlying kinematic processes of visuo-motor and audio-motor synchronization can be observed in humans regardless of musical experience (Colley et al., 2017; Hove & Keller, 2010; Zelic et al., 2016).

To examine ancillary movements, we measured the upper-body and head motion of participants. A commonly applied method of quantifying spatiotemporal structure in body movement, including body sway (Blázquez et al., 2009), is detrended fluctuation analysis (DFA), which can categorize time series by noise color (Kantelhardt et al., 2001; Peng et al., 1994). This measure gives an indication of how structured movements are, on a scale from random (un-structured white noise) to deterministic (very structured Brownian noise). We hypothesized that head movements would be more structured (i.e. follow a pattern of motion) and of greater magnitude in the virtual conductor condition, as the naturalistic visual rhythm was expected to entrain ancillary motion (Schmidt et al., 2007). As a means of linking instrumental and ancillary movements, we also expected a negative relationship between body movement structure and asynchrony, meaning those who move in a more structured way would show lower asynchronies (Phillips-Silver & Trainor, 2008).

2. Methods

2.1. Participants

We recruited 29 musicians (14 female) aged 18–50 years, and 28 nonmusicians (19 female) aged 18–35 years. Criteria for inclusion as a musician were five or more years of musical training (median = 14.43 years, range = 10–37 years), currently practicing/performing, and, having had experience playing with a conductor. The criterion for nonmusicians was having no musical training. This rather strict criterion was uphelp by listing it in the study advertisments, and verifying with participants when they signed up for the study, and when they arrived. Despite having no musical training, all nonmusician participants reported listening to music on a daily basis. Most participants were recruited through the Western Sydney University School of Psychology, and received course credit. Some of the musician sample were recruited from various music ensembles around Sydney. They were paid $20 to reimburse travel costs. All participants provided written informed consent prior to the experiment, which was approved by the Western Sydney University Ethics Committee.

2.2. Study design

The experiment was a 2 × 3 mixed design. There were two *expertise* levels as the between-subjects factor (musician and nonmusician) and three levels of *visual cue* as the within-subjects factor (stationary circle, no-acceleration motion, and conductor).The dependent variables were mean absolute asynchrony, an index of temporal anticipation, standard deviation of movement, and fluctuation of movement (i.e., αDFA).

2.3. Apparatus

An Alesis Percpad (tapping pad) was used to collect the synchronization data. Participants used a drum stick rather than finger, as recent studies have shown that synchronization drumming results in fewer missed taps than synchronization tapping (Madison et al., 2013; Manning, Harris, & Schutz, 2017). Participants' movements were recorded with a 12-camera Vicon motion capture system at 100 Hz sampling rate, with reflective markers arranged using the built-in upper body model in the Nexus software package. The motion capture recording and the drum recording were synced by sending a serial trigger signal to Nexus at the onset of each trial. The experimental procedure (data collection, stimuli presentation, and trigger signals) was programmed using the OpenFrameworks coding environment for C + + on a 2015 Macbook Pro. Auditory stimuli were sent through stereo speakers, and visual stimuli were presented on a 17″ monitor with a 60 Hz refresh rate.

2.4. Auditory stimuli

Three short pieces (3 m 22 s) were created (by author IDC) for the experiment using the notation software *Musescore*. The intention was to create stimuli with a constant and unambiguous beat, but with some melodic and harmonic interest to simulate a musical setting. Thus, the only rhythmic values used were quarter notes in the upper two voices (glockenspiel and xylophone) and eighth notes in the lower voice (harp). These instruments were chosen as they had rapid onsets and were voted as the most pleasing MIDI instruments during pilot testing. There were no rests (i.e., silent beats), meaning every beat as defined in 4/4 meter included an audible note in the music. The pitch range was C2-A5, which is well within typical musical ranges. Melodies and harmonies were based on basic practices in Western music theory. The xylophone and glockenspiel played complementary melodies, while the harp accompanied with chords. Score excerpts are included in Appendix A. The length was chosen to reflect a typical short piece of music and to allow for more reliable analyses of motion capture data, as discussed later.

To create the tempo changes, the Musescore files were exported as MIDI files, which were converted to ASCII format, then edited in Matlab to change the note on/off times. The music started at 120 bpm or a 500 ms inter-onset interval (IOI). This steady tempo phase continued for eight beats, then a tempo change would occur over eight beats, either slowing or accelerating. The direction of change would then reverse to bring the music back to 120 bpm for eight beats. Thus the location of tempo changes was regular, but the direction of change, and the magnitude of change were randomly generated. There were six rates of change for the tempo changes: ± 10, ± 16, and ± 22 ms per beat. These rates of change were chosen based on pilot test results. After editing in Matlab, the files were saved as MIDI files, then opened in Garageband to set the instruments for each track, and lastly saved in AIFF format.

2.5. Visual stimuli

There were three visual stimuli: the stationary circle (Fig. 1A), the no-acceleration circle (Fig. 1B), and the virtual conductor (Fig. 1C). All three stimuli used a red circle with 13 mm diameter against a black background. The no-acceleration circle moved vertically between two turnaround points 132 mm apart, with a constant speed within each cycle. Turnaround points always corresponded to a musical beat (e.g. beat one corresponded to the lowest position, beat two to the highest). Thus, the speed between cycles would change instantaneously to match the tempo changes, but the speed within a cycle would not change, hence the nomenclature "no-acceleration." We made the virtual conductor by averaging the motion capture recordings of three conductors (Wöllner et al., 2012). The resulting position coordinates determined the trajectory of the circle during a conductor trial. In addition to changing speed within a beat cycle, the conductor differed from the no-acceleration stimulus by moving horizontally as well as vertically, as is common for a conductor pattern.

2.6. Virtual conductor

The three conductors contacted to participate in motion capture recording as part of the design for the virtual, morphed conductor had at least 10 years experience conducting a variety of ensembles, including student string orchestras, full symphonic orchestras, and an army band. They were reimbursed $30 for their assistance.

The conductors were sent the audio files and scores of the music one week before the scheduled motion capture recording. They were asked to practice conducting the three pieces at least twice per day (about 20 min per day), or until they "felt as if [they] were leading a small ensemble," and encouraged to notate the scores in whatever way was useful. On the day of the recording, the conductors—who were recorded individually—were outfitted with reflective markers according to the upper-body model included in the Nexus software (a motion capture program that recorded the motion of markers, which were attached to conductors with tape and elastic bands). However, the model was edited to include a baton with two additional markers: one at the handle, and one at the tip. Although we intended to only use the baton tip marker for this experiment, we recorded the full upper-body for use in future studies.

We recorded three takes of each of the three pieces for a total of nine takes. The experimenter started the music, which was preceded by four count-in beats using a woodblock sound. The conductors were asked to start conducting on the third count-in beat in a 4/4 pattern (Fig. 1). A trigger signal was sent to the motion capture system when the music count-in started so the recordings could be synced offline.

To average the motion capture recordings, we exported the position data of the baton tip as an ASCII file. The frames were trimmed to start at the trigger signal and end one second after the final beat. To match the motion capture to the refresh rate, the recordings were down-sampled from 100 Hz to 60 Hz, and filtered with a 10 Hz low-pass Butterworth filter in Matlab. The resulting vectors were 3D position coordinates of the baton tip, but we only used the x and z planes to make the 2D virtual conductor (the z plane in the motion capture software corresponds to the vertical plane, or y, in 2D Cartesian space, which would be the coordinate system for the stimuli). The vectors were shifted so the minimum value was zero, and scaled to fit within the computer screen. Lastly, the vectors were averaged using a simple arithmetic mean (as in Wöllner et al., 2012), and saved as text files.

2.7. Procedure

Upon arrival, participants were briefed on the task, then read and signed a consent form, and filled out a questionnaire of musical experience to verify that they met the criteria for either musician or nonmusician. Next, the experimenter attached the reflective markers for the motion capture recording according to the built-in upper-body model in Nexus. Participants were contacted before the day of testing and asked to wear a tight-fitting shirt if possible, so as to minimize extraneous motion of the markers. As the experimenter attached the markers, he explained the task. Participants were instructed to stand on a marked location in front of the testing monitor, which was placed on a high table and adjusted so the center of the screen was at eye level. They were told to stand comfortably and that they were free to move, so long as they continued to face the monitor. No other explicit instructions regarding movement were given.

For each trial, the experimenter would start the motion capture recording, then prompt the participant to start the music by pressing the 'return' key on the testing computer when they were ready. This would begin the four-beat count-in, and participants would start drumming with the music after the fourth count-in beat. There was no electronically generated auditory feedback from the drum, just the sound the stick hitting the drum. To ensure they were observing the visual stimuli, a letter would appear at random points throughout a trial in the middle of the screen, and participants were told to say the letter out loud. This is similar to procedures in other visuo-motor synchronization studies (Varlet et al., 2012; Varlet et al., 2015a). Due to the length of our trials, several letters would appear throughout every trial to sustain participants' attention. There was one practice trial, which used the stationary circle. Then, each of the three pieces of music was paired with the three visual stimuli twice (3 × 3 × 2) making 18 experimental trials. This was divided into three blocks of six trials to give participants breaks. Each block contained the three visual conditions twice, but in a random order. Participants were instructed to keep in time with the music even as it changed speed, to continue drumming until the music stopped, and to always watch the monitor. After the experiment, participants were debriefed and asked for feedback about the experiment and usefulness of the visual cues.

3. Data analysis

3.1. Drumming SMS

There were two main dependent measures of instrumental movements (i.e. the drumming data): mean absolute asynchrony and an index of temporal anticipation. For both measures, the inter-drum interval (henceforth inter-tap interval [ITI] for consistency with other timing studies) series needed to be the same length as the IOI series of the music. On average, 83% of the trials in the musician group, and 67% of trials in the nonmusicians group had an equal number of ITIs and IOIs. If the series lengths did not match, we used the following interpolation procedure: ITI values that were twice as large (with a tolerance of +/− 10%) as the corresponding IOI were split into two equal values to account for the presumed missed tap. The same was done for ITI values that were three and four times as large as the corresponding IOI, but split into three and four equal values respectively. Any trials with more than three consecutive missed beats were discarded. If an ITI was < 100 ms, it was considered a double-tap (meaning two successive and rapid taps occurred in the space of one musical beat), and added to the previous ITI under the assumption that the sum of the two successive intervals represent the participant's intended tap interval. Once the series were the same length, we calculated the mean absolute asynchrony as a general representation of how far off from the beat participants were on average. To do this, we subtracted the cumulative IOI from the corresponding cumulative ITI at each beat, converted the differences to absolute values, and averaged this asynchrony series. We removed trials for which the mean absolute asynchrony was 500 ms or greater, as this was the average IOI in the auditory stimuli. This was about 3% of all trials across all participants.

Temporal anticipation was quantified using a *prediction/tracking index* (P/T index) using cross-correlation (CC) (Colley et al., 2017). If participants are anticipating IOIs, then the ITI series should resemble the IOI series at lag-0 (i.e. the actual IOI series). If they are tracking the tempo changes, then the ITI series will resemble lag-1 of the IOI series. By dividing the coefficient of the lag-0 CC by that of the lag-1 CC, we get a measure of the extent to which individuals are predicting (quotient > 1) or tracking (quotient < 1). The main analysis was a 2 × 3 mixed ANOVA with *expertise* as the between-subjects factor (musician or nonmusicians), and *visual cue* as the within-subjects factor (stationary circle, no-acceleration, conductor). This was done for both mean absolute asynchrony and the P/T index.

3.2. Ancillary movements

Our analysis of ancillary movements focused on one marker located on the head (the right forehead marker), as we found that most participants moved their head rather than torso during pilot testing (we still recorded the whole upper-body for use as a visual stimulus in future studies). Furthermore, we were specifically interested in using motion capture to understand ancillary movements, so we did not analyze the arm movements, which are considered instrumental movements. To standardize the movement volume of participants, the four markers around the hips were averaged to create a center point for each trial, which was used as the origin for the other markers. To reduce processing time of the series, the 100 Hz recordings were down-sampled to 50 Hz. Next, the series were filtered with a 10 Hz low-pass Butterworth filter. To assess the amplitude of movement, we calculated the standard deviation (Stoffregen et al., 2013; Varlet et al., 2014b; Varlet et al., 2015b) of the position coordinates on each of the three axes. To assess fluctuations and how structured the movements were, we used DFA in the RStudio package "nonlinearTseries." The primary dependent measure that is given by DFA is the scaling exponent, α, which ranges from 0.5 (white noise/random behavior) to 1.5 (Brownian motion/brown noise/deterministic behavior). A value of 1.0 indicates pink noise, which is associated with default coordination in movement such as standing balance sway (Blázquez et al., 2009; Wang & Yang, 2012).

DFA works by first breaking a time series into windows of size *n*. The time series within each window is detrended (usually linearly), and analyzed for variance. The variance is then averaged across all windows to produce a fluctuation value at that window size. The size of *n* is then increased to the next power of two, and the process repeated until *n* is about half of the whole series length. Alpha (αDFA) is the slope of the regression relating fluctuation to each window size, and therefore represents how a system operates over multiple time scales. We used window sizes from 2 to 4096, where 2 is the smallest power of two, and 4096 is a power of two that is about half our time series length. We used a regression range from window sizes 1 to 1000, as this was the linear region of the relation between variance and window size; window sizes above 1000 tended to produce exponential increases in variance, which would overestimate αDFA. We again used 2 × 3 (*expertise* by *visual cue*) mixed ANOVAs, but this time ran separate tests for the three spatial axes (*x*, *y*, *z*, henceforth side-to-side, forward-backward, and up-down, respectively). This was performed for each of the two motion capture dependent measures (standard deviation of movement and αDFA).

3.3. Multiple regression

To relate the head movement data to the drum timing data, we used a multiple regression model with αDFA and P/T index as predictors of asynchrony. Asynchrony was chosen as the dependent variable as it was the measure of performance success; participants were instructed to synchronize, and low asynchrony is desirable in most music performances. αDFA represents participants' behavior at the level of ancillary movements (head movements), and P/T index represents a process that we assume is related to instrumental movements (drum timing).

4. Results

4.1. Asynchronies and prediction/tracking indices

For asynchrony (see Fig. 2) there was a significant main effect of *expertise*, $F_{(1,\ 55)} = 9.97$, $p < .01$, partial $\eta^2 = 0.15$, such that musicians produced lower asynchronies (were more accurate) than nonmusicians. There was also a main effect of *visual cue*, $F_{(1.32,72.65)} = 4.21$, $p < .05$, partial $\eta^2 = 0.07$ (Greenhouse-Geisser corrected), such that the conductor condition produced lower asynchronies than both the

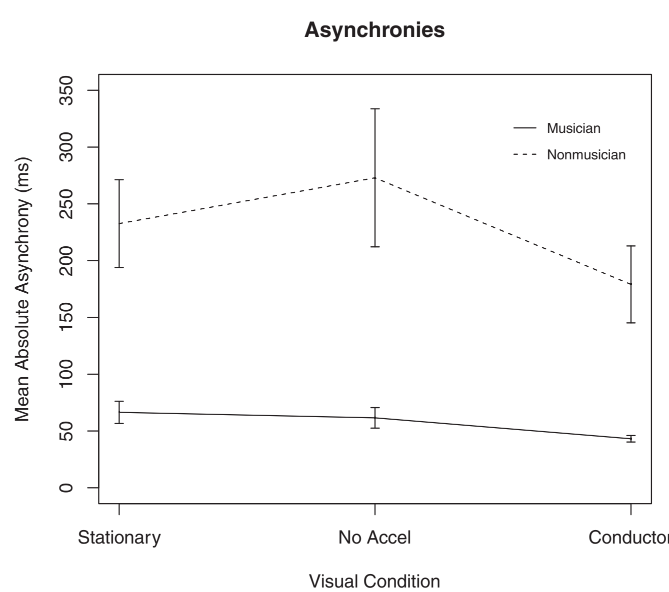

Fig. 2. Mean absolute asynchronies for each exptertise group (musician and nonmusician) in each visual cue condition. Error bars represent standard error.

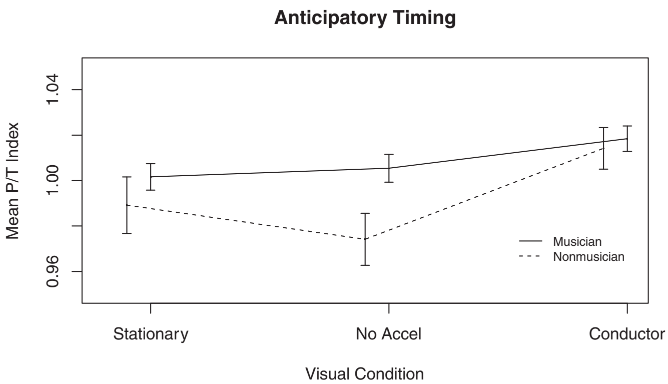

Fig. 3. Mean P/T Index for each exptertise group (musician and nonmusician) in each visual cue condition. Error bars represent standard error.

stationary circle ($p < .001$) and the no-acceleration conditions ($p < .05$), Bonferroni corrected. There was no difference between the stationary circle and no-acceleration circle conditions.

For the P/T index (temporal anticipation; see Fig. 3), there was no main effect of *expertise* or *expertise* by *visual cue* interaction. There was a main effect of *visual cue*, $F_{(2,110)} = 13.40$, $p < .001$, partial $\eta^2 = 0.20$. Bonferroni corrected post-hoc comparisons showed the conductor condition yielded higher P/T indices than both other conditions, $p < .001$.

There was also a significant negative correlation between asynchrony and P/T index (averaged over visual cues) across all participants, $r_{(55)} = -0.24$, $p < .01$, indicating higher P/T index related to lower asynchrony overall. This relation was not driven by one group in particular, as the correlation was significant for musicians, $r_{(27)} = -0.25$, $p < .05$, and for nonmusicians, $r_{(26)} = -0.24$, $p < .05$ across all visual cues.

4.2. Motion capture analysis

First, we considered the standard deviation of movement, which is a measure of movement amplitude (see Fig. 4, panels A and B), which was positively skewed for all conditions and groups, so a log-10 transform was used. For the side-to-side movements there was a main effect of *expertise* such that the nonmusicians moved more (higher standard deviation) than the musicians, though the effect size was quite small, $F_{(1, 55)} = 30.32$, $p < .000001$, partial $\eta^2 = 0.06$. However, there was no effect of *visual cue* on standard deviation of side-to-side movement. For the forward-backward and up-down movements, there was no main effect of group or visual cue.

Next we considered αDFA (Fig. 4) along each axis of movement. For the side-to-side axis there was no main effect of *expertise* or of *visual cue*. However, there was an interaction effect of *expertise* by *visual cue* along the side-to-side axis, $F_{(1.46,\ 80.28)} = 14.37$, $p < .001$, partial $\eta^2 = 0.21$ (Greenhouse-Geisser corrected). This indicated that for the nonmusician group, αDFA values were significantly higher in the conductor condition compared to both the no-acceleration ($p = .001$) and the stationary circle ($p = .01$), and values in the no-acceleration condition were significantly higher than the stationary circle ($p < .05$), Bonferroni corrected. The effect of *visual cue* on side-to-side axis αDFA for musicians was not significant. For both the forward-backward and up-down axes, there were no significant effects of group, visual cue, or interactions.

4.3. Relating movement, prediction, and synchronization

Lastly, given the effect of visual cue on αDFA of head movements and on P/T indices for the nonmusician group, we tested whether these two variables (αDFA and P/T index) could predict asynchrony in a multiple regression. We used values from all three visual cue conditions, but limited the analysis to the nonmusician group, as this was the only group that showed an effect of visual cue on movement. The regression was significant, $F(2, 81) = 5.94$, $p < .01$. Both αDFA (standardized $\beta = 0.22$, 95% CI [11.0–481.08], $p < .05$) and P/T index (standardized $\beta = -0.32$, 95% CI [−1427.94- -294.85], $p < .01$) were significant predictors of asynchrony with a total R^2 of 0.12. Nonmusicians' asynchronies were low to the extent that head motion was unstructured and temporal anticipation was high (see Fig. 5).

5. Discussion

This experiment investigated how visual cues that are relevant to music performance affect sensorimotor synchronization with tempo-changing auditory sequences at both the level of instrumental movements (drumming accuracy) and ancillary movements (head motion). Overall, we found that visual cues that are derived from conductors' gestures can improve temporal anticipation and synchronization performance both for people with musical experience, and for people with no musical training. This supports our hypothesis that temporal information provided by continuous visual cues containing salient changes in acceleration can improve the prediction of beat timing and thereby facilitate synchronization with auditory sequences.

More generally, our findings suggest that two multimodal cues that occur simultaneously and provide non-conflicting information can improve SMS relative to a single cue, presumably through efficient multisensory integration (Elliott, Wing, & Welchman, 2014; Ernst & Bülthoff, 2004). The effects of visual cues on ancillary movements appear to be less generalizable, as we found an effect on movement fluctuations for nonmusicians only. This partially supports our hypothesis that visual cues provided by a virtual conductor encourage larger and more structured ancillary movements, but the results also suggest that these effects are modulated by musical expertise.

Within the musician group, the conductor stimulus was associated with lower asynchronies and higher P/T indices relative to both other conditions. This means that participants were better able to synchronize their drumming with the tempo changes in the pacing sequence when they observed visual cues based on conductor gestures, presumably because the continuous and naturalistic nature of these cues provided temporal information about the onset of upcoming beats. Interestingly, when questioned following the experiment, 11 of the 29 musicians reported that the two moving visual cues were not helpful, or sometimes even distracting. Given that most of the musician sample could synchronize quite easily with just the auditory stimulus (as seen in the stationary circle condition), any difference in performance between conditions may have gone unnoticed by these participants due to a near-ceiling effect. However, as reported above, the conductor did objectively improve performance slightly but significantly compared to the stationary circle and the no-acceleration circle. This supports the idea that compatible cues from different modalities (Hills et al., 2002), as well as a dynamic velocity profile with clear deceleration towards a turnaround point (Balasubramaniam, Wing, & Daffertshofer, 2004; Luck & Toiviainen, 2006; Varlet et al., 2014a), are beneficial to performance even if skilled participants remain unaware of these benefits.

The nonmusicians also benefited from visual cues, though their asynchrony scores were much higher and more variable compared to the musicians. To validate the relation between asynchrony and P/T index measures, we correlated the two variables within both groups, and across all participants. Indeed there were significant negative correlations as expected, suggesting that high prediction resulted in lower asynchrony. While a few conductor studies have found that synchronization relates to high acceleration of the conductor baton (Luck & Nte, 2008; Luck & Toiviainen, 2006), they were not concerned with the mechanism through which acceleration impacts visuo-motor synchrony. Our finding that temporal anticipation was greatest with the conductor visual cue in this study provides causal evidence that, as

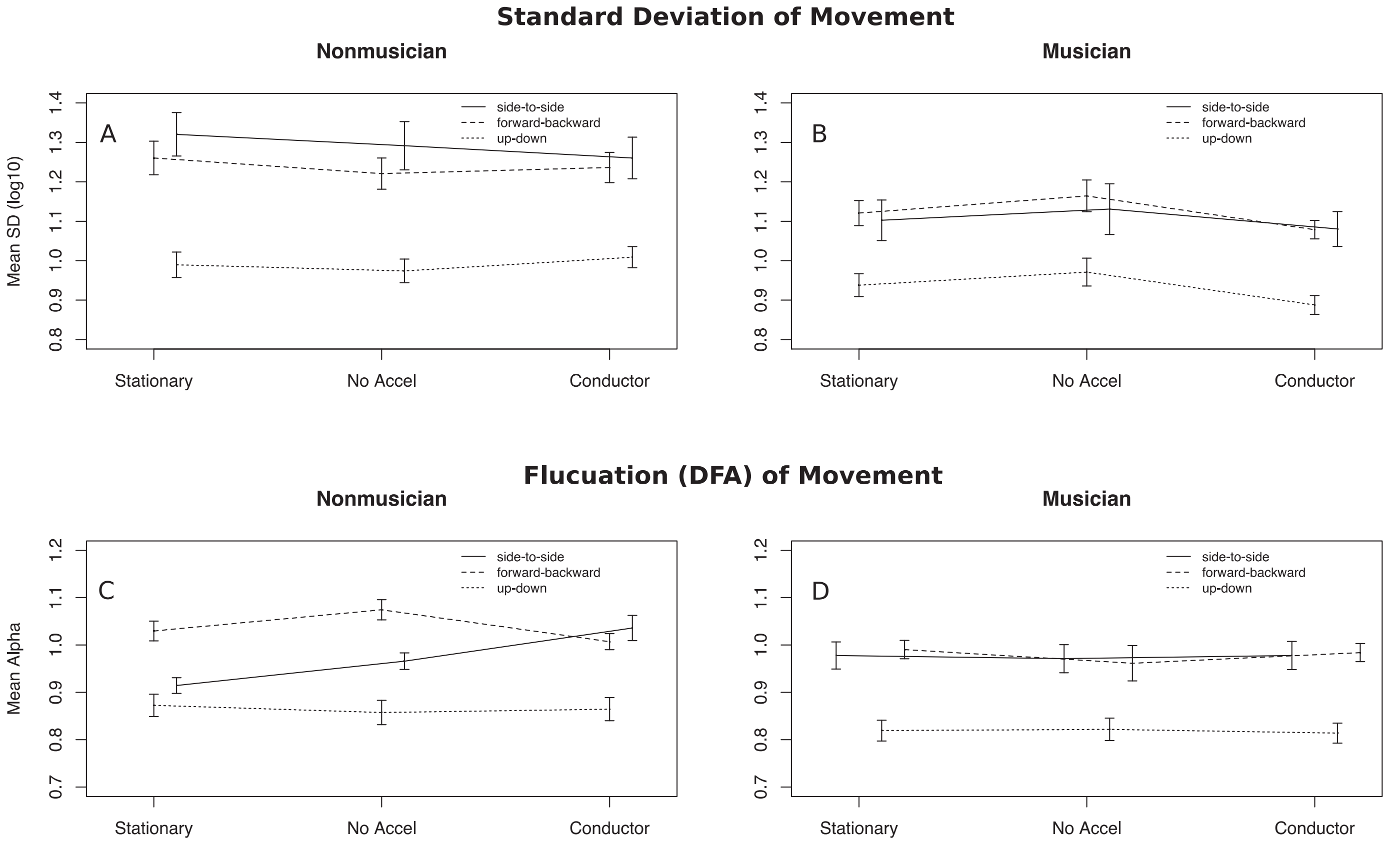

Fig. 4. Average standard deviation of movement (log 10 transformed, panels A and B) and average αDFA (panels C and D). Expertise group is separated by panel, and direction of movement is separated by line type within a plot. Error bars represent standard error.

hypothesized, the way in which a conductor helps an ensemble is, at least partly, by facilitating temporal predictions.

For both expertise groups, the no-acceleration stimulus had no effect on drumming performance relative to the stationary circle. This is important when set against the effects observed with the virtual conductor stimulus, as it suggests that visuo-motor timing is influenced by noticeable changes in speed of a moving stimulus, rather than by the motion itself. This interpretation is consistent with previous studies that found that particular velocity profiles are important for visuo-motor tracking both in ecologically valid conducting (Luck & Nte, 2008; Luck & Toiviainen, 2006) and more basic experimental tasks (Varlet et al., 2014a; Zelic et al., 2016). However, the no-acceleration stimulus in this experiment was not representative of natural human movement, as periodic motion in the human motor system is not constant in velocity. Thus, the no-acceleration condition could be considered incompatible with participants' actions (Viviani, n.d.; Hove, Spivey, & Krumhansl, 2010; Lacquaniti, Terzuolo, & Viviani, 1983; Saygin & Stadler, 2012; Viviani & Flash, 1995)—especially during the circle's upward movement (Hove et al., 2010)—and this could explain why it was not as helpful as the virtual conductor. However, a study of visuomotor synchronization with similar visual stimuli to our own (Hove et al., 2010), albeit presented at a steady tempo, found a benefit of non-biological stimuli where we did not. This could be because the tempo changes our auditory stimuli were comparatively difficult to synchronize with, and the sounds were the synchronization target rather than visual signals alone. Again, this lends support for the importance of a dynamic velocity profile in human movement coordination.

The results of the kinematic analysis showed only a small effect of visual cue on ancillary movement, but this still offers some intriguing considerations regarding movement and music. First, the group difference in movement amplitude is interesting as it shows that for this task, nonmusicians were moving their heads more than musicians. This could be because the nonmusicians found the task more challenging (as evidenced by their larger asynchronies) and needed to embody the beat by activating vestibular networks (see Todd & Lee, 2015) more than musicians needed to, as musicians are generally better able to predict tempo changes and correct errors when synchronizing with auditory sequences alone (Manning et al., 2017; Pecenka & Keller, 2011; Repp, 2010). Indeed, there are some studies showing how movement, particularly of the head, can help establish or reinforce musical beat and meter (Phillips-Silver & Trainor, 2005; Phillips-Silver & Trainor, 2007; Phillips-Silver & Trainor, 2008), that head movements increase with difficulty in a musical task (Goebl & Palmer, 2009), and that spontaneous movements relate to beat-intervals (Toiviainen, Luck, & Thompson, 2010). The musicians on the other hand may have moved more with syncopated (complex) rhythms, rather than predictable beat sequences that have been shown to be too simple to induce movement (Witek et al., 2017). Ancillary movements might sometimes be communicative (Kawase, 2014; Keller & Appel, 2010) or serve as coordination smoothers (Vesper et al., 2010), leading musicians to move more in the presence of a co-performer, which could be addressed in a future study. However, both groups showed low levels of movement overall, so while the group difference is statistically significant, the effect size is small.

We also found varying responses to visual cues depending on expertise, as seen in the side-to-side movements, which were more structured—meaning the movements followed a more rhythmic pattern—in the conductor condition than the other two conditions for the nonmusicians only. That is, as the complexity of the visual cue increased (no movement ➔ no-acceleration ➔ conductor) so did the determinism of side-to-side movement. In other words, the no-acceleration motion elicited more structured movement than the stationary circle, and the conductor elicited more structured movement than both other conditions in the nonexpert group. However, within this group,

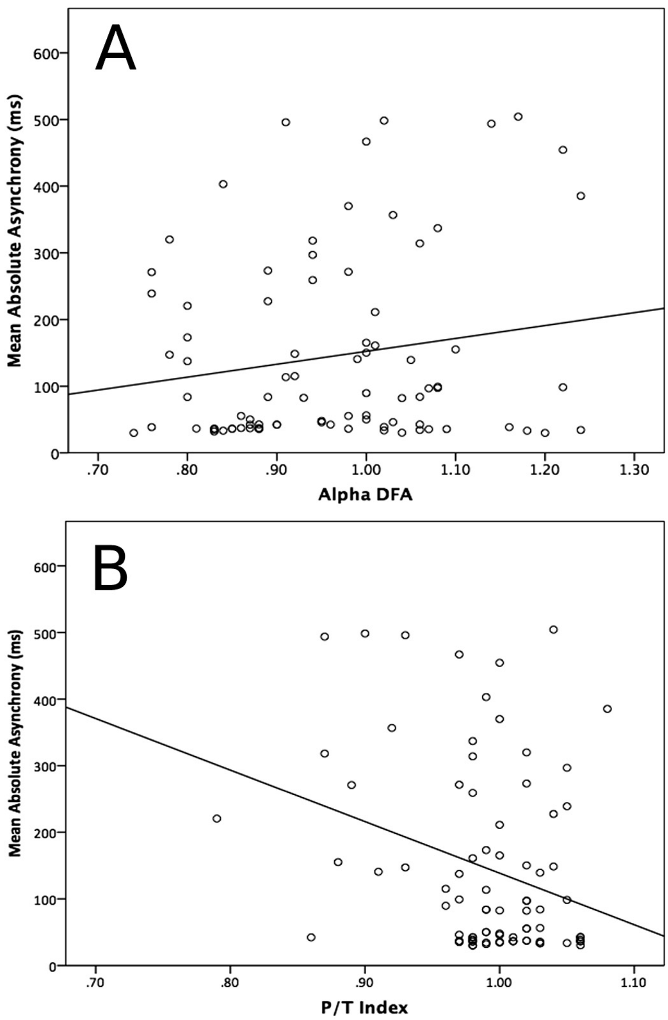

Fig. 5. Scatterplots showing the relationship between movement fluctuations and asynchrony (panel A), and the P/T index and asynchrony (panel B).

higher αDFA was associated with higher asynchrony, suggesting that more structured movement might indicate rigidity, which is not conducive to synchronization.

This finding could be a matter of criticality (Bak, Tang, & Wiesenfield, 1987), the idea that a dynamical system will stay within a flexible regime (i.e. pink noise, or $1/f$ fluctuations) in order to be able to adapt to the environment. Musicians, therefore, may have a more adaptable sensorimotor system in this context, which is realized by keeping ancillary fluctuations within a window very close to $1/f$. Indeed, this pattern of fluctuation is often associated with a flexible, well-functioning system (Hove et al., 2012; Pressing, 1999; Wang & Yang, 2012). Some nonmusicians on the other hand, may have transitioned out of a flexible regime into a deterministic or rigid regime. This sort of transition is commonly seen in pathological or sub-optimal performance (Stergiou & Decker, 2011; Wang & Yang, 2012), suggesting that in this task, rigid movements were associated with poorer performance. This finding, while contrary to our hypothesis that more deterministic movements would relate to better performance, corroborates findings that experts tend to show lower alpha values than non-experts—indicative of greater flexibility—in measures of the experts' domain (e.g. trained runners show lower alphas in measures of running gait cycles compared to non-runners) (Cohen & Sternad, 2009; Nakayama, Kudo, & Ohtsuki, 2010; Wilson et al., 2008). While the conductor visual cue was associated with lower asynchroies at the group level, the conductor visual cue also yielded higher αDFA than the other cues. However, αDFA and asynchrony showed a positive relationship in the regression analysis, suggesting that a deterministic regime was prompted by the conductor, but was not helpful for synchronization for some people.

However, the regression also showed that temporal anticipation (P/T index) can statistically predict lower asynchrony for non-experts. This means that in addition to potential influence from embodied cognitive processes as measured by αDFA, nonmusicians' synchronization performance was influenced by anticipatory cognitive processes. With more experience synchronizing with tempo changing beat sequences, the nonmusicians might be able to rely on internal predictive processes more, and embodied processes less, or learn to maintain ancillary movements in a flexible range of fluctuations ($1/f$-type fluctuation) as the musicians do.

Future studies might consider the effect of visual cues in synchronization without an accompanying auditory sequence, in order to approximate the situation faced by ensemble musicians more closely. In this study the auditory stimulus was always presented during a trial, which created a clear objective: match the beat of the music. However, in most cases of music performance, the performers create sound without an auditory beat provided. Thus, it could be the case that participants—especially the musician group—would show more complex or rhythmically salient movements without an auditory sequence, as the task of following a visual reference alone is more difficult (Grahn, 2012; Repp, 2003). Alternatively, synchronization without an auditory reference may give participants more control over their actions, allowing ancillary movements to unfold in a more flexible regime. Given evidence that people will use the most reliable modality of timing information (Elliott, Wing, & Welchman, 2010; Ernst & Banks, 2002), participants might then use proprioceptive cues via ancillary movement if the auditory information is unreliable (i.e. not externally driven). Of course, if the task becomes too difficult movement could become highly irregular or even task-irrelevant. Overall, the role of movement in music is complex, and is likely mediated by numerous variables including individual differences or preferences for movement, the presence of co-performers, the difficulty or rhythmic complexity of the music, and the expressive qualities of the music since movements are not strictly related to timing, but to expression as well (Castellano et al., 2008; Davidson, 2012). These issues notwithstanding, the present experiment provides evidence that instrumental and ancillary processes can be modulated by multisensory cues and expertise to influence SMS performance.

6. Conclusion

In this study, we have shown that a typical conducting pattern characterized by rapid changes in vertical velocity is, to some extent, causally linked to improved musical synchronization. The conductor also improved temporal anticipation, suggesting that conductor kinematics facilitate the prediction of beat timing, which may be the mechanism through which synchronization is improved. Interestingly, the effect on prediction was true for both ensemble musicians, and people with no formal musical training. We also examined head movements and found no effect of visual cue on the magnitude or structure of musicians' movements, but a small effect of visual cue on the structure of nonmusicians' movements. These results suggest that visual cues could be beneficial to interpersonal timing, particularly in the ecologically valid case of a music ensemble. Although the role of ancillary movements in timing is still unclear, we have provided some evidence that conductor gestures promote more structured movements (relative to a simple moving stimulus devoid of acceleration changes) in non-experts, and that this increase in movement structure was associated with a group-level increase in asynchrony. This suggests that for this task, ancillary movements are most useful in a flexible regime, as seen in the musicians, and that individual differences in ancillary movements can be problematic if they become too rigid as seen in the nonmusicians. However, this process is moderated by experience and context.

Declarations of interest

None.

Appendix A

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