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Bimanual coupling effects during arm immobilization and passive movements

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ABSTRACT

When humans simultaneously perform different movements with both hands, each limb movement interferes with the contralateral limb movement (bimanual coupling). Previous studies on both healthy volunteers and patients with central or peripheral nervous lesions suggested that such motor constraints are tightly linked to intentional motor programs, rather than to movement execution. Here, we aim to investigate this phenomenon, by using a circles-lines task in which, when subjects simultaneously draw lines with the right hand and circles with the left hand, both the trajectories tend to become ovals (bimanual coupling effect). In a first group, we immobilized the subjects' left arm with a cast and asked them to try to perform the bimanual task. In a second group, we passively moved the subjects' left arm and asked them to perform voluntary movements with their right arm only. If the bimanual coupling arises from motor intention and planning rather than spatial movements, we would expect different results in the two groups. In the Blocked group, where motor intentionality was required but movements in space were prevented by immobilization of the arm, a significant coupling effect (i.e., a significant increase of the ovalization index for the right hand lines) was found. On the contrary, in the Passive group, where movements in space were present but motor intentionality was not required, no significant coupling effect was observed. Our results confirmed, in healthy subjects, the central role of the intentional and predictive operations, already evidenced in pathological conditions, for the occurrence of bimanual coupling.

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1. Introduction

The relationship between intention and action has long been debated by philosophers and psychologists and now constitutes a central argument in cognitive neuroscience, in particular in the area of motor cognition. Bimanual incompatible tasks can represent an ideal experimental tool to investigate the relationship between motor intention and action execution. In these tasks, when people simultaneously perform different movements with both hands, strong bimanual coupling arise and neither of the two hands is able to perform independent actions. Different kinds of modulation (both spatial and temporal) can be observed, depending on the action performed (for reviews, see Swinnen, 2002). As regards the spatial domain, one of the most extensively employed paradigms for revealing the reciprocal influence of hand actions requires people to simultaneously draw lines with one hand and circles with the other (circles-lines task). Here, the coupling effect consists in the fact that participants tend to ovalize both trajectories (i.e., to produce curved lines and line-like circles) (Franz, Zelaznik, & Mccabe, 1991; Garbarini, D'Agata et al., 2013; Piedimonte, Garbarini, Rabuffetti, Pia, & Berti, 2013).

It has been proposed that such motor constraints are tightly linked to abstract representations of action, rather than to movement execution. The results of studies involving healthy subjects have suggested that the interference effect cannot be modulated by manipulating afferent sources of information, concluding that spatial interference primarily emerges at the efferent level of movement planning and organization (e.g., Swinnen et al., 2003; see also de Boer, Peper, & Beek, 2013; Dounskaia, Nogueira, Swinnen, & Drummond, 2010; Ridderikhoff, Daffertshofer, Peper, & Beek, 2005; Spencer, Ivry, Cattaert, & Semjen, 2005). Accordingly, in pathological conditions, bimanual coupling effects can be observed even in the absence of actual movements of one hand. Garbarini and colleagues (2012) described spatial coupling effects in right-brain-damaged patients affected by contralateral (left) hemiplegia and anosognosia for hemiplegia (denial of paralysis, e.g., Berti et al., 2005; for temporal coupling effects in anosognosic patients see Pia et al., 2013; see also Garbarini & Pia, 2013). These patients claimed to move both hands when asked to draw lines with their right (intact) hand and circles with their left (paralyzed) hand. Although no movement of the left hand occurred, lines drawn with the right hand showed significant "ovalizations". Using the same circles-lines paradigm, similar results were also found in amputees with illusory movements of the phantom limb (Franz & Ramachandran, 1998) and in brain-damaged hemiplegic patients affected by an atypical form of hemiasomatognosia, who identified other people's limbs as belonging to themselves (Garbarini, Pia et al., 2013). In all these pathological conditions, where motor execution is damaged but motor intention is spared, actual movement execution seems unnecessary for bimanual coupling to occur: motor intention and programming are sufficient to trigger the interference effects. By contrast, patients affected by motor neglect, with spared motor execution but damaged motor intention, did not show these bimanual constraints (Garbarini et al., 2012).

The aim of the present study was to further investigate, in healthy subjects, the role of motor intention in bimanual coupling, by manipulating the circles-lines task in two opposite experimental situations: one with motor intention but without movement in space, the other with spatial movement but without motor intention. In a first experimental group (*a*), the subject's left arm was immobilized in order to prevent spatial movement and they were asked to try to perform the bimanual circles-lines task. In a second group (*b*), the subject's left arm was passively moved and they were asked not to implement any intentional motor program with their left arm while performing the bimanual circles-lines task. Because our investigation was related to the motor domain and aimed at directly comparing the role of motor execution and motor intention in bimanual coupling effects, visual feedback was avoided by blindfolding the subjects during the experiment (note that the coupling effect is still present in blindfolded people; e.g., Garbarini et al., 2012; Piedimonte et al., 2013).

According to literature on pathological conditions, where the prominent role attributed to motor intention and planning in determining bimanual coupling was extensively described (Franz & Ramachandran, 1998; Garbarini et al., 2012; Garbarini, Pia et al., 2013; Pia et al. 2013), we expected to find a significant coupling effect (i.e., a significant increase of the ovalization index for the right hand lines; see details in Methods, paragraph 2.5) in experimental situation *a*, in which motor intention was required although spatial movement was prevented by immobilizing the arm. On the contrary, we did not expect to find any coupling effect in experimental situation *b*, in which the intentional motor program was not implemented although the movements in space were present.

