



# The influence of pacer-movement continuity and pattern matching on auditory-motor synchronisation

Gregory Zelic<sup>1</sup> · Patti Nijhuis<sup>1</sup> · Sarah. A. Charaf<sup>1</sup> · Peter E. Keller<sup>1</sup> · Chris Davis<sup>1</sup> · Jeusun Kim<sup>1</sup> · Manuel Varlet<sup>1</sup>

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## Abstract

People commonly move along with auditory rhythms in the environment. Although the processes underlying such sensorimotor synchronisation have been extensively investigated in the previous research, the properties of auditory rhythms that facilitate the synchronisation remain largely unclear. This study explored the possible benefits of a continuity matching between auditory pacers and the movement produced as well as of a spatial pattern matching that has been previously demonstrated with visual pacers. Participants synchronised either finger tapping or forearm oscillations with either discrete or continuous pacers. The pacers had either a spatial pattern (left–right panning) that matched the movement pattern produced or no spatial pattern. The accuracy and variability of synchronisation were assessed by the mean and standard deviation of the asynchronies, respectively, between participant’s movement and the pacers. Results indicated that synchronisation was more accurate and less variable for discrete pacers and continuous movement (i.e., forearm oscillations). The interaction between those two factors involved a more complex relationship than a simple continuity match benefit. Although synchronisation variability increased with continuous pacers for both types of movement, this increase was smaller for continuous movement than discrete movement, suggesting that continuous movement is more beneficial only for continuous pacers. Moreover, the results revealed limited benefits of spatial pattern matching on auditory-motor synchronisation variability, which might be due to lower spatial resolution of the auditory sensory modality. Together, these findings confirm that sensorimotor synchronisation is modulated by complex relations between pacer and movement properties.

**Keywords** Sensorimotor synchronisation · Coordination · Auditory rhythm · Continuity · Panning · Tapping

## Introduction

People commonly move in synchrony with music (Lesaffre et al. 2008). This ability to coordinate bodily movements with rhythms in the environment is referred to as sensorimotor synchronisation (SMS) (Repp and Su 2013). SMS is a routine part of daily life (e.g., in musical activities, when dancing or singing to a beat or with others) and can be observed across all cultures and ages (Martin 2005; Eerola et al. 2006; Zentner and Eerola 2010; Miyata et al. 2017). This widespread phenomenon raises questions as to why and how we synchronise our movements and to which rhythms.

In spite of being investigated for more than a century, many questions related to SMS remain open (Repp and Su 2013).

Previous research has shown that SMS is affected by a variety of stimulus properties (see Repp 2005 and Repp and Su 2013 for reviews), and in particular, the sensory modality of the pacing stimuli. A well-accepted finding is that synchronising movements with a visual pacer are less accurate and more variable than with an auditory one (e.g., Lorås et al. 2012; Repp and Penel 2002, 2004). This result has been attributed to the poorer temporal resolution of the visual sensory system compared to the auditory one (Conway and Christiansen 2005). However, recent studies have suggested that data about the influence of stimulus sensory modality on synchronisation performances might have been biased by the nature of the continuity of the stimuli, i.e., whether the pacer was a discrete sequence (e.g., auditory tones, like a metronome) or provided a continuous flow of information (e.g., visual display of a finger moving up and down). Indeed, the superiority of an auditory pacer for synchronisation

✉ Manuel Varlet  
m.varlet@westernsydney.edu.au

<sup>1</sup> The MARCS Institute for Brain, Behaviour and Development, Western Sydney University, Locked Bag 1797, Penrith, NSW 2751, Australia

performance traditionally demonstrated with sequences of discrete auditory and visual (flashing lights) stimuli has been shown to disappear when the auditory and visual stimuli were both of a continuous nature (Hove et al. 2013; Varlet et al. 2012). Varlet et al. (2012) showed that the continuous nature of the stimulus even reduced the variability of SMS, demonstrating lower variability of synchronisation when swinging a wrist pendulum along with continuous stimuli compared to discontinuous stimuli.

