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The temporal coupling effect: Preparation and execution of bimanual reaching movements

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ABSTRACT

The study of bimanual movements has allowed to describe an interesting phenomenon known as the *bimanual coupling effect:* a lack of independence between the two hands that induces an interference process, which has been reported in both the spatial and temporal domain. Here, we studied for the first time the electro-cortical activity of the *temporal bimanual coupling effect,* specifically focused on the motor preparation of the two hands movements. Participants performed *congruent movements*, with both hands heading towards easy or difficult targets, and *incongruent movements*, with the two hands heading to separate targets (i.e. left to the easy target and right to the difficult target). Motor Related Cortical Potentials (MRCPs) showed no effect of conditions or difficulty on the early phase of the activity (posterior and anterior BP). Additionally, the two hands were prepared together, as if a single movement was about to start. As such, behavioral results showed strong synchronization between the hands, which always tended to start and end their movement together. Importantly, the effect of movement difficulty was present at the movement onset and just after it when the movement unfolded. Coherently with behavioral results, difficult movements generated a strong Post-motor potential (N4), more prominent when the right hand was heading towards the difficult target. Our findings show that bimanual movements are actually planned and programmed as a single motor program, but movement difficulty emerges in the execution of the action.

1. Introduction

The hands are the primary mean by which primates interact with the environment. During the entire childhood and adolescence, human beings develop and evolve important skills to learn how to use their hands for different purposes, often requiring coordinated movements of both hands and fingers (Piedimonte, Garbarini, Rabuffetti, Pia, & Berti, 2014). Two important theories were proposed to address the topic of bimanual movements and coordination. The first theory, the generalized motor program (GMP), proposes that a single motor program is implemented for both hands and, as such, it claims that the entire shape of the action is planned (Schmidt, 1975). On the contrary, the inter-manual crosstalk model, predicts that the two hands undergo two different motor plans and each hand is programmed according to specific parameters related to its specific target (Marteniuk & MacKenzie, 1980). To date, the GMP seems to better account for the numerous results collected in studies on motor control, and the discovery of the "*bimanual coupling effect*" had an important role in it (Franz, 1997; Franz, Zelaznik, & Mccabe, 1991; Kelso et al., 1979a; Kelso, Southard, & Goodman, 1979b; Swinnen, Dounskaia, Levin, Duysens, 2001).

The *bimanual coupling effect* is a remarkable phenomenon for which the simultaneous execution of incongruent movements gives rise to interferences between the two motor programs that result into a drift to a synchronization in space (amplitude and direction) or time of the two hands. This event has been widely described in the space domain, whereas little is still known about the temporal aspects of this effect especially with respect to the cortical networks involved. With the present study, we aim to better understand the mechanisms underneath this specific type of bimanual coupling effect, namely the *temporal coupling effect*, by

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combining the use of a behavioral and electroencephalographic (EEG) approach.

In the spatial domain, the *spatial coupling effect* has been mostly investigated by the use of incongruent actions paradigms. In these tasks, subjects are required to draw different figures (e.g. circles and lines or two lines of different amplitudes) with the two hands simultaneously. Punctually, subjects tended to drift towards a more homogeneous movement pattern in which both shapes were prone to turn oval or the two lines were drawn with a similar amplitude (Franz & Ramachandran, 1998; Franz et al., 1991; Franz, 1997; Garbarini et al., 2012, 2014; Piedimonte et al., 2014).

Neuroimaging and psychophysiological studies have recently shed light on the neural circuits underneath this not-congruent bimanual behavior. Functional magnetic resonance imaging (fMRI) studies have reported a well-distributed network (interference network) in the superior parietal-dorsal premotor areas involved in such directional and amplitude coupling (Diedrichsen, Grafton, Albert, Hazeltine, & Ivry, 2006; Wenderoth, Debaere, Sunaert, & Swinnen, 2005), particularly localized in the right hemisphere (Garbarini et al., 2014). Furthermore, a recent neurophysiological investigation has described *when* the interference network was active, reporting that spatially incongruent movements affected already the preparatory phase of the movement (Lucci, Berchicci, Spinelli, & Di Russo, 2014). The authors reported for the first time a pair of preparatory brain activities, initiating 2.5 s before the action and associated with the incongruent task only (e.g. one hand drawing a circle and the other drawing a line): the early central positivity (CP) component, likely originating from premotor areas, followed by a late fronto-lateral positivity (FPL) localized in dorsolateral prefrontal cortex. The CP has been linked to the task complexity, while the FLP may be related to the effort to resolve competition between the well-established and actually incompatible bimanual motor engrams (Bozzacchi, Giusti, Pitzalis, Spinelli, & Di Russo, 2012; Lucci et al., 2014). Based on these results, we can conclude that incongruent movements in the spatial domain are particularly demanding for frontal circuits not only during their execution but already during their preparation.

The study of the temporal form of this bimanual coupling effect has received much less attention in the literature. Pioneering research on it was carried out in the 70's by Kelso and colleagues (Kelso et al., 1979a, 1979b), who applied the speed-accuracy trade-off law (Fitts, 1954) to bimanual coordination. The Fitts's law is one of the most robust laws in motor control [$MT = a + b \log^2 2A/W$], which states that the movement time [MT] is expressed by a fixed relation between the movement amplitude [A] and the width of the targets [W] that defines the index of difficulty [ID] of the movement. Based on this principle, extended literature on reaching and grasping showed that moving towards a small or distant target requires longer time to complete and many movement parameters (e.g. peak acceleration, maximum grip aperture, deceleration phase) also depend on these features (Jeannerod, 1984; Mon-Williams & Tresilian, 2001; Smeets & Brenner, 1999). In such circumstances, this index of difficulty usually triggered movement asynchrony between the two hands (Bingham, Hughes, & Mon-Williams, 2008). Nevertheless, by the study of bimanual movements with targets of different width and at different distances, Kelso and colleagues described a temporal coupling between the two hands. In contrast to Fitts's law predictions, the two hands adjusted their pace in order to start and end their movements simultaneously, even when they were heading to incongruent/asymmetric targets (Kelso et al., 1979a, 1979b).

In 2006, Diedrichsen and colleagues investigated the neural regions related to this movement conflict in a fMRI study. They suggested that the conflict induced by incongruent movements is associated with a higher cerebral activity in the superior parietal cortex. They defined this region as the site for conflicts that arise during the planning and execution of bimanual movements (Diedrichsen et al., 2006). Nonetheless, a clear distinction between movement planning and execution is not trivial, as shown by studies on the *spatial coupling effect* that reported different regions involved in the two phases (Garbarini et al., 2014; Lucci et al., 2014; Wenderoth et al., 2005).

In the light of this literature, we ask whether the neural correlates similar to those involved in the *spatial coupling* are responsible also for the *temporal coupling effect*, with specific attention to the motor preparation phase. For this purpose, we used the motor related cortical potentials (MRCP). The MRCP is an event related potential time-locked to the initiation of the movement. It is represented as a slow negative waveform raising around 3 s before movement initiation (Bozzacchi et al., 2012a) and composed of different subcomponents: the posterior Bereitschaftpotential (posterior BP), the anterior Bereitschaftpotential (anterior BP), the Negative Slope (NS') and the Motor potential (MP). These different components emerge from different cortical structures and their timing and amplitude is modulated by movement features such as complexity, amplitude, speed, and movement selection (Shibasaki & Hallett, 2006). Crucially, to detect a clear motor preparation activity, it is important that the movement is performed at a self-paced rate rather than as a fast response to a stimulus (i.e. reaction time). In view of this, it is worth noting that the paradigms previously used to describe the *temporal coupling effect* always involved fast responses to the stimuli. Hence, we also intend to verify whether the behavioral phenomenon can be extended to self-paced movements in which participants have all the time to prepare their response.

The aim of this study is twofold: i) to verify whether the temporal coupling effect also applies to a self-paced motor task, and ii) to explore whether the motor system coordinates the action separately for each hand, also taking into account the difficulty index of the two actions, or, instead, it elaborates the bimanual action as a single motor plan of reaching movements.

2. Material and methods

2.1. Participants

Seventeen participants volunteered in the experiment (mean age 23.7 years; 12 females) and they were reimbursed for their participation. None of them presented neurological or psychiatric disease and all were unfamiliar with the task and the purpose of the study. All participants were self-reported right-handed. Their handedness was additionally evaluated with the use of the Edinburgh Handedness Inventory (Oldfield, 1971) (LI > 70). After a full explanation of the procedures, they provided written informed consent. The study was approved by the ethical committee of the IRCSS Santa Lucia Foundation.

2.2. Apparatus

The apparatus consisted of a Plexiglas platform (32 cm in length, 32 cm wide and 8 cm thick) with two home keys and four light target keys (Fig. 1). The home keys were round (ø 2 cm) and located at the lower side of the device close to the participant at a distance of 15 cm from each other. The target keys were two large rectangular buttons (7.2 cm wide, termed easy target) situated at 6 cm from the home keys and two small rectangular buttons (3.6 cm wide, termed difficult target) situated at 24 cm from the home keys. The target keys were equipped with an underneath warning light appearing for 1000 ms to instruct participants about which button combination to press. The warning light did not represent a starting cue.