2. Materials and methods

2.1. Participants

Twenty healthy participants were recruited for the experiment. According to the between-subjects design, half of them were involved in the Blocked condition, and the other half in the Passive condition.

For the Blocked group, we recruited ten young subjects (5 males; 5 females; age range: 22–23 years; mean age ± S.D.: 22.7 ± 0.7 years). For the Passive group, we recruited ten young subjects (5 males; 5 females; age range: 20–25 years; mean age ± S.D.: 23.3 ± 1.4 years). None of the subjects had a history of psychiatric or neurological illness, and all were right-handed (Blocked group: mean ± SD: 0.95 ± 0.08; Passive Group: mean ± SD: 0.91 ± 0.12) according to the Edinburgh Handedness Inventory (Oldfield, 1971).

The protocol was approved by the local Ethics Committee ("Comitato di Bioetica d'Ateneo", University of Turin, Italy). All subjects gave their written informed consent for the study.

2.2. Experimental setup

Participants, blindfolded, were seated on a chair (without wheels and with a rigid back in order to avoid accidental movements during the experiment), in front of a table on which the tablet PC had been placed, positioned to the right of the participant's sagittal midline. A weightlifting belt was used to fix the subject's back to the seatback, in order to mechanically restrain the movements of the torso.

In the Blocked condition, the participant's left arm was inserted into a fiberglass cast, properly fitted to immobilize the wrist and elbow joints. The blocked limb was then fixed to the chair armrest to minimize shoulder movements. Finally, the subject's left fingers were immobilized together with the pen using a bandage.

During the Passive condition the examiner moved the subject's left arm (according to the experimental condition), holding it at the elbow and hand, in which a pen was placed and fixed using a bandage.

2.3. Experimental design

In this between-subjects experimental design there were a common Baseline condition and two experimental conditions, Blocked and Passive, performed by two different groups of subjects (see below). For each condition, two different tasks were required, consisting either in Congruent or in Non-Congruent drawing movements. There were thus 6 experimental conditions, which are described below (see Fig. 1).

2.3.1. Baseline (common between groups)

1. Active Congruent movement Lines–Lines (A-LL): subjects simultaneously drew vertical lines with both hands.

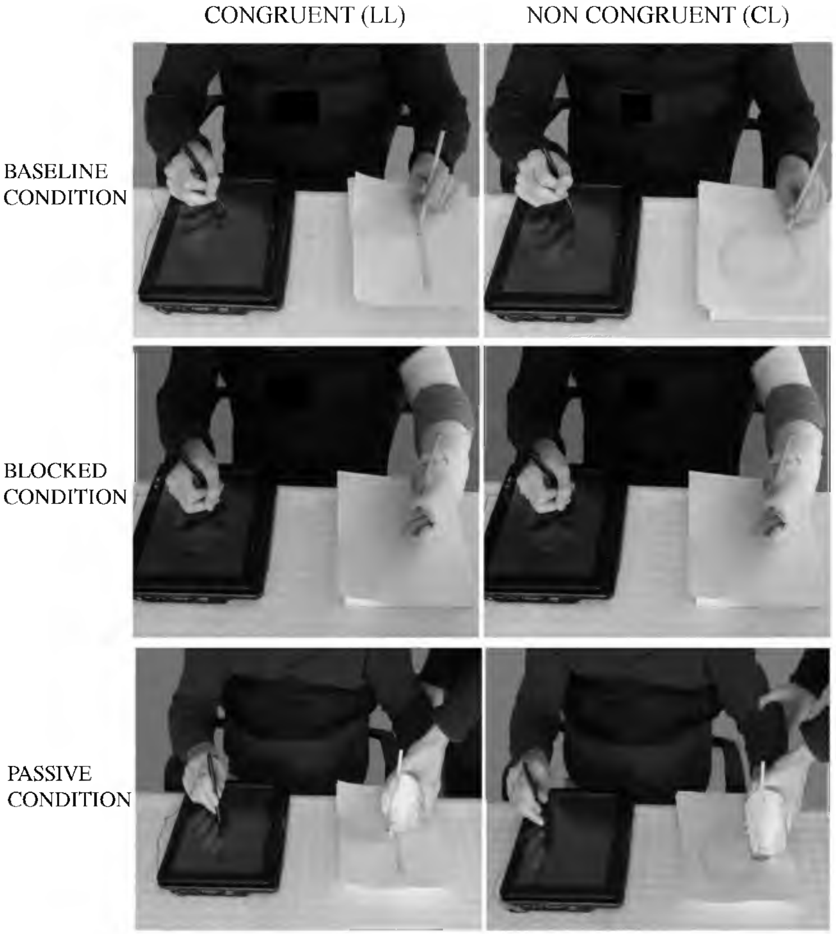

Fig. 1. Experimental paradigm. From top to bottom: the common Baseline condition, where bimanual movements were actually performed; the Experimental condition in the Blocked group, where left arm movements were prevented by the fiberglass cast; the Experimental condition in the Passive group, where the subject's left arm was passively moved by the examiner. For all conditions, the Congruent task (LL) is shown on the left and the Non-Congruent task (CL) on the right.