SMS is not only affected by the stimulus continuity, but also the continuity of synchronised movements (Repp and Su 2013), that is, whether the movement is discrete (discontinuous SMS), e.g., finger taps, or continuous (continuous SMS), e.g., forearm oscillations. Previous research with auditory pacers showed that discontinuous SMS is less variable in comparison with continuous SMS (Elliot et al. 2009; Lorás et al. 2012; Studenka and Zelaznik 2011a; Torre and Delignières 2008). This superiority of discontinuous SMS over continuous SMS has been explained by the nature of the mechanisms of timing control supporting both types of synchronisation. An event-based form of timing has been shown to underpin discontinuous SMS, whereas an emergent form of timing has been implicated in continuous SMS, and it has been suggested that the event-based form of timing might favour better synchronisation (lower and less variable asynchronies) compared to the emergent form of timing (Torre and Balasubramaniam 2009).

Zelic and colleagues have recently proposed an alternative or complementary account for the superiority of discontinuous SMS over continuous SMS: the continuity-matching hypothesis (Zelic et al. 2016b, 2018). The authors noted that the previous research comparing the variability of continuous and discontinuous SMS has only ever used discrete auditory stimuli. Zelic and colleagues suggested that the typical finding in the previous studies that discontinuous SMS is less variable than continuous SMS could be explained by the difference in the match between the characteristics of the stimuli and the movements produced. That is, discontinuous SMS might have benefited from the matching in continuity between the discrete sequence of stimuli and the discrete movements of synchronisation, in contrast to the continuous SMS that might have been hindered by the mismatch in continuity between the discrete sequence and the continuous movements of synchronisation.

It has been previously demonstrated that compatible perceptual–motor interactions are beneficial for sensorimotor performance. For instance, a decrease in reaction time has been shown when the spatial location of the stimulus matches with the spatial location of the motor response; a benefit likely due to a simplification of the processes binding the sensory processing of the perception of the external event and the motor implementation (Hommel 1996; Hommel and Prinz 1997; Iacoboni et al. 1998; Prinz 1997;

Umiltá and Nicoletti 1990). Compatible perceptual–motor interactions have also been shown to facilitate the stabilisation (decreased variability) of bimanual coordination by an external pacer and enhance multisensory integration in such coordinated behaviours (Zelic et al. 2012, 2016a).

Consistent with Zelic et al.'s hypothesis, McAnally (2002) reported a benefit from such continuity matching for discrete SMS, whereby the synchronisation of discrete taps (discontinuous SMS) with discrete auditory beats was less variable than with a sound that was continuously frequency-modulated. For continuous movement tasks, Zelic et al. (2016b) argued that continuous stimuli would increase the perception–action coupling, and thus, decrease the variability of the synchronisation. The continuity-matching hypothesis was supported by the finding that the synchronisation of continuous tracking movements with a continuous stimulus was less variable than the synchronisation achieved with discrete finger tapping (Zelic et al. 2016b). Interestingly, the continuity-matching hypothesis was also supported in Varlet et al. (2012) that showed that continuous movement was synchronised with less variability with a continuous visual pacer in comparison with a sequence of visual flashes.

Following up on the continuity-matching hypothesis, Zelic and colleagues tested the hypothesis that the variability of discontinuous SMS and continuous SMS is influenced by the spatial pattern of the stimulus, called the pattern-matching hypothesis (Zelic et al. 2018). Whereas continuity refers to whether a stimulus is a discrete sequence or provides a continuous flow of information, spatial pattern refers to the direction of the stimulus movement (i.e., left–right movement). The pattern-matching hypothesis predicts that SMS performance should be improved when the stimulus moves in the same direction to the movement. The results of Zelic et al. (2018) supported this hypothesis by showing that horizontal arm movements were better synchronised (lower asynchrony variability) to visual stimuli displaying a horizontal pattern of oscillations, whereas vertical finger-tapping movements were better synchronised to stimuli oscillating with a centred pattern (clockwise–anticlockwise circular movement with a single turning point).

The above studies were conducted exclusively using visual pacing stimuli and it is unknown whether these results will extend to the auditory domain. Therefore, the present study investigated the extent to which the pattern-matching effect and the continuity-matching effect on SMS generalise to the auditory modality. More specifically, we examined whether the continuous vs. discontinuous nature of an auditory rhythm (continuity), along with the direction of the stimulus movement (pattern), influences the variability of continuous and discontinuous auditory–motor synchronisation (AMS).

