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Influence of pacer continuity on continuous and discontinuous visuo-motor synchronisation☆

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ABSTRACT

Previous research has reported that synchronising movements with an external pacer, known as sensorimotor synchronisation (SMS), is more stable when the movements are discrete/discontinuous rather than continuous. A standard explanation considers that more efficient mechanisms are involved for regulating synchronisation when producing discontinuous movements. To date, however, only discontinuous pacers (e.g., metronomes) have been investigated to compare discontinuous and continuous SMS. We propose an alternative explanation whereby the discontinuous SMS has benefited from the matching between the (dis)continuous nature of the pacer and the (dis)continuous nature of the movements of synchronisation. The present experiment tested this explanation by examining the relative stability of discontinuous and continuous SMS when synchronising with a continuous pacer. Twelve participants finger tapped (discontinuous SMS) or continuously oscillated their forearm (continuous SMS) in synchrony with an oscillatory visual target. The continuity of the pacer was manipulated by varying the kinematic (harmonic to Rayleigh-like oscillations) and the frequency (0.5 and 1 Hz) of the target oscillations. Overall, the results showed a more stable continuous than discontinuous SMS. Furthermore, the stability of the discontinuous SMS improved when increasing the discontinuity of the target displacements (high nonlinear kinematic and low frequency), showing an interaction between movement type and pacer continuity in SMS.

1. Introduction

Sensorimotor synchronisation (SMS) epitomizes our ability to coordinate bodily movements with rhythms from the environment (Repp & Su, 2013). This fundamental skill is routinely exercised in daily life either intentionally (e.g., in musical activities, when dancing or singing to a beat or with someone else) or unintentionally (e.g., when applauding – Néda, Ravasz, Brechet, Vicsek, & Barabási, 2000; or when speaking – Shockley, Santana, & Fowler, 2003). It is, however, a particularly fragile skill, sensitive to developmental problems such as attention deficit, hyperactivity disorder and dyslexia (Schulte-Körne & Bruder, 2010; Toplak, Dockstader, & Tannock, 2006), or the brain damage that occurs with Parkinson's disease or strokes (Koch, Oliveri, & Caltagirone, 2009). In spite of being investigated for more than a century, many questions related to SMS remain open (Repp, 2005). In particular, Repp and Su (2013) concluded from a recent review that the "sensorimotor coupling is generally weaker with continuous than with discrete movements" and highlighted the need for research to improve our understanding of the synchronisation mechanisms involved for these two types of movements. The present study addressed the stability of SMS performances when producing discrete or continuous movements of synchronisation and examined to which extent their relative stability is affected by the (dis)continuous nature of the pacer.

There are consistent reports of less stable SMS performances when producing continuous movements of synchronisation, referred to henceforth as continuous SMS, rather than discrete movements of synchronisation, discontinuous SMS, e.g., wrist oscillations vs. finger taps (Torre & Delignières, 2008), continuous pulsed forces vs. pulsed forces (Elliott, Welchman, & Wing, 2009), circle drawing vs. tapping (Lorås, Sigmundsson, Talcott, Öhberg, & Stensdotter, 2012; Repp & Steinman, 2010; Studenka & Zelaznik, 2011a).

A classical explanation for the superiority of discontinuous SMS over continuous SMS is based on the efficiency of the synchrony correction mechanisms involved. That is, two different mechanisms have been suggested to regulate SMS when producing discrete or continuous movement of synchronisation. For discontinuous SMS, an 'event-based' form of regulation has been proposed, based on the linear combination of two mechanisms of error correction. Error produced by central cognitive mechanisms in estimating a movement period matching the

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pacer tempo is adjusted by a period correction process (Mates, 1994; Repp, 2001, 2005; Repp & Keller, 2004; Semjen, Vorberg, & Schulze, 1998). A phase correction process is also involved to immediately correct the synchronisation error that is typically related to movement execution (Mates, 1994; Pressing & Jolley-Rogers, 1997; Schulze & Vorberg, 2002; Semjen et al., 1998; Vorberg & Wing, 1996). For continuous SMS performances, an ongoing "within-cycle" regulation of the synchronisation has been proposed. This mechanism is well captured through the limit-cycle dynamics of an oscillator coupled to a continuous periodic forcing (Assisi, Jirsa, & Kelso, 2005; Jirsa, Fink, Foo, & Kelso, 2000; Schöner & Kelso, 1988). The strength of the coupling determines the amplitude and variability of the error of synchronisation. Several factors can affect the strength of the coupling. For instance, more stable visual tracking has been found when there is a minimal difference between the preferential movement tempo and the target tempo (Lopresti-Goodman, Silva, Richardson, & Schmidt, 2008; Schmidt, Richardson, Arsenault, & Galantucci, 2007), for in-phase tracking compared to antiphase tracking (Roerdink, Peper, & Beek, 2005), or for larger amplitude of displacements of the visual target (Varlet, Coey, Schmidt, & Richardson, 2012a).

Based on the above account, the greater stability observed for discontinuous SMS results from the greater efficiency of the 'event-based' regulation mechanisms in comparison to the within-cycle regulation involved for continuous SMS. We propose an alternative account in which the superiority of discontinuous SMS to continuous SMS reflects the benefit of a matching between the (dis)continuity of the movement performed and the (dis)continuity of the pacer. This proposal may appear to be a radical one, but it is worth noting that the relative stability of continuous and discontinuous SMS has really only ever been investigated when synchronising with discontinuous pacers such as metronomes. In such a case, the discontinuous movements of synchronisation (e.g., finger taps, pulsed forces) systematically matched in continuity the discontinuous nature of the pacers whereas the continuous movements of synchronisation (e.g., wrist oscillations, continued pulsed forces, circle drawing) systematically mismatched the discontinuous nature of the pacers. We argue that the relative stability typically observed in previous research between continuous and discontinuous SMS may have been affected by such systematic continuity matching occurring for discontinuous SMS and continuity mismatch occurring for continuous SMS. Indeed, the benefit of compatible perceptuo-motor interactions for sensorimotor performances has been extensively demonstrated. For instance, reactive behaviours are sped up when the spatial location of the stimulus matches with the spatial location of the motor response, likely due to a simplification of the processes binding the sensory processing of the external event perceived and the motor implementation (Hommel, 1996; Hommel & Prinz, 1997; Iacoboni, Woods, & Mazziotta, 1998; Prinz, 1997; Umiltá & Nicoletti, 1990). Compatible perceptuo-motor interactions have also been shown to facilitate the stabilization of bimanual coordination by an external pacer and to condition the efficiency of multisensory integration in such coordinated behaviours (Zelic, Mottet, & Lagarde, 2012, 2016). In view of the aforementioned mechanisms proposed to regulate discontinuous and continuous SMS, we suggest that perceiving a discontinuous pacer benefits the 'event-based' form of regulation involved in discontinuous SMS and inversely weakens the within-cycle form of regulation involved in continuous SMS. Indeed, the clear extraction of single metronome beats likely facilitates the estimation of the metronome tempo as well as the estimation of the synchronisation error via a direct comparison of the occurrences of the metronome beats and of the movement onsets. In contrast, the ongoing within-cycle regulation mechanisms involved for continuous SMS is likely to be more efficient with a continuous rather than discontinuous flow of information from the pacer dynamics.

A review of the relevant literature shows that a number of results support the hypothesis that SMS stability can benefit from a continuity matching between the (dis)continuity of the pacer and the (dis)continuity of the movement of synchronisation. In a task of visuo-motor tracking, Varlet, Marin, Issartel, Schmidt, and Bardy (2012b) found a more stable continuous SMS (pendulum swinging) when synchronising with a visual target that continuously and periodically changed colour rather than with a discrete rhythmic flash. Rodger and Craig (2011) found larger but less variable synchronisation errors when synchronising continuous oscillatory movements of the finger with a sound which continuously and periodically changed in tone, rather than with discrete auditory beats. Also, McAnally (2002) showed that the synchronisation of discrete taps (discontinuous SMS) with discrete auditory beats was more stable than with sound that was continuously frequency-modulated.

Building on the above findings, the present experiment explicitly examined whether, and to what extent, continuity matching affects SMS. In particular, we tested whether the synchronisation with a continuous pacer might reverse the relative stability of discontinuous and continuous SMS. Previous research has typically found more stable continuous and discontinuous SMS with auditory pacing than with visual pacing, likely due to an auditory dominance in processing temporal cues (Lorås et al., 2012; Pollok, Krause, Butz, & Schnitzler, 2009; Repp & Penel, 2002; Repp & Su, 2013). To date however, there is no evidence that SMS would differently be affected by continuity matching depending on the sensory modality of the pacing. Given this, visual pacing was selected in the present experiment for two reasons: First, visuo-motor performances have been shown to be particularly affected by the manipulation of target continuity, e.g., in interception tasks (McBeath, Shaffer, & Kaiser, 1996) or in synchronisation tasks (Hove & Keller, 2010; Iversen, Patel, Nicodemus, & Emmorey, 2015). Second, visuo-motor synchronisation, being less stable than auditory-motor synchronisation, may be more likely to reveal the influence of continuity matching. The task consisted in synchronising forearm oscillations (i.e., continuous SMS) and finger's taps (i.e., discontinuous SMS) with a visual target continuously and periodically oscillating on the horizontal axis of a screen. Two factors found to affect the (dis)continuous nature of movement were manipulated to vary the continuity of the pacer: the movement rate and the movement kinematic.

In regard to the first of these, movement rate, it is important to note the key role that this variable has in defining the concepts of discrete and continuous movements. Discrete movements, such as reaching for an object or knocking on a door, are target-directed and are marked by clear breaks in movement flow. In contrast, no clear discontinuities are apparent for continuous movements that are characterised by an uninterrupted smooth motion which is often periodic such that a movement pattern is repeated over time (e.g., swimming, walking, cycling – Hogan & Sternad, 2007). Discrete movements can be repeated over time as well, which will, at fast rates, lead to some ambiguity with the concept of continuous movement, i.e., when periods without motion become smaller, movement discontinuity will be reduced thereby making the movement more "continuous" (Schaal, Sternad, Osu, & Kawato, 2004; Sternad, 2008). The role of movement rate for determining the (dis)continuous nature of rhythmic movements is exemplified on phase flow topologies, i.e., the structure of the movement trajectories in the position-velocity space (Huys, Studenka, Rheaume, Zelaznik & Jirsa, 2008). Here, discrete and continuous movements belong to distinct movement classes that can be characterised by two different topological structures (Huys et al., 2008; Huys, Studenka, Zelaznik, & Jirsa, 2010; Jirsa & Kelso, 2005; Schöner, 2002). Using this paradigm, Huys et al. (2008) showed the extent to which the (dis)continuous nature of movement is affected by the movement rate. Their results indicated that a repetitive finger tapping performance can be classified either as discrete at slow movement rates or as continuous at fast movement rates (beyond 2 Hz).

In regard to movement kinematics, it is also important to point out that different movement kinematics occur as a function of the (dis)continuous nature of movement (Nourrit, Delignières, Caillou, Deschamps, & Lauriot, 2003; Nourrit-Lucas, Zelic, Deschamps, Hilpron, & Delignières,