2. Active Non-Congruent movement Circles-Lines (A-CL): subjects simultaneously drew vertical lines with the right hand and circles with the left hand.

2.3.2. *Experimental condition (Blocked group)*

1. Blocked Congruent movement Lines–Lines (B-LL): subjects drew vertical lines with the right hand and, simultaneously, tried to draw lines with the immobilized left hand.
2. Blocked Non-Congruent movement Circles–Lines (B-CL): subjects drew vertical lines with the right hand and, simultaneously, tried to draw circles with the immobilized left hand.

2.3.3. *Experimental condition (Passive group)*

1. Passive Congruent movement Lines–Lines (P-LL): subjects drew vertical lines with the right hand while, simultaneously, the examiner passively moved their left hand, producing vertical lines.

2. Passive Non-Congruent movement Circles–Lines (P-CL): subjects drew vertical lines with the right hand while, simultaneously, the examiner passively moved their left hand, producing circles.

There were 6 trials for each condition and each trial lasted 12 s, followed by a rest of 6 s. In both groups, 12 trials of the experimental condition, either Blocked (B-LL-/B-CL randomized) or Passive (P-LL-/P-CL randomized) depending on the group, were preceded and followed by 6 trials of the Baseline condition (A-LL/A-CL randomized). Accordingly, two balanced sequences (24 trials each) were generated as follows. Blocked group: 6 A-LL/A-CL – 12 B-LL-/B-CL – 6 A-LL/A-CL; Passive Group: 6 A-LL/A-CL – 12 P-LL-/P-CL – 6 A-LL/A-CL.

2.4. Instructions for participants and for the examiner

While blindfolded, subjects were asked to perform self-paced movements, consisting in continuously drawing vertical lines and/or circles, without interruption for 12 s on each trial. Subjects were always asked to use their right hand to draw vertical lines, the trajectories of which were registered on a 12-inch tablet PC. With their left hand they drew on a sheet of paper. Previous data (Garbarini, D'Agata et al., 2013) have shown that subjects are automatically able to maintain a similar frequency between conditions; consequently, subjects were directed to perform ecological, self-paced movements rather than externally imposing a fixed movement frequency. They were required to draw freely, but, at the same time, they were instructed to be constant in the drawing amplitude across conditions. In particular, they were explicitly directed to perform vertical lines of the same length in the LL task and circles with a diameter of the same length as that of the lines in the CL task.

In the common Baseline condition, participants were asked to actually perform the required bimanual movements, simultaneously with both hands. The "blocked" participants were asked to perform the required bimanual movement, trying to simultaneously move their free right arm and their immobilized left arm, for the entire trial duration. The "passive" participants were asked to actually perform the right arm movements and to keep the left arm completely passive. They were instructed to focus their attention on the left side, in order to avoid any voluntary movement with their left arm (this was a highly demanding request for the subjects). This meant that, although the subjects had to perform unimanual movements in the passive condition, their attention was divided between the two hands.

The examiner moved the subject's left arm, drawing either circles or lines according to the task, and had to maintain a constant amplitude across conditions, using, as a template, lines or circles previously drawn by the subjects in the Baseline active conditions (6 trials of the Baseline condition always preceded the 12 trials of the Experimental condition; see the experimental design description above). Moreover, the examiner had to synchronize his movements with those performed by the subject's right arm. During the experiment, we verified that the movements of both the examiner and the participants were synchronous.

2.5. Instrumented analysis of bimanual coupling during drawing

For each trial an ovalization index (OI) was calculated as a deviation of the right hand drawing trajectory from an absolute vertical axis. The OI index consists of the percentual ratio between the standard deviation of the drawing horizontal coordinate and the standard deviation of the drawing vertical coordinate. The OI index ranges from 0, marking . straight vertical trajectories without any sign of ovalization; to 100 marking perfect circular trajectories; values between 0 and 100 represents oval trajectories with a longer vertical than horizontal axis (for details, see Garbarini et al., 2012). The strength of any bimanual coupling/interference effect was signaled by an increased OI value in the Non-Congruent task (left hand drawing circles and right hand drawing lines) compared to the Congruent (both hands drawing lines) task. Furthermore, drawing frequency was monitored and obtained by averaging the inverse of each drawing cycle duration, identified as the time spanning two consecutive apical points of the drawn trajectory. Preliminary observations evidenced that bimanual drawing shared a common time pattern and therefore a common drawing frequency. Such assumption was checked and guaranteed during the experiments.

2.6. EMG recording and analysis

In order to verify (a) the presence of an intentional component of the movement even in the absence of actual motor performance (in the Blocked group) and (b) the absence of an intentional component of the movement during passive mobilization (in the Passive group), skin electrodes for electromyography (EMG) were placed on three left arm muscles involved in the task: anterior deltoid (contributes to shoulder flexion-abduction and, apparently at a pilot experiment, the muscle most active in the drawing tasks), posterior deltoid (shoulder extension-abduction) and biceps brachii caput longum (mainly elbow flexion with a less important role in shoulder flexion). Other potential target muscles (i.e., the forearm supinator and the pectoralis major) involved in the tasks were initially identified but afterwards dropped because EMG recording was not feasible in some of the experimental conditions (supinator EMG recordings not feasible in presence of a cast) or because the EMG recording of the muscle was not compatible with the experimental setup (electrodes on the pectoralis major are affected by the belt for restraining trunk movements). A wireless surface EMG recording system (WaveEMG©, Cometa S.R.L., Italy, http://www.cometasystems.com) was adopted (unit µV, analog 10-500 Hz pass band filter embedded in the electrode units, 2 kHz A/D conversion, no digital filter hereafter). Since the muscle activity time profile in the drawing tasks has a phasic feature (burst of activity alternated with silent, or less active, phases), an index mostly related to the burst phases, the 95th percentile of the EMG rectified values, was chosen as an index of activity level.