Based on the above-mentioned studies, it may be expected that the continuity-matching hypothesis will be

supported (Hove and Keller 2010; Rodger and Craig 2011; Varlet et al. 2012). However, contradictory results have been reported by Varlet et al. (2012), showing the improvement of continuous SMS (less variable) in the visual domain for continuity matching, but not in the auditory domain. In addition, considering the heightened temporal accuracy for auditory processing compared to spatial accuracy (Conway and Christiansen 2005; Posner et al. 1976), it is possible that pattern matching does not influence synchronisation in the auditory domain in contrast to the visual domain (Zelic et al. 2018). Studies in the auditory domain have so far failed to demonstrate the decreased variability of AMS when the spatiotemporal information of the pacer matches the movement pattern (Armstrong and Issartel 2014; Armstrong et al. 2013; Hove and Keller 2010).

Therefore, the aim of the current study was to determine the influence of continuity matching and pattern matching on auditory-motor synchronisation. It was hypothesised that a match between the continuity of the auditory pacer and the movement produced would facilitate synchronisation. In line with the previous studies, it was also hypothesised that a match between the spatial pattern of the pacer and the produced movement would facilitate synchronisation, although the influence of pattern matching might be more limited here due to lower spatial resolution in processing of the auditory modality compared to the visual modality.

## Method

### Participants

Fifteen students from the Western Sydney University (11 females, 4 males,  $M$  age = 22.8 years,  $SD = \pm 3.34$  years) were recruited by word of mouth to participate in the experiment, which was approved by the Human Research Ethics committee of Western Sydney University. A priori power analysis in G\*Power 3 was used to estimate a target sample size of  $N = 15$  to capture within-subject main effects of medium sizes ( $f = .25$ ) using  $\alpha = .5$  with at least 80% statistical power (Cohen 1988; Faul et al. 2007). All participants were right-handed, with normal or corrected to normal vision, and no prior musical training. All participants provided written informed consent prior to the experiment.

### Apparatus

The experimental setup was similar to that of Zelic et al. (2016b). Participants were seated on a chair located 2.5 m in front of a large monitor (55", 122 cm wide, 1920–1080 px). The height of the chair was adjusted so as to ensure that the eyesight level of the participant matched the centre of the screen, which was 119 cm. Participants wore headphones

(Sennheiser HD 280 Pro Headphones) from which five auditory rhythms (pacers) were presented. Pacers were created and presented using the PsychToolbox (Brainard 1997; Pelli 1997) for Matlab software (see section Stimuli). To measure the participant's movement, a reflective marker was taped to the right index finger and recorded with an eight-camera Vicon motion capture system (Lake Forest, CA, 4 MX40 and 4 MXF40 cameras—100 Hz sampling rate). The audio stimuli presented to the participant were also sent to the analogue inputs of the Vicon system and recorded together with the movement data for precise synchronisation.

### Stimuli

Five auditory pacers were presented through the headphones: discrete (D), discrete panning (DP), amplitude modulation (AM), amplitude modulation panning (AMP), and panning only (PO). All five pacers had a fixed constant pitch of 300 Hz, which is within the range typically used in the previous tapping literature (Repp and Su 2013). Each pacer consisted of Inter-Onset Intervals (IOI) of 625 ms (ms).

The discrete pacer (D) consisted of a sequence of discrete auditory tones that were presented simultaneously on the left and right channels of the headphones for a duration of 80 ms each and at a "standard" intensity determined in pre-tests to be comfortable for the participants. The discrete panning pacer (DP) also consisted of discrete auditory tones of 80 ms, but the presentation alternated between the left and right channels of the headphones. The amplitude-modulated pacer (AM) consisted of an auditory tone that continuously increased and decreased in amplitude from silence to the "standard" intensity. The amplitude modulation panning pacer (AMP) also consisted of a continuous auditory tone that was modulated in amplitude; however, the pacer also panned continuously from the left to the right and vice versa. Finally, the panning only (PO) pacer consisted of an auditory tone that continuously panned from the left to the right, but was not modulated in amplitude (the sum of left and right intensity remained constant) and vice versa.

### Procedure

The experiment was conducted in two successive sessions, one session for the finger-tapping task and one session for the forearm-tracking task. The order of the sessions was counterbalanced across participants. At the beginning of each session, participants were instructed about the movement to produce and were asked to try their best to ensure synchronisation between their movements to the auditory pacers (finger tapping or forearm tracking). Participants were given some time to practice producing the correct movement without pacers.

Each session consisted of three blocks of five trials, where participants synchronised movement with each of the five auditory pacers (D, DP, AM, AMP, and PO). The order of the five trials was randomized for each block and for each participant. Over the two sessions, participants performed a total of 30 trials, each trial having a duration of 90 s. A break was taken between the two sessions and participants were permitted to rest at other times between trials if they wished to do so.

## Task

The forearm-tracking movement required participants to place their right lower arm at a 90° angle with their hand in a closed fist and the index finger extended and to continuously oscillate their forearm along the horizontal axis from a right endpoint to a left endpoint and so on. The finger-tapping movements were executed placing the right hand on a table beside the participant in a closed fist, with their index finger extended to tap down on the table.

Participants were instructed to synchronise each movement onset with each stimulus onset, which occurred every 625 ms for all conditions. For forearm oscillations, both left and right movement turning points were considered as movement onsets, resulting in two movement onsets per forearm oscillations of 1250 ms. For finger tapping, in line with the previous research, only the tap (maximum flexion—contact on the table) was considered as movement onset, resulting in one movement onset (the tap) per finger oscillations of 625 ms.

For the discrete pacers (D and DP), participants were instructed to synchronise the forearm maximal flexion and extension (i.e., left and right movement turning points) with the auditory tones presented every 625 ms, congruently with the left–right position of the auditory tone for DP. For the continuous pacers (AM, AMP, and PO), participants were required to synchronise the forearm maximal flexion and extension endpoints with maximum stimulus intensity (occurring every 625 ms), congruently with the left–right position of the auditory tone for AMP and PO.

For the discontinuous tapping movements, participants were instructed to synchronise each finger tap with each stimulus onset (every 625 ms) of the discrete auditory pacers (D and DP) and each maximum (left and right) intensity of the continuous pacers (AM, AMP, and PO).

## Analyses

For the tracking and tapping movements, the analyses were conducted on the oscillations of the movements along the first axis of variance determined by a principal component analysis (Jolliffe 2002) to correct for any deviation from the instructed movement axis and 3D motion capture reference.

The first ten seconds of each trial were removed prior to the analyses to avoid any effect of transient behaviour. Finger movements were mean-centred and low-pass filtered with a zero-lag 8-Hz second-order Butterworth filter (Varlet et al. 2014b; Zelic et al. 2016b).

First, to confirm the difference of movement continuity between the forearm tracking and finger tapping, we calculated the nonlinearity (NL) in participants' movement trajectories, as the deviation from a straight line in the Hooke's portraits (Roerdink et al. 2008; Varlet et al. 2014a). NL is equal to  $1 - r^2$ , where  $r^2$  is the amount of variance explained by the linear regression of position onto acceleration and attributed to a perfectly harmonic oscillation. Higher values of NL indicated stronger nonlinearity (i.e., discontinuity) in participants' movement.

Next, the movement onsets were determined to analyse the relation to the pacer onsets. For the tracking movements, the maximal flexion and extension of the forearm, corresponding to the reversal points of the forearm movements, were determined at a threshold of 2% of peak velocity. The same process was applied for the tapping movements to extract the finger tap occurrences.

Asynchronies, known as the synchronisation error, were defined as the temporal gap between each pacer onset and the closest movement onset produced by the participants. Positive asynchronies indicate that the movements lag the pacer onset, while negative asynchronies signify movements that precede the pacer onset. Asynchronies of 0 would indicate perfect synchronisation of movements with the pacer. Asynchronies that were found to be greater in absolute value than 50% of the pacer period were identified as outliers (< 5% in all conditions) and removed from the analyses.

Continuous and discontinuous AMS were compared with respect to two aspects of SMS performance: accuracy and variability. The average of asynchronies within a trial (mean asynchrony) gave the accuracy of synchronisation, while variability was given by the standard deviation (SD) of the asynchronies. The lower the asynchrony SD, the greater the synchronisation.

## Statistical analyses

The experiment consisted of a 2 ("SMS Type": Discrete Finger Tapping, Continuous Forearm Tracking) × 5 ("Pacer Type": Discrete, Discrete Panning, Amplitude Modulation, Amplitude Modulation Panning, and Panning only) repeated measures factorial design. Repeated measures analyses of variance (ANOVAs) were performed on the movement nonlinearity, and mean and standard deviation of the asynchronies. In addition, pairwise contrasts with Bonferroni corrections for multiple comparisons were used to determine which specific conditions showed significant differences. Mauchly's test of sphericity indicated some violations of

sphericity; thus, significance ( $p$ ) values (set at the alpha level of .05) were adjusted with the Greenhouse–Geisser correction where necessary.

## Results

### Movement continuity

The ANOVA on the movement discontinuity (NL) indicated a significant main effect of SMS type,  $F(1, 14) = 1338.49$ ,  $p < .05$ ,  $\eta_p^2 = .99$ , confirming more continuous movement trajectory for forearm tracking than finger tapping. The ANOVA did not yield any other significant effect ( $p$  values  $> .05$ ).

### Synchronisation accuracy

The ANOVA on the mean asynchronies revealed a significant main effect for SMS type,  $F(1, 14) = 7.97$ ,  $p < .05$ ,  $\eta_p^2 = .37$ , for Pacer type,  $F(2.86, 40.16) = 6.22$ ,  $p < .05$ ,  $\eta_p^2 = .31$ , and a significant interaction between SMS type and Pacer type,  $F(2.51, 35.18) = 4.85$ ,  $p < .05$ ,  $\eta_p^2 = .26$ .

### SMS type

The main effect of SMS type indicates that participants exhibited more negative asynchronies for discontinuous SMS compared to continuous SMS (see Fig. 1). The asynchronies produced for discontinuous SMS were more negative, suggesting greater anticipation when tapping, whereas asynchronies closer to 0 with continuous SMS

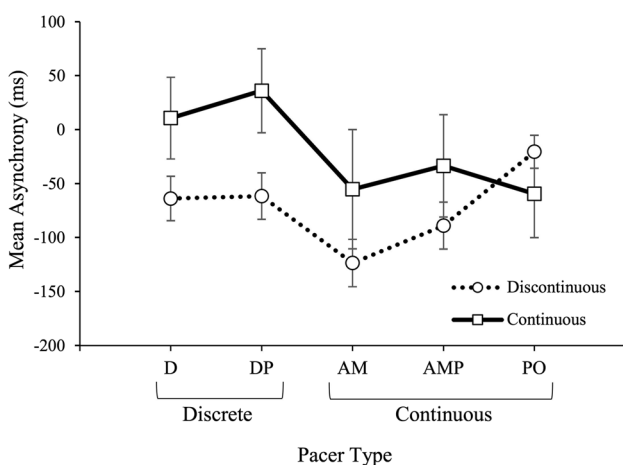
suggest greater accuracy when tracking. However, pairwise contrasts revealed significant differences between continuous and discontinuous SMS for the discrete stimuli only, namely, the D and DP pacers ( $p$  values  $< .05$ ), for which the mean asynchrony was smaller for continuous than for discrete movement.

### Pacer type

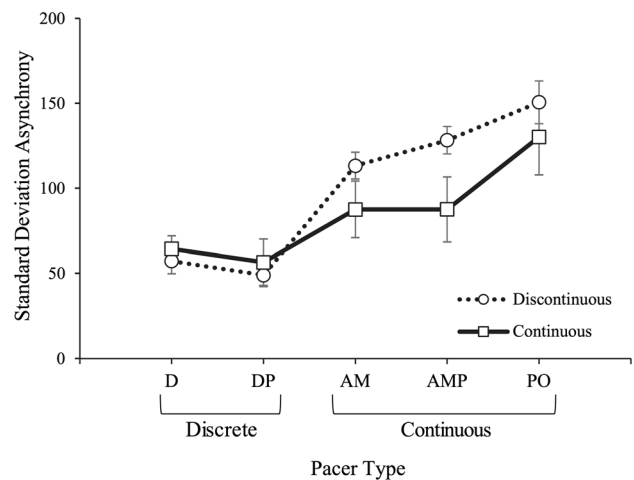
Pairwise contrasts yielded that there was no difference in mean asynchrony for any of the pacers for discontinuous SMS ( $p$  values  $> .05$ ). For continuous SMS, as shown in Fig. 1, pairwise contrasts indicated that participants' movements lagged behind discrete auditory pacers and preceded continuous auditory pacers. Pairwise contrasts revealed significant differences between DP pacer and all continuous pacers (AM, AMP, PO,  $p$  values  $< .05$ ) and between the D pacer and AM pacer ( $p = .014$ ) while indicating no significant differences between D and DP pacers,  $p = .082$ , and between AM, AMP, and PO pacers ( $p$  values  $> .05$ ).

### Synchronisation variability

The ANOVA on the synchronisation variability data revealed a significant main effect for SMS type,  $F(1, 14) = 10.25$ ,  $p < .05$ ,  $\eta_p^2 = .42$ , for Pacer type,  $F(4, 56) = 34.86$ ,  $p < .05$ ,  $\eta_p^2 = .19$ , and a significant interaction between the two,  $F(4, 56) = 3.19$ ,  $p < .05$ ,  $\eta_p^2 = .19$  (see Fig. 2).



**Fig. 1** Mean asynchrony exhibited when synchronising with the five different pacers (D, DP, AM, AMP, and PO) for discontinuous (dotted line, circle marker) and continuous SMS (plain line, square marker). The error bars represent the within-subjects' standard error (Franz and Loftus 2012)



**Fig. 2** Variability of asynchronies with the five different pacers (D, DP, AM, AMP, and PO) for discontinuous, (dotted line, circle marker) and continuous SMS (plain line, square marker). The error bars represent the within-subjects' standard error (Franz and Loftus 2012)



## SMS type

These effects indicate that the variability of asynchronies during continuous SMS was significantly lower than during discontinuous SMS for continuous auditory pacers (i.e., AM, AMP, and PO), although pairwise contrasts only revealed a significant difference between continuous and discontinuous SMS for the AMP pacer ( $p < .05$ ).

## Pacer type

The main effect of Pacer type indicates that continuous stimuli led to more variable SMS, as shown in Fig. 2. For both continuous and discontinuous SMS, pairwise contrasts yielded significantly lower asynchrony variability for the discrete pacers (D and DP) compared to the continuous pacers (AM, AMP, and PO;  $p$  values  $< .05$ ). Pairwise contrasts revealed no significant differences in the variability of asynchronies between the D and DP for both continuous and discontinuous SMS ( $p$  values  $> .05$ ), or between the three continuous pacers (AM, AMP, and PO) for discontinuous SMS ( $p$  values  $> .05$ ). For continuous SMS, pairwise contrasts indicated no significant difference between the AM and AMP pacers, but significant differences between PO pacer and AM and AMP pacers ( $p$  values  $< .05$ ).

## Discussion

In this study, the effects of continuity and spatial pattern of the stimulus on AMS were investigated to establish if a match between the type of movement and pacer would benefit AMS. The results indicated that, in general, AMS with discrete pacers was more precise and less variable than with continuous pacers. Continuous AMS (forearm tracking) was also found to be less variable than discontinuous AMS (finger tapping). Evidence for a partial influence of continuity matching was found in the interactions between the movement continuity and the pacer continuity factors, as detailed in the following sections. The individual effects of pacer and movement continuity will first be discussed, after which the implications for continuity and pattern matching will be addressed.

### Stimulus continuity (pacer type)

As hypothesised, synchronisation with discrete pacers was less variable than synchronisation with continuous ones. That is, regardless of the type of synchronised movement, i.e., finger tapping or forearm tracking, performance was less variable when synchronised with a discrete auditory pacer as opposed to a continuous auditory one. This is in line with the previous literature that has reported lower

variability for discrete finger tapping when paired with discrete pacers as opposed to continuous pacers (Hove et al. 2013; McAnally 2002; Repp and Su 2013), and demonstrates that this advantage extends to continuous movement (i.e., forearm oscillations). Zelic et al. (2016b) explained such findings by the involvement of an event-based form of timing and error correction mechanisms that are based on two estimates: pacer tempo and synchronisation error (Mates 1994; Repp 2005; Repp and Keller 2004; Semjen et al. 1998; Torre et al. 2013). Both these estimates require the extraction of pacer and movement onsets. We suggest that these onsets are more salient for discrete pacers than for continuous ones; therefore, the extraction of onset times is more accurate. This enables better estimates of pacer tempo and synchronisation error that are critical for event-based regulation, and thus, decreased synchronisation variability. Therefore, in future studies, it would be interesting to compare perceptual responses to discrete and continuous pacers. In addition, in future research, the perceptual centre as well as electroencephalography measures could be used to investigate this question and determine if differences in perceptual responses could explain differences in movement synchronisation (Lenc et al. 2018; Nozaradan et al. 2016; Vos et al. 1995).

### Movement continuity (AMS type)

Our results indicated an overall effect of movement type (continuous vs. discrete). Averaged over all pacer conditions, AMS was found more accurate and less variable for continuous synchronisation movement (i.e., forearm oscillations) as opposed to discrete movements (i.e., finger tapping), in line with the findings of Zelic et al. (2016b) in the visual domain. However, in the current study, an interaction was observed which was not observed by Zelic et al. That is, continuous AMS was found *more precise* than discontinuous AMS, except for the PO pacer, and continuous AMS was found less variable than discontinuous SMS, but only for the continuous pacers. The advantage of continuous movement over discrete movement goes against the outcome of the previous research, which found better synchronisation with discrete movements (Elliot et al. 2009; Studenka and Zelaznik 2011a; Lorås et al. 2012).

### Continuity matching

The results only partially supported the continuity match hypothesis for the auditory domain. Consistent with this hypothesis, the results showed that with continuous pacers, there was decreased synchronisation variability for continuous movement compared to discrete movement. However, the variability of this synchronisation remained larger than the one exhibited with discrete pacers for both

the continuous and discontinuous movements. Moreover, there was no increase of accuracy or decrease of variability for discrete movement compared to continuous movement when synchronising with discrete pacers, contrary to what has been previously reported in the visual domain (Zelic et al. 2016b).

The present results suggest that continuity matching only works in one direction. Independently of movement continuity, synchronisation was less variable with discrete stimuli, as established in the previous work (Hove et al. 2013; McAnally 2002; Repp and Su 2013). Thus, continuous AMS was not less variable with continuous stimuli than discrete stimuli. The only advantage that can be attributed to a continuity matching is that the synchronisation variability was less negatively impacted by continuous stimuli for continuous AMS than it was for discrete AMS. This might seem to be in contrast with the results of Varlet et al. (2012), who found an increase in SMS performance instead of deterioration for continuous visuo-motor coordination. However, this previous study was in the visual domain and additionally found that there was no difference between continuous and discrete pacers in the auditory domain. It would seem that the benefit of continuity matching is more limited in the auditory domain.

### Pattern matching

There was no significant improvement of AMS accuracy or variability observed when the auditory pattern matched the movement pattern, i.e., no effect of pattern matching was found. This is different to the pattern-matching effect that Zelic et al. (2018) found in the visual domain and suggests that the pattern-matching hypothesis does not hold in the auditory domain. One possibility is that the poor spatial processing of auditory stimuli compared to the high-resolution spatial processing of visual stimuli prevents the influence of pattern matching (Conway and Christiansen 2005).

### Limitations

There are a number of limitations in the current study that could be addressed in future research to better understand the continuity and pattern effects of movements and pacers.

First, the movement tasks included in the current study leave several open questions. For forearm tracking, both left and right movement turning points were considered as movement onsets to synchronise with pacer onsets, resulting in forearm oscillations of 1250 ms. For finger tapping, in line with the previous research, only the tap (contact on the table—maximum flexion) was considered as movement onset, and thus, resulting in finger oscillations of 625 ms. Using finger tapping with contact, and thus only one movement onset per cycle, was justified in the current study to

ensure a difference of continuity between the two SMS types, but might have influenced the current results due to differences in movement frequency (not pacer frequency) and overall movement velocity, a limitation that should be explored in future studies. Indeed, differences in synchronisation might not only be due to differences in movement continuity, but also differences in movement frequency and overall velocity. It can also be noted that although there was a clear difference in movement continuity between the two movement tasks, so it is possible that no difference between continuous and discontinuous AMS were found for discrete pacers, because forearm oscillations still involved a certain degree of discontinuity due to the reversal points. Thus, in future work to further test the continuity hypothesis, it would be of interest to use a movement task that is even more continuous such as circle drawing (e.g., Spencer et al. 2003; Studenka and Zelaznik 2011b; Studenka et al. 2012).

Second, concerning pattern matching, the current manipulations were chosen to be similar to those used in Zelic et al. (2018), which revealed clear effects of pattern matching with visual pacing stimuli. The manipulations resulted in a centred stimulus pattern that was more compatible with the up–down–tapping pattern than a right–left stimulus pattern, and a right–left stimulus pattern that was more compatible with the right–left forearm pattern than the centred stimulus pattern. Thus, one might consider that forearm tracking was tested with compatible and neutral pattern-matching conditions, while tapping was tested more with neutral and incompatible matching conditions. To gain a deeper understanding of the effects of pattern matching, future studies should explore the effects of more symmetrical pattern compatibility–incompatibility manipulations for both movement tasks, although the number of movement onsets in tapping and forearm tracking would have to be taken into account.

Third, synchronisation accuracy and variability were assessed in the current study at the level of movement onsets. Within-cycle synchronisation modulations that were not captured with discrete timing analyses might have, therefore, occurred in the different pacer and movement conditions. In particular, it is possible that continuous pacers strengthened forearm synchronisation particularly between movement onsets. Continuous relative phase analyses might be used to assess synchronisation through the entire movement cycle, but these do not offer a straightforward solution, as these analyses are not only influenced by the strength of synchronisation but also by the trajectory (non)linearity of the movements involved (Peters et al. 2003; Varlet and Richardson 2011), which was manipulated in the current study, encouraging further explorations in future work.

Some of the current results contradict those reported in the previous literature, and it is tempting to argue that this could be explained by differences between modalities tested. However, there are other possible confounding factors that

make comparing studies rather complicated, for example: movement frequency; movement task; the kind of manipulations of stimulus continuity; and the measure of synchronisation performance. Setting these factors aside, it is still worthwhile to point out that the auditory and visual systems are very different in how they process perceptual information, so it seems reasonable to assume that results from these two modalities will be unlikely to generalise, specifically for continuity and pattern matching and more broadly for synchronisation performance. This study, therefore, emphasizes the necessity for a careful investigation of modality effects across different movement tasks and stimulus designs.

## Conclusion

The present results partially support the continuity-matching hypothesis with auditory rhythms. Although, in general, discrete pacers led to less variable synchronisation compared to continuous pacers regardless of the movement continuity (discrete or continuous), synchronisation with continuous pacers was found to be less variable with continuous movement. However, no difference between continuous and discrete movement was found for discrete pacers. The benefit of a continuity match for synchronisation to continuous pacers, however, was only significant when spatiotemporally also matched. Therefore, even though the pattern-matching hypothesis was not directly supported and requires further investigations, the benefit of this combination could be in the use of both continuity (amplitude-modulated) and pattern (the left–right movement) matching of the pacer. These results encourage future research to investigate different types of continuous movement, such as circle drawing, which do not have reversal points, and to examine the interaction with stimulus modality and the multisensory characteristics of pacer continuity and pattern for both auditory-motor and visuo-motor synchronisation performance. More generally, the findings of the present study show that the synchronisation of an individual's movements with environmental stimuli is influenced by complex constraints involving movement characteristics, stimulus characteristics, and interaction between the two, which need to be carefully considered to understand and optimizing human sensorimotor performance.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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