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RESEARCH ARTICLE

Single (1:1) vs. double (1:2) metronomes for the spontaneous entrainment and stabilisation of human rhythmic movements

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Abstract
Rhythmic movements produced by humans become spontaneously entrained to auditory rhythms in the environment. Evidence suggests that synchronisation to external auditory rhythms can contribute to the stabilisation of movements in time and space, opening new perspectives for motor training and rehabilitation. Here we compared the effects of single (1:1) and double (1:2) metronomes (i.e., one or two stimulations per preferred movement cycle) on spontaneous movement entrainment and stabilisation. We examined the spontaneous entrainment of self-paced hand-held pendulum swinging when single or double metronomes were presented either at the participant's preferred tempo or slightly slower or faster (± 10%). The results showed that participants' movements spontaneously entrained to auditory rhythms, and that the strength of this entrainment was the same for single and double metronomes. However, double metronomes decreased movement tempo stability, whereas single metronomes increased movement tempo stability compared to a control condition without a stimulus. These effects preferentially occurred for metronomes presented at participants' preferred movement tempi and especially for participants whose movements were intrinsically more variable. Participants' movement amplitude stability was also modulated in such a way that the stability of participants who were intrinsically less stable increased, whereas the stability of intrinsically more stable participants decreased with auditory rhythms, an effect that was stronger with double than single metronomes. Moreover, movement stabilisation in time and space were positively correlated, suggesting that tempo and amplitude stabilisation depend on similar processes and may be complementary. These findings provide new insight into the processes underlying auditory-motor entrainment and how auditory rhythms can be used to improve movement stability in time and space.

Keywords Entrainment · Synchronisation · Movement · Variability · Metronome

Introduction

Auditory-motor synchronisation is ubiquitous in everyday life. It occurs in a wide variety of situations, exemplified by the induction of body movements while listening to music or by gesturing in response to a conversation partner (Burger et al. 2014; Miyata et al. 2017; Demos et al. 2012; Néda et al. 2000; Phillips-Silver et al. 2010; Repp and Su 2013; Torre et al. 2013; Van Dyck et al. 2015). While auditory-motor synchronisation can occur intentionally, it often arises spontaneously, such as when the steps or body sway of an individual become spontaneously and intermittently synchronised with external auditory rhythms without the intention to do so (Néda et al. 2000; Repp 2006). Auditory-motor synchronisation can also modulate individual movement dynamics, and in some circumstances, improve the stability of an individual's movements in time and space (Fink et al. 2000; Kudo et al. 2006; Roerdink et al. 2009). In clinical contexts, it has been shown that the movement of patients with motor disorders can be enhanced by presenting auditory rhythms (Hove and Keller 2015; McIntosh et al. 1997; Thaut et al. 1996, 1997). The gait of patients with Parkinson's disease or stroke, for instance, can be improved with auditory cueing (Ghai et al. 2018). Benefits of auditory rhythms have also been demonstrated in running performance through the improvement of movement stability, especially when the tempo of the auditory rhythms matches the runner's cadence (Bood et al. 2013; Van Dyck et al.

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2015). The aim of the present study is to better understand the properties of auditory rhythms that modulate the occurrence and strength of spontaneous auditory-motor entrainment. Here we investigate whether the use of single (1:1) or double (1:2) metronomes (one or two stimulations per preferred movement cycle) influences spontaneous movement entrainment and stabilisation.

Rhythmicity is a fundamental property of biological systems and human movement systems are no exception (Kelso 1997; Kugler and Turvey 1987; von Holst 1973). Rhythmicity characterises a broad range of movement patterns exhibited by humans, such as when speaking, walking, running, or playing music. Although these movement patterns occur at preferred tempi that depend on individual biomechanical constraints, they can be attracted or entrained to external rhythms that are faster or slower than an individual's preferred tempo (Beek et al. 1995; Kay et al. 1987; Schmidt and O'Brien 1997). The speech, body sway, footsteps or hand movements of an individual, for instance, can be spontaneously attracted to auditory and visual rhythms in the environment, including those produced by other people acting at their own preferred tempo (Burger et al. 2014; Demos et al. 2012; Richardson et al. 2007; Tognoli et al. 2007; Varlet et al. 2011, 2014; van Ulzen et al. 2008).

Previous research has provided evidence that spontaneous movement synchronisation to external rhythms is governed by the dynamical entrainment processes of coupled oscillators (Coey et al. 2012; Kelso 1997; Large 2008; Néda et al. 2000; Schmidt and Richardson 2008; Schmidt and O'Brien 1997; Varlet et al. 2017a). Movements thus become spontaneously and intermittently synchronised with external rhythms in a manner predicted by the well-established Haken–Kelso–Bunz (HKB) coupled oscillator model (Coey et al. 2011; Haken et al. 1985; Richardson et al. 2007; Schmidt and O'Brien 1997; Schmidt and Richardson 2008). A key phenomenon is that more consistent movement-stimulus phase relations occur spontaneously over time (Pikovsky et al. 2003). Furthermore, in accordance with the HKB model's predictions, it has been shown that the occurrence and strength of entrainment depend on the difference in tempo between an individual's preferred movement and the external rhythm (Assisi et al. 2005; Fuchs et al. 1996; Lopresti-Goodman et al. 2008; Schmidt and O'Brien 1997; Varlet et al. 2016). The strongest entrainment occurs when the difference between the tempo of the external rhythm and the individual's preferred movement tempo is minimal, whereas entrainment vanishes when the tempo difference is too large to be compensated for by spontaneous sensory-motor coupling. This frequency detuning effect has been observed for movement synchronisation with visual and auditory rhythms (Bardy et al. 2015; Leman et al. 2013; Lopresti-Goodman et al. 2008; Styns et al. 2007; Van Dyck et al. 2015; Zamm et al. 2015, 2016). However, the properties of rhythms that support stronger coupling—hence more effective compensation for frequency detuning and enhanced entrainment—remain largely unclear, especially in the context of auditory-motor synchronisation.

Of particular relevance in the present context, research conducted predominantly on intentional synchronisation (e.g., situations, where individuals are instructed to synchronise with an auditory metronome) suggests that coupling can be stronger with double metronomes (i.e., two stimulations per movement cycle) than with single metronomes (i.e., one stimulation per movement cycle). Fink et al. (2000) investigated the stability of bimanual coordination when movement rate was progressively increased, and found that participants were able to maintain anti-phase coordination between their two index fingers at faster movement rates when paced by a double metronome compared with a single metronome. Greater bimanual coordination stability with double metronomes was also found by Kudo et al. (2006), and Repp (2003) showed a related 'subdivision benefit' in the case of unimanual synchronisation of finger taps with auditory and visual pacing sequences. Benefits of double metronomes have also been reported for locomotion. Roerdink and colleagues examined stroke patients and control participants who were instructed to synchronise with metronome beats pacing either the footfalls for just one foot (single metronome) or both feet (double metronome). More stable synchronisation was found with double metronomes in both control and stroke groups (Roerdink et al. 2009). Although these studies mostly examined intentional synchronisation in situations involving intrapersonal coordination (e.g., coordination between hands or legs), the results suggest that double metronomes (i.e., two stimulations per preferred movement cycle) might strengthen the coupling and spontaneous entrainment of a single self-paced rhythmic movement compared to single metronomes.

It is, furthermore, noteworthy that the presentation of auditory metronomes does not only facilitate the stability of synchronisation with the external signal, but can also help to reduce an individual's own movement variability in both time and space (Byblow et al. 1994; Fink et al. 2000; Kudo et al. 2006; Roerdink et al. 2009, 2013). Beneficial effects of auditory cueing have been reported with regard to various properties of a variety of movements. Although these effects occur with single metronomes, the studies described above indicate stronger effects with double metronomes. Fink et al. (2000) found that the spatial variability of participants' movement trajectories at maximal flexion and extension points decreased with double metronomes compared with single metronomes. It has been suggested that this local 'anchoring' effect contributes to the stabilisation of global bimanual coordination (Jirsa et al. 2000). Kudo et al. (2006) reported increased movement amplitude of participants with double metronomes, although Roerdink et al.

(2009) did not find a corresponding difference between the types of metronomes at the level of step width in locomotion. Together, these results suggest that double metronomes (i.e., two stimulations per preferred movement cycle) might not only strengthen the coupling and entrainment but also modify intrinsic movement dynamics in time and space to a greater extent than single metronomes (i.e., one stimulation per preferred movement cycle).

The aim of the current study is to address the effects of double metronomes on rhythmic movement by comparing the effects of single vs. double metronomes on the occurrence of spontaneous auditory-motor entrainment and movement stabilisation. Participants were instructed to swing a hand-held pendulum at their preferred tempo while listening to the two types of auditory metronomes, which were presented either at the participant's preferred tempo or slightly slower or faster than the preferred tempo (i.e., 10%). It was hypothesized that double metronomes (i.e., two stimulations per preferred movement cycle) would lead to stronger entrainment and movement stabilisation (reduced variability in tempo and amplitude) than single metronomes (i.e., one stimulation per preferred movement cycle). We also assumed that movement stabilisation would preferentially occur for individuals who have intrinsically more variable movements. While this assumption is supported by stabilisation effects reported for populations exhibiting relatively large variability in movement tempo and amplitude, such as elderly people or stroke and Parkinson's patients (Dotov et al. 2017; Hove and Keller 2015; Roerdink et al. 2009, 2011; Thaut et al. 1996, 1997), it is unclear whether it holds in the general population.

Method

Participants

Twenty-two psychology undergraduates from Western Sydney University volunteered to participate in the experiment (12 females and 10 males aged from 18 to 47 years; $M = 26.43$, SD 7.29). All participants were right-handed, had normal hearing and normal or corrected-to-normal vision. Participants received credit in partial fulfilment of course requirements and all provided written informed consent prior to the experiment, which was approved by the Western Sydney University Ethics Committee.

Apparatus

Apparatus included a chair with a custom-built support on the right armrest, upon which the participant's forearm was positioned to perform the pendulum-swinging task. The chair was positioned in front of a 22-inch BenQ computer monitor that displayed visual stimuli for a letter detection task.

Auditory metronomes consisted of 400 Hz sine tones. The duration of the tones was 150 ms, including a 10 ms linear fade in and fade out. The metronomes tones were presented via Sennheiser HD 280 pro headphones (Sennheiser, Wedemark, Germany) at a comfortable intensity, which was kept the same for all participants.

The pendulum-swinging task was carried out using a wooden pendulum with a length of 45 cm and a 75 g mass attached at its base, resulting in an eigenfrequency of 0.94 Hz. A $1 \times 1 \times 1.5$ cm sensor was attached to the pendulum to record the oscillations produced by the participant via a Polhemus LIBERTY motion-tracking system (Polhemus Ltd., VT, USA) at a sampling rate of 240 Hz with 0.01 mm spatial resolution. Movement data were recorded together with the metronomes presented to the participant on a PC computer for off-line analyses.

A letter detection visual task requiring constant vigilance was presented to participants on the monitor to prevent intentional synchronisation and visuomotor interference due to eye movements (Lopresti-Goodman et al. 2008; Varlet et al. 2016). For this task, a fixation cross displayed at the centre of the monitor alternated with letters, occurring briefly for 0.67 s at random time intervals between 4 and 18 s, throughout each trial. The participant was asked to read aloud the letters and the experimenter monitored the participant's responses.

Procedure

On arrival, an information sheet was given to the participant before obtaining written consent. The information sheet described the main task as a letter detection task with auditory and movement distracter tasks, requiring the participant to swing a hand-held pendulum at her/his preferred tempo, while reading aloud letters that flashed at random times at the centre of the monitor. This cover story was used to ensure that the movement synchronisation of participants was spontaneous.

While seated in the chair in front of the monitor, the participant was then instructed to swing the pendulum from the right wrist joint parallel to the sagittal plane (ulnar–radial flexion–extension) (see Fig. 1; Lopresti-Goodman et al. 2008; Varlet et al. 2016). The participant practiced swinging the pendulum until a comfortable preferred movement tempo was established. The participant's preferred movement tempo was then recorded in three trials of 60 movement cycles without any auditory metronomes presented. The participant was then provided with headphones (over which the auditory metronomes were presented) before starting the experimental trials.

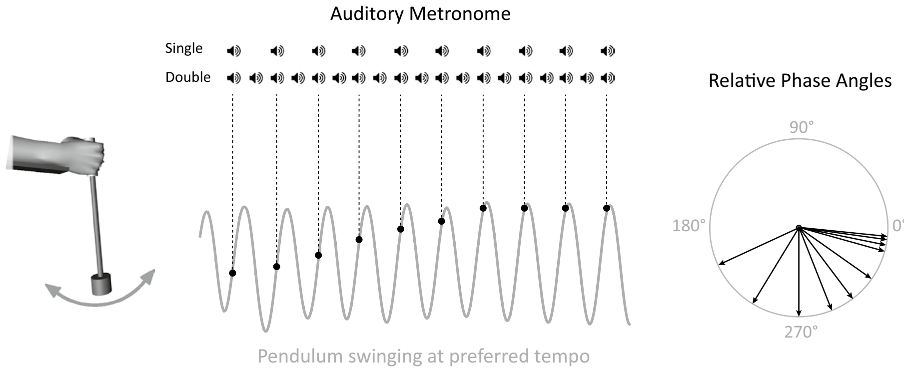

Fig. 1 Illustration of the pendulum-swinging task performed by participants when listening to single (i.e., one stimulation per preferred movement cycle) and double (i.e., two stimulation per preferred movement cycle) metronomes, and of a representative movement time series with the corresponding movement-metronome relative phases angles

Two independent variables, metronome condition [single, double, and control (mute)] and tempo (− 10%, preferred and + 10%), were manipulated across 36 trials presented in randomized order. Single and double metronome trials consisted of 8 s without auditory stimulus followed by 45 cycles of the auditory stimulus. Control trials were the same duration, 8 s followed by 45 cycles, but with the auditory stimulus muted to estimate the degree of synchrony that could occur by chance. Control trials were used in the different conditions (despite participants not being able hear and distinguish the muted metronomes), because the degree of synchrony that occurs by chance can differ depending on the stimulus tempo (i.e., with metronomes at preferred tempi leading to greater incidental synchrony). Single and double metronomes corresponded to one (single, 1:1) or two (double, 1:2) tones per participant's preferred movement cycle (Preferred condition) or one or two tones per participant's preferred movement cycle ± 10%. In other words, single and double metronomes were the same except that the frequency of double metronomes was twice as fast as the frequency of single metronomes. The participant was asked to swing the pendulum at her/his preferred movement tempo throughout each trial, while reading aloud the letters that flashed on the screen. The participant's responses were monitored (but not recorded) by the experimenter to make sure that the participant remained focused on the letter detection visual task. The participant was asked to start swinging the pendulum and then the experimenter initiated each trial manually at a random phase of the participant's oscillation.

Experimental trials were completed in approximately 45 min with short breaks between trials taken as required. At the end of the experiment, the participant was asked to complete a questionnaire to obtain demographic information, and he or she was debriefed on the purpose of the study.

Design and analysis

The first 10 s of each trial were discarded to remove transient fluctuations in movement time series. The movement time series data were then centred around zero and bandpass filtered between 0.1 and 15 Hz using a bidirectional Butterworth filter to remove very slow and high frequency fluctuations (Richardson et al. 2007; Varlet et al. 2016).

The length of the mean resultant vector of the relative phase angles between participants' movements and stimulus onsets was then computed using circular statistics to obtain the degree of synchrony, with 0 corresponding to no synchrony (i.e., all possible phase relations occurring equally often over the trial) and 1 corresponding to complete synchrony (i.e., a constant phase relation throughout the trial) (Batschelet 1981; Pikovsky et al. 2003). The relative phase angles were obtained by calculating the continuous phase of participants' movement time series with a Hilbert Transform and extracting phase values at stimulus onsets. The phase synchrony in the control trials was computed the same way with the exception that auditory stimuli were mute. Synchrony was computed for the different conditions, because the degree of incidental synchrony that is expected to occur by chance differs depending on the stimulus tempo.

The time between the points of maximum angular extension, as defined by the maxima of the movement time series, was also extracted to compute the participant's average preferred movement period (tempo), and the corresponding coefficient of variation (COV = SD/Mean × 100), which was used to index the magnitude of the variability of movement tempo. The distance between maximum angular flexion and extension of each movement cycle, as defined by the difference between two consecutive minima and maxima of the movement time series, was computed to determine the average movement amplitude and the corresponding COV.

Repeated-measures analyses of variance (ANOVAs) with factors of metronome condition [single, double, and control (mute)] and tempo (− 10%, preferred, + 10%) were conducted on each of the five dependent variables—movement synchrony, movement period (mean and COV), and movement amplitude (mean and COV). Post hoc analyses were conducted when necessary using Bonferroni post hoc tests.

To examine whether the effects of auditory metronomes on participants' movement variability depended on individual participant's intrinsic levels of variability, we computed separately for each participant a stabilisation index for the movement period and amplitude. This stabilisation index was calculated by subtracting the COV (period or amplitude) obtained in the control conditions (all tempo conditions averaged together) from the COV (period or amplitude) obtained in the different single and double metronome conditions. Negative values of these indexes indicated the occurrence of stabilisation (decrease of period or amplitude variability) compared to the control condition. For each tempo condition, correlation analyses between the stabilisation index and the COV exhibited in the control condition were conducted to determine whether the inherent level of movement variability of participants predicted the degree of stabilisation occurring when the metronome was presented.

Results

Movement synchrony

The ANOVA performed on movement synchrony data (see Fig. 2) yielded a significant main effect of Metronome, $F(2, 42) = 6.00$, $p = 0.0051$, $\eta_p^2 = 0.222$. Post hoc comparisons indicated that synchrony in both the single ($p = 0.01$) and the double ($p = 0.02$) conditions were significantly higher than the control condition, but not significantly different from each other ($p = 1.0$). The ANOVA also revealed a significant main effect of Tempo, $F(2, 42) = 17.00$, $p < 0.0001$, $\eta_p^2 = 0.46$. Post hoc comparisons indicated larger synchrony in the preferred tempo condition ($M = 0.35$, SD 0.04) compared to the −10% ($M = 0.09$, SD 0.02, $p < 0.0001$) and +10% ($M = 0.18$, SD 0.03, $p = 0.002$) conditions. No interaction between stimulus condition and tempo was found, $F(4, 84) = 1.39$, $p = 0.24$, $\eta_p^2 = 0.062$. This pattern of results indicates that synchrony was higher in the preferred tempo condition irrespective of whether or not a metronome was presented, and that greater synchrony with the single and double metronomes relative to the control condition occurred across the different tempo conditions.

Movement period

The ANOVA performed on the mean movement period data revealed a significant main effect of Tempo, $F(2, 42) = 3.365$, $p = 0.044$, $\eta_p^2 = 0.14$. This effect indicates that that participants' mean movement period decreased with faster metronomes ($M = 1.013$, SD 0.001) and increased with slower metronomes ($M = 1.023$, SD 0.004) compared to metronomes presented at the preferred tempo ($M = 1.017$, SD 0.002). The ANOVA on mean movement period did not yield any other significant effects (all p values > 0.05), indicating that participants exhibited the same movement tempo for single and double metronomes.

The ANOVA performed on the COV of participants' movement period revealed a significant main effect of Metronome, $F(2, 42) = 3.85$, $p = 0.029$, $\eta_p^2 = 0.16$, and a significant interaction between Metronome and Tempo, $F(4, 84) = 2.77$, $p = 0.032$, $\eta_p^2 = 0.12$. This pattern of results indicates that participants' movement tempo variability increased with double metronomes compared to single and control metronome conditions, especially when metronomes were presented at participants' preferred movement tempi (see Fig. 3). Post hoc comparisons indicated a significant difference between the single and double metronomes for the preferred tempo condition ($p = 0.044$).

Correlation analyses conducted on the stabilisation index values of participants' movement period yielded significant correlations between the degree of stabilisation (or destabilisation) occurring when auditory metronomes were presented and participants' intrinsic movement variability (in the

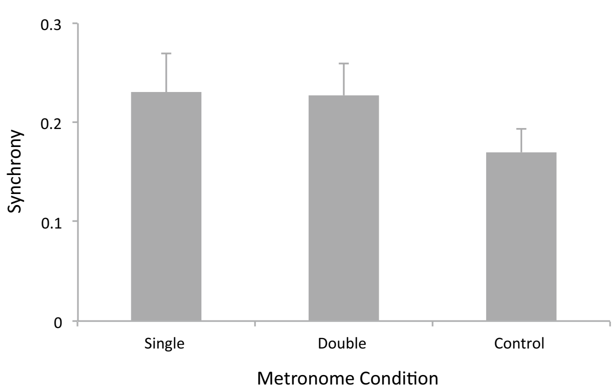

Fig. 2 Movement synchrony as a function of the different metronome conditions. The error bars represent the standard error of the mean

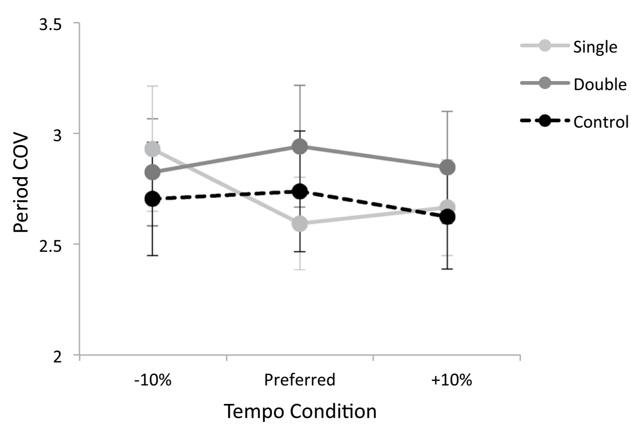

Fig. 3 Movement tempo variability as a function of the different metronome and tempo conditions. The error bars represent the standard error of the mean

control condition without metronomes). As seen in Table 1 and Fig. 4, the correlations for single metronomes in the preferred and + 10% tempo conditions were significant (p values < 0.05). If corrected for multiple comparisons using Bonferroni correction, only the correlation in the preferred tempo condition remained significant ($p < 0.008$). These results show that participants' movement timing was modulated as a function of their intrinsic stability—stabilisation for intrinsically less stable participants and destabilisation for more stable participants—only with single metronomes, especially when presented at the preferred tempo. Although stabilisation index values were not correlated with participants' intrinsic movement variability for the double metronome conditions, it can be noted that the values were in general more positive, especially for the preferred tempo condition, in line with the destabilisation effects revealed by the ANOVA.

Movement amplitude

The ANOVAs performed on the mean and COV of participants' movement amplitudes did not reveal any significant effects (all p values > 0.05). As seen in Table 1 and Fig. 4, correlation analyses conducted on the stabilisation index values of participants' movement amplitudes yielded significant correlations for single metronomes in + 10% tempo condition and for double metronomes in − 10% and + 10% (p values < 0.05). Only the correlation for the double metronome in − 10% condition was close to significance if corrected for multiple comparisons (p value close to 0.008). These results suggest that the movement amplitude of intrinsically less stable participants tended to stabilise, whereas movement amplitude of more stable participants tended to destabilise while listening to auditory metronomes, a modulation that seems to appear clearer with double metronomes.

Table 1 Correlational analyses on period and amplitude movement stabilisation

	Period stabilisation ($n = 22$)				Amplitude stabilisation ($n = 22$)			
	Single		Double		Single		Double	
	r^2	p	r^2	p	r^2	p	r^2	p
− 10%	0.038	0.386	0.085	0.187	0.015	0.585	0.292	0.009*
Preferred	0.493	0.0003*	0.001	0.879	0.051	0.312	0.009	0.681
+ 10%	0.258	0.016*	0.015	0.589	0.219	0.028*	0.203	0.035*

*p < 0.05

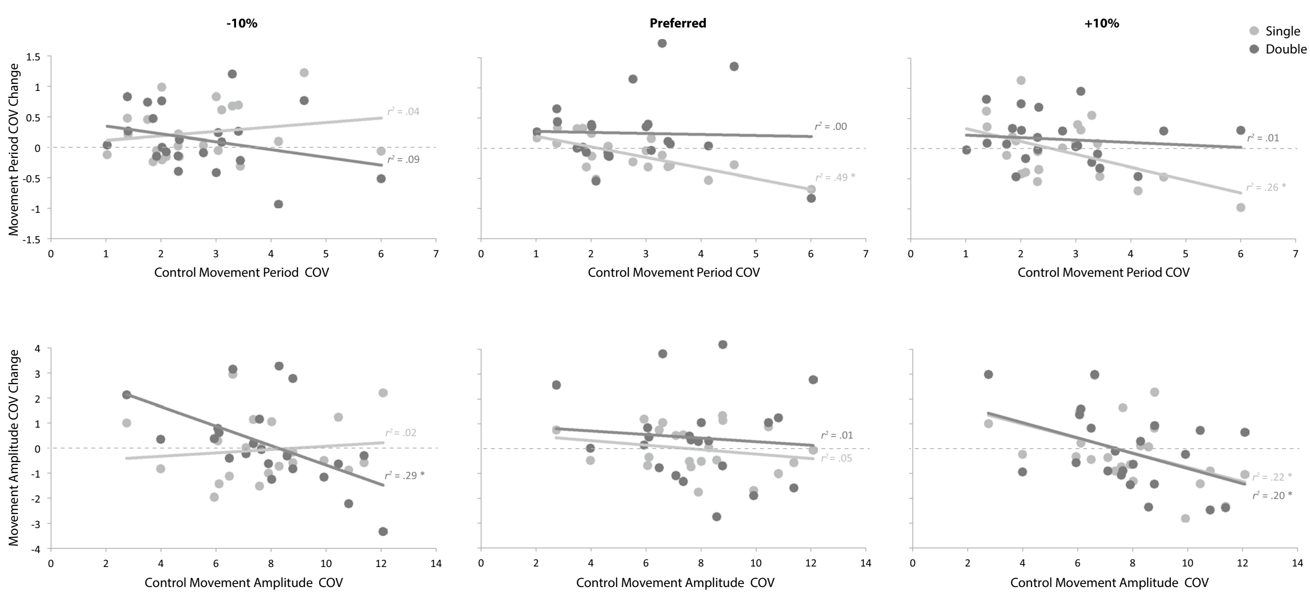

Fig. 4 Correlational analyses between movement (tempo and amplitude) coefficient of variation in the control condition with no metronome and movement (tempo and amplitude) stabilisation occurring with metronomes. Data are presented for single (light grey) and double (dark grey) metronomes for the different tempo conditions. The diagonal indicates the line of best fit

Discussion

The present study investigated the effects of single (1:1) vs. double (1:2) metronomes (1 vs. 2 stimulations per preferred movement cycle) on the occurrence of auditory-motor entrainment and movement stabilisation. Participants swung a hand-held pendulum at their preferred tempo while listening to either single or double metronomes that were presented at each individual's preferred movement tempo or slightly slower or faster (± 10%). The results demonstrated that single and double metronomes led to the same degree of movement entrainment but differing modulations of participants' movement stability.

Auditory-motor entrainment

Despite participants being instructed only to maintain their preferred movement tempo when swinging the pendulum, the results demonstrated spontaneous entrainment to the metronomes, in line with previous studies investigating sensorimotor entrainment (Burger et al. 2014; Demos et al. 2012; Lopresti-Goodman et al. 2008; Néda et al. 2000; Varlet et al. 2016). Phase relations between participants' movements and metronome beats were more consistent when listening to auditory metronomes compared to the control condition in which metronome beats were mute. The movement tempo (period) exhibited by participants also tended to match the stimulus period in the auditory metronome conditions. The results showed, however, that spontaneous movement entrainment was not strengthened with double metronomes compared to single metronomes. Two stimulations per preferred movement cycle did not increase the coupling strength and the entrainment of the oscillator driving movement. Specifically, the consistency of movement-metronome phase relations did not increase with double metronomes, and the movement period exhibited by participants with single and double metronomes did not differ.

These finding suggest that benefits of double metronomes on between-hand or between-leg motor coordination observed in previous research might not arise due to more stable auditory-motor coordination. As suggested by Fink et al. (2000), increased stability of bimanual coordination occurring with double metronomes may rather originate from reduced movement variability in space (an 'anchoring' effect), contributing in turn to stabilising global coordination between the two hands [see also Beek (1989) for seminal work on anchoring]. We observed similar changes in variability, as discussed below, suggesting a potential role of anchoring in spontaneous auditory-motor synchronisation.

Movement stabilisation in time

The results of the current study show that the presentation of an auditory metronome can stabilise an individual's movement tempo, especially when it is presented at his or her preferred movement tempo and when the individual's movement is intrinsically low in stability. By contrast, destabilisation tended to occur when participants' movements were intrinsically more stable. Interestingly, correlations between the degree of stabilisation in time and intrinsic movement variability were not observed with double metronomes. Furthermore, when presented at participants' preferred movement tempi, double metronomes in fact were associated with larger variability than single metronomes. Movement stabilisation of a single movement oscillator might, therefore, be optimal with single metronomes, with double metronomes leading to interference rather than stabilisation. This finding has implications for optimising movement stabilisation using auditory cueing in more complex, natural motor behaviours such as gait or running, as double metronomes might benefit global coordination by stabilising different effectors but at the same time increase variability at a more local level.

Movement stabilisation in space

In addition to effects of timing, the current results revealed spontaneous modulations of participants' movement spatial variability in the presence of auditory metronomes. Correlation analyses suggested that these modulations were stronger with double metronomes compared to single metronomes, which is in line with the effects reported in previous studies of between-hand and between-leg coordination (Fink et al. 2000; Kudo et al. 2006; Roerdink et al. 2009). As seen in Fig. 4, amplitude variability of intrinsically less variable participants tended to increase, whereas amplitude variability of intrinsically more variable participants tended to decrease with the presentation of metronomes, especially the double metronome. This finding supports the hypothesis advanced in previous studies that between-effector coordination is facilitated by double metronomes due to their stronger effect in stabilising movement variability in space (Beek 1989; Fink et al. 2000; Jirsa et al. 2000; Roerdink et al. 2013).

Interaction between movement stabilisation in time and space

One might assume that the destabilising effects of double metronomes on participants' movements in time may be attributable to the effects of these metronomes on movement spatial variability. On this account, double metronomes might have led to overly rigid constraints in space, which in turn degraded stability in time. However, correlation analyses of movement period and amplitude stabilisation indexes

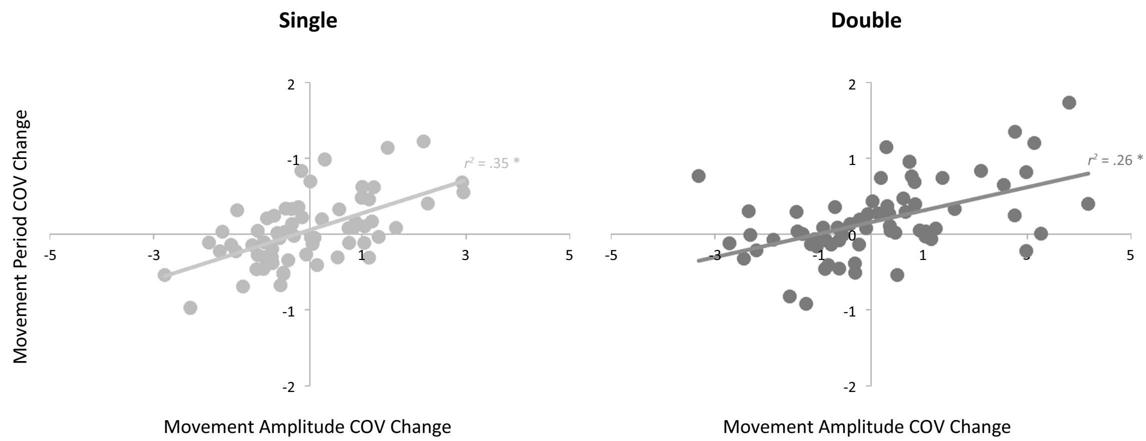

Fig. 5 Correlational analyses between movement tempo stabilisation and movement amplitude stabilisation with single (light grey, left panel) and double (dark grey, right panel) metronome conducted on all tempo conditions pooled together. The diagonal indicates the line of best fit

in the three tempo conditions (pooled together) revealed positive relationships for both single ($n=66$; $r^2=0.35$; $p<0.0001$) and double ($n=66$; $r^2=0.26$; $p<0.0001$) metronomes, as shown in Fig. 5.

These results indicate that auditory rhythms influence movement stability in both time and space in a co-dependent manner, which suggests that the dynamical stability of movement period and amplitude are underpinned by similar processes. This possibility could be explored in future studies using electrophysiological and brain stimulation techniques (e.g., Varlet et al. 2017a, b).

More generally, the results of this study confirm that human rhythmic movements are modulated at both global and local levels through synchronisation with auditory rhythms, and that these modulations can occur spontaneously in the absence of the intention to synchronise (Beek 1989; Byblow et al. 1994; Fink et al. 2000; Kudo et al. 2006; Miyata et al. 2018). It is noteworthy that the external rhythms affected the dynamics of rhythmic behaviour at multiple levels, including the spontaneous stabilisation of movement-stimulus phase relations, as well as movement tempo and amplitude. This finding may be particularly relevant to understanding auditory-motor processes in musical and dance performance, where entrainment and synchronisation occur at multiple levels (MacRitchie et al. 2017; Walton et al. 2015). Co-performers' movements can spontaneously align with one another, which can lead to modifications of individual performance, as recently shown with visual rhythms during the production of simple dance movements (Miyata et al. 2017, 2018). It can be noted, however, that the present results suggest that the amount of auditory information (i.e., two stimulation events per preferred movement cycle rather than one event) does not influence the strength of entrainment and the spontaneous modulation of an individual's movement dynamics, which seems to contrast with previous results in visuomotor entrainment studies (Richardson et al. 2007; Varlet al. 2015). The intrinsic variability of an individual's movements seems to be of greater importance, especially for decreasing the variability of movement tempo and amplitude. Therefore, further studies in musical and dance contexts may be fruitful for exploring whether the modification of co-performers' movement through auditory-motor entrainment is moderated by expertise. The benefits of auditory rhythms demonstrated here for individuals with relatively high intrinsic variability are also relevant for motor rehabilitation protocols using auditory rhythms (e.g., Ghai et al. 2018; Sihvonen et al. 2017; Thaut et al. 1996, 1997). Patients usually exhibit higher level of movement variability, and thus, appear more likely to benefit from auditory-motor entrainment.

To conclude, the findings of the present study confirm the occurrence of spontaneous movement entrainment and (de)stabilisation with the presentation of auditory metronomes. Our results further the understanding of mechanisms underlying motor improvement via external pacing by demonstrating that double metronomes are not always better than single metronomes, as they do not necessarily facilitate movement entrainment and might actually lead to greater destabilisation in time. These findings open new perspectives for the development of auditory cueing in motor learning and rehabilitation.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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