The procedure for computing the EMG index $E95_{\text{muscle}}$ required the following steps depicted in Fig. 2: for each of the three recorded muscles, first the EMG signal, which is a zero-mean signal, was rectified by applying the absolute value operator, then the rectified signal values were sorted and the 95th percentile value (the smallest value which is larger than 95% of the EMG values and smaller than the remaining 5%) was assumed as the $E95_{\text{muscle}}$ value.

Such percentile-based index allows for comparison across conditions for a single muscle in an intra-individual setting, with the only requirement of not moving the electrodes across conditions.

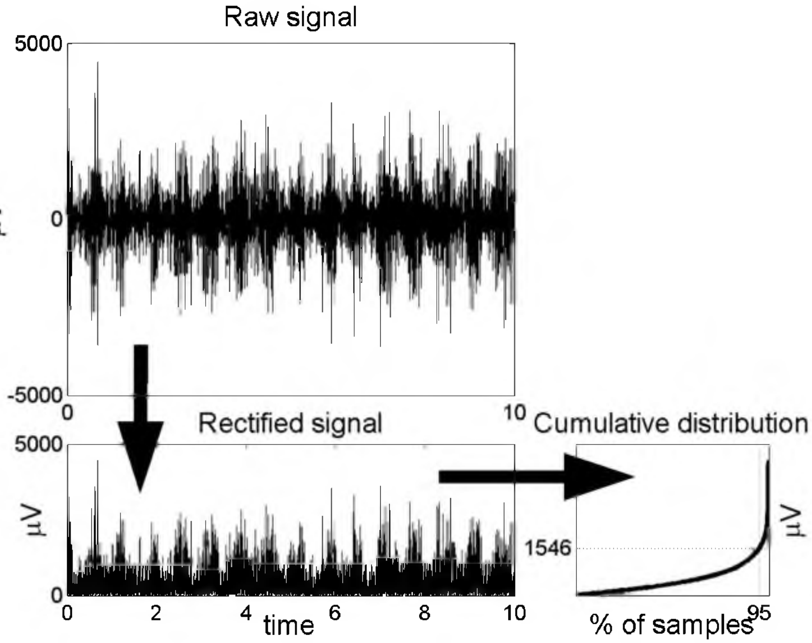

Fig. 2. Algorithm for computing the EMG index $E95_{\text{muscle}}$. The raw EMG signal is reported in the upper left, it is then rectified (lower left) and a cumulative distribution (lower right) of the values of the rectified signal is built in order to identify the index value as the 95th percentile value (larger than 95% of all the rectified values).

Any inter-muscle and/or inter-individual comparison of EMG parameters would require normalization procedures which were not implemented since they are outside the scope of the present study.

3. Results

3.1. Behavioral results

Since frequency can influence trajectories in bimanual drawing movements (Dounskaia et al., 2010), we investigated whether, despite the self-paced movement design, subjects would automatically maintain a similar movement frequency between the two conditions (Baseline and Experimental), in both groups (Blocked and Passive). In each group, a paired t-test (two tailed) on drawing frequency mean values was performed for the contrast between the Baseline (Blocked group: Mean ± SD: 1.1 ± 0.3 Hz; Passive group: mean ± SD: 1.1 ± 0.2 Hz) and Experimental conditions (Blocked group: mean ± SD: 1.2 ± 0.3 Hz; Passive group: mean ± SD: 1.1 ± 0.2 Hz). Overall, no significant difference was found for drawing frequency between these conditions (Blocked group: $P = .4$; Passive group: $P = .2$).

In the behavioral analysis we used the OI mean value as the dependent variable. To compare the experimental groups, we performed a 2 × 2 × 2 mixed ANOVA with Group (Blocked; Passive) as a between-subjects factor and two within-subject factors, Condition (Baseline; Experimental) and Task (Congruent LL; Non-Congruent CL). The ANOVA found main effects of Condition ($F(1, 18) = 10.010$; $P = .005$) and Task ($F(1, 18) = 96.371$; $P < .0001$), and, more importantly, an interaction Group* Condition* Task ($F(1, 18) = 5.576$; $P = .029$).

In the Blocked group, Duncan post hoc comparisons confirmed the presence of the bimanual coupling effect (i.e., significant increase in the OI value in the Non-Congruent CL task with respect to the

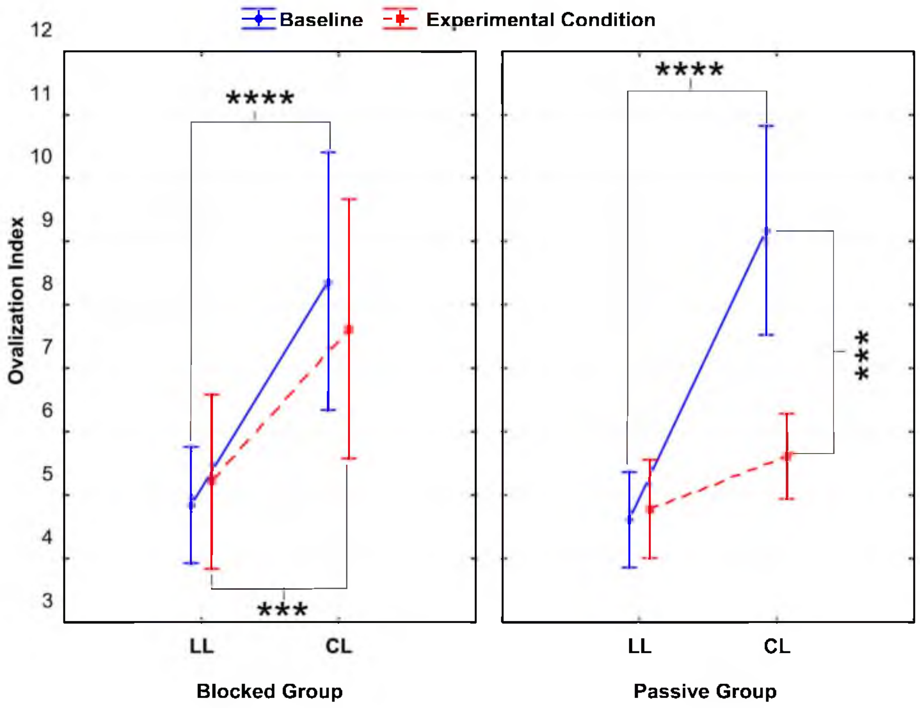

Fig. 3. Behavioral results. The graph shows the OI mean values in all conditions of the experiment, for both the Blocked and Passive groups. Vertical bars represent the standard deviation. Significant differences between conditions are also shown (***$P < .0005$; ****$P < .00005$).

Congruent LL task) in both conditions, Baseline and Experimental ($P = .00004$; $P = .0004$ respectively). On the other hand, in the Passive group, Duncan post hoc comparisons confirmed the presence of the bimanual coupling effect in the Baseline condition only ($P = .00002$); in the Experimental condition the difference between the Congruent LL and Non-Congruent CL tasks was not significant ($P = .186$). Coherently, the OI value in the CL task was significantly higher in the Baseline than in the Experimental condition ($P = .00007$). See Fig. 3, showing, for each group, the OI mean values in all conditions of the experiment.

Illustrative examples of the right hand trajectories in the crucial CL condition are shown in Fig. 4, for both conditions (Baseline and Experimental condition) of both Groups (Blocked and Passive).

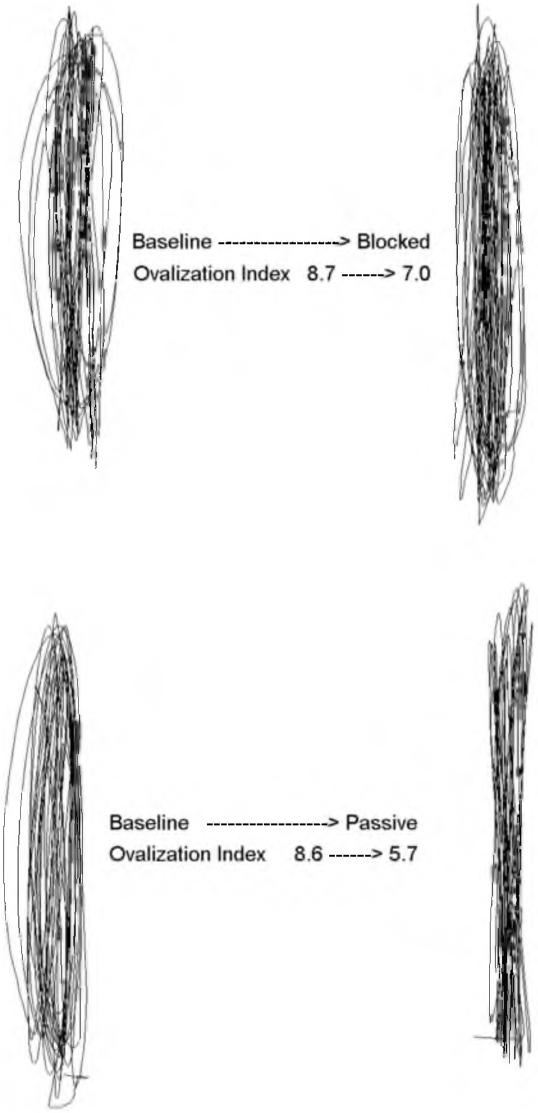

Fig. 4. Examples of right hand trajectories for both the Blocked and Passive groups in the crucial CL condition, in both the Baseline and Experimental conditions. Note in the Blocked Group (A) a similar ovalization (coupling effect) in both the Baseline and Experimental conditions; in the Passive Group (B) the different ovalization in the Baseline condition with respect to the Experimental condition.

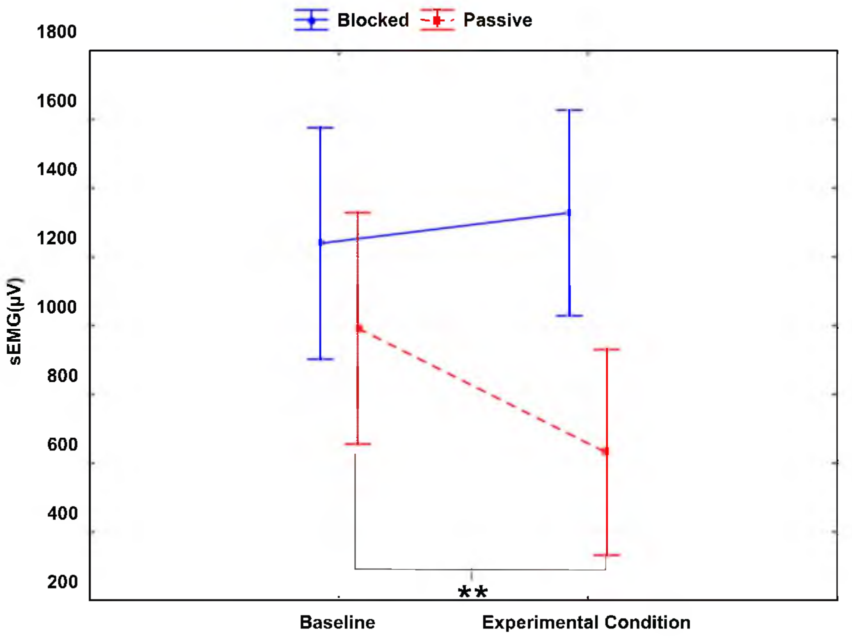

Fig. 5. EMG results. The graph shows the average of the EMG value recording from the left arm muscles involved in the task (anterior deltoid, posterior deltoid, biceps brachii caput longum) for both the Blocked and Passive groups in the Baseline and Experimental conditions. Vertical bars represent the standard deviation. In the Blocked group, the significant difference between the Baseline and Experimental condition is also shown (**$P < .005$).

3.2. EMG results

In the EMG analysis, we used as the dependent variable the $E95_{muscle}$ mean value for each of the three left arm muscles recorded during the task (anterior deltoid, posterior deltoid, biceps brachii caput longum) (see Fig. 5).

In the Blocked Group, planned comparisons did not show any significant difference between the Baseline and Experimental conditions ($P = .465$), suggesting the presence of a similar EMG activity in both Tasks. On the contrary, in the Passive Group, Duncan post hoc comparison showed a significant decrease in the EMG value in the Passive condition with respect to the Baseline condition ($P = .007$). Furthermore, in the Blocked Group, planned comparison on each muscle did not show any significant difference between the Baseline and Experimental conditions ($P > .1$ for each planned comparisons), suggesting the presence of a similar EMG activity in both Tasks. On the contrary, in the Passive Group, we found in each muscle a significant decrease in the EMG value in the Passive condition with respect to the Baseline condition ($P < .01$ for each planned comparisons). In none of the muscles, both in Blocked and Passive group, planned comparisons showed significant differences in Tasks (Congruent LL; Non-Congruent CL), suggesting that a difference in the activity level of the three muscles cannot be evidenced in the lines versus the circles drawing movement.

In Fig. 6, examples of EMG recording from the left anterior deltoid muscle during the CL condition, in the Baseline or Experimental condition, are presented for both the Blocked and Passive Groups. Note that in the Passive group the EMG 95th percentile value is approximately halved in the Experimental condition compared to the Baseline condition.

4. Discussion

The present study aimed to further investigate the role, already evidenced in previous studies on both healthy volunteers (Swinnen et al., 2003; see also de Boer et al., 2013; Dounskaia et al., 2010;

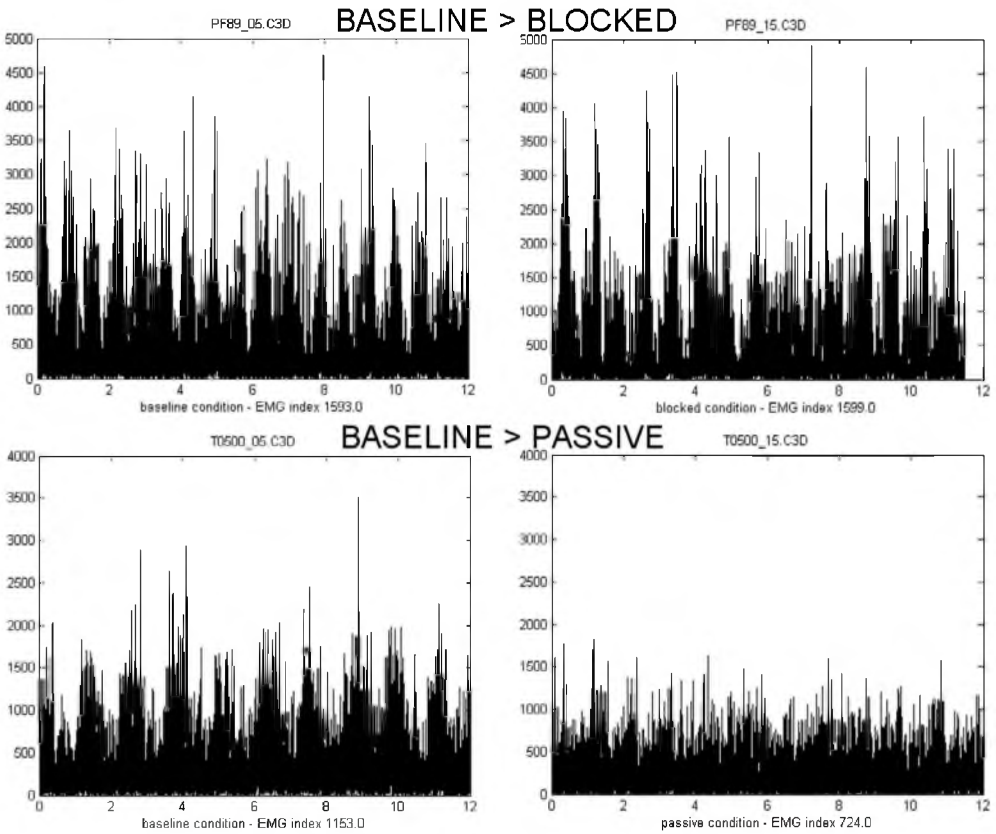

Fig. 6. Example of the EMG recording from the left anterior deltoid muscle in the crucial CL condition, in both the Baseline and Experimental conditions of the Blocked and Passive Groups. Note, (a) in the Blocked Group, similar EMG activity in both the Baseline and Experimental conditions; (b) in the Passive Group, lower EMG activity in the Experimental condition with respect to the Baseline condition.

Ridderikhoff et al., 2005; Spencer et al., 2005) and pathological conditions (Franz & Ramachandran, 1998; Garbarini et al., 2012; Garbarini, Pia et al., 2013; Pia et al. 2013), of the intentional and predictive operations for the occurrence of bimanual coupling. In the Blocked group, where motor intentionality was required but movements in space were prevented by immobilization of the arm, a significant coupling effect (i.e., significant increase in the OI value in the Non-Congruent CL task with respect to the Congruent LL task) was found, comparable to that found during the actual performance of bimanual movements (Baseline condition). On the contrary, in the Passive group, where movements in space were present but motor intentionality was not required, no significant coupling effect was observed.

In the present study we recorded surface electromyography (EMG, detection of electrical potential of muscle fibers associated with mechanical muscle tensioning) of the muscles involved in the drawing tasks as a marker of motor intention, independently of the occurrence of the movement in space. In the Blocked group, the EMG data indicated a lack of difference in muscular activation between the Baseline and the Experimental condition, suggesting that the subjects tried, as requested, to perform the task despite their arm being immobilized (see below, "Section 4.1"). Vice versa, in the Passive group, the lack of intentional components was confirmed by the EMG data, which showed a significant drop in muscular activation between the Baseline, in which subjects actually performed the bimanual task, and the Experimental condition.

The analysis of the EMG data concerning the Passive group poses relevant questions about the nature of the reduced EMG activity when compared to the Baseline and Experimental conditions and particularly about whether or not such activity is caused by a motor intention. In healthy subjects, muscle contractions and the related electrical activity may result either from a top-down central nervous system (CNS) voluntary conscious command or may be elicited as a reflex resulting from proprioceptive, esteroceptive, tactile and pain sensory feedback or from unconscious anticipatory postural adjustments (APA; Esposti & Baldissera, 2011) as well as mirrored activity (Ridderikhoff et al., 2005). All these latter categories of muscular reflex, APA or mirrored activity, share the common feature of being unconscious and involuntary, and are therefore not to be interpreted as related to an intention. While the experimental setup was designed to limit such passive limb EMG activity, particularly by adopting a trunk restraint which reduced the need for postural adjustments in the passive left limb (Esposti & Baldissera, 2011), it is worth reporting that Ridderikhoff and colleagues (2005) have shown that EMG activity of the muscles in the arm not intended to move may occur coherently with the activity of the active contralateral limb during a unimanual rhythmic task in healthy adults. Such involuntary EMG activity with lower values did not result in a detectable functional movement. Given such evidence, we assumed that in our experimental data concerning the passively moved limb, non-zero EMG activity was composed of uninhibited neural cross-talk and ipsilaterally and peripherically generated involuntary components, including mirrored activity. Though the random occurrence of intentional low-level muscle activation cannot be absolutely excluded in the present setup. Possible ways of managing and reducing such factor will be discussed later as a future development (see below, “Section 4.1”).

In the context of motor cognition, the crucial role of intentional motor programs has been described within the predictive model of motor control (Blakemore, Wolpert, & Frith, 2002; Haggard, 2005; Wolpert, Ghahramanim, & Jordan, 1995). According to this model, once the motor commands related to a desired movement are selected and sent to the periphery, for the contractions of the muscles specific for the execution of the willed action, a forward model, which represents the prediction of the sensory consequences of the movements, is formed. If the movement is actually performed, the prediction will be compared, by a comparator system, to the sensory feedback from the periphery. This comparison makes it possible to distinguish, in normal conditions, between a movement produced successfully and possible errors in movement execution. It can also distinguish between movement/no movement conditions when an action is intended but not executed (for instance when some external events prevent motion or in the presence of a pathological condition). Previous findings on pathological conditions, where the movement of only one hand is allowed, have demonstrated that, when movement execution by the other hand is completely absent, motor intention is sufficient to trigger bimanual coupling effects (Franz & Ramachandran, 1998; Garbarini et al., 2012; Garbarini, Pia et al., 2013). Other clinical studies have reported coupling effects even in the absence of somatosensory consequences of the movement, as in patients with peripheral sensory loss (Drewing, Stenneken, Cole, Prinz, & Aschersleben, 2004; Spencer et al., 2005). During bimanual Non-Congruent movements, the coupling effect was observed in these patients, as in healthy subjects. Such studies were therefore able to conclude that it was not influenced by the absence of sensory information coming from the arm periphery, and suggested that the afferent level of information is not necessary for the emergence of this effect. Accordingly, the present study shows that, in healthy subjects, (a) the bimanual coupling occurs despite the absence of spatial movements during the blocked condition; (b) the presence of proprioceptive information during passive movements was not able to trigger any coupling effect, suggesting that it primarily emerges at the efferent level of motor intention and planning (see also Swinnen et al., 2003).

The novelty of our study is related both to the task, combining passive movement of one limb with active movement of the other, and to the domain used to quantify the interference effects, namely the spatial domain (e.g., Franz et al., 1991; Swinnen et al., 2003). Previous studies (e.g., Serrien, Li, Steyvers, Debaere, & Swinnen, 2001; Swinnen, Dounskaia, Verschueren, Serrien, & Daelman, 1995) investigated how coordinated rhythmic movements of two limbs (either homologous or ipsilateral) is disrupted by a third limb movement imposed by an external operator with a different spatio-temporal pattern from the coordinated rhythmic movement of the other two limbs. The disruption was quantified in the time domain as incremented phase-shift between the coordinated movements of the two active limbs. These data indicate that passive movement disturbed the temporal dynamics of the subject's coordination during the actual execution of bimanual rhythmic movements. The present results for the Passive group showed that unimanual performance is not disrupted by spatially incongruent kinesthetic contralateral feedback. We can speculate that a possible explanation of this discrepancy are both different domain (temporal vs. spatial) and different task (bimanual vs. unimanual). Alternatively, it is possible that, in the present study, the subjects were able to suppress the proprioceptive influence because passive motion was well predictable, in contrast to unpredictable perturbations in the other studies.

Since we were interested in the motor domain, we only considered kinesthetic feedback, and excluded visual feedback (participants were blindfolded during the experiment) thus, the present results are not informative about a possible effect of vision on bimanual interference. However, our results are consistent with those of a previous study investigating the effect of visual feedback in inducing spatial interference during unimanual movements (Garbarini, Pia et al., 2013). It has been demonstrated that, in healthy subjects, simply observing the examiner's hand drawing circles (in either an egocentric or allocentric position) cannot affect one's own hand drawing lines (i.e., in this task, a coupling effect cannot be induced by visual feedback). However, in the visual domain, other studies (e.g., Romero, Coey, Schmidt, & Richardson, 2012) have shown that, when using different tasks, visual coupling induces spatial interference and this depends on the degree to which the movements are visually synchronized. As far as synchrony is concerned, in the Passive group, participants were not explicitly asked to synchronize their movements with those of the examiner, using their proprioceptive and kinesthetic information. Although we verified (by visual inspection) that a spontaneous synchronization emerged in all subjects in the Passive group, this aspect will need to be systematically controlled in future experiments to investigate whether spatial interference effects might depend on the degree to which active movements are kinesthetically synchronized with passive ones (based on the model used in Romero and colleagues' study in the visual domain).

4.1. Limitations of the study and future perspectives

We acknowledge a number of limitations of the present study. The Blocked group can be considered as a first attempt in the exploration of the role of motor intention in determining bimanual coupling in healthy subjects. This experimental condition is principally different from that observed in amputees and in paralyzed patients who cannot activate their muscles. In the Blocked group, the motor control was not limited at the level of intentional, feed-forward components but feedback about the generated muscle forces (sensory feedback only from Golgi organs and not from spindles) and skin-cast contact pressures was still present. Further experiments are therefore necessary in order to confirm the hypothesis that motor intention is a sufficient condition for bimanual coupling in healthy subjects. It must be added, however, that efferent and afferent signals should not correspond in the Blocked group (an error signal should be generated by the motor monitoring system) and, as a consequence, the coupling effect may, at least in part, still be related to the predictive models triggered by intentional activation.

As regards the Passive group, the main problem is how to exclude the occurrence of intentional muscle activity in the passive limb which is moved by an external operator during a unimanual rhythmic task on the contralateral active limb. While it has been demonstrated that residual EMG activity may be present as mirrored or peripherally-generated activity, the neural pathway able to transport the intention to move from the CNS to the muscles is still enabled.

Future experimental designs could act at different levels in order to overcome the limitations of the present study. A provoked ischemic arm block might prevent the action potential from reaching the muscle of one limb by blocking the neural pathway between the CNS and the muscle, thus inhibiting any kind of proprioceptive feedback while maintaining motor intention in case of voluntary movement (thus overcoming the limitations of the Blocked group) or allowing for passive movement of the arm without any occurrence of residual intentional and/or mirrored muscle activity (thus overcoming the limitations of the Passive group). Another experimental design, possibly complementing the present data in the Passive group, could allow the incongruent task to be implemented without intention: an impedance-controlled robot could introduce external movement-related forces which change the planned movement; such external force component could force a planned linear trajectory into a circular one, thus achieving the incongruent condition regardless of the subject's intention.

5. Conclusions

In the present study, we manipulated the circles-lines task to investigate the role of motor intention in triggering bimanual coupling in healthy subjects. Two experiments were designed: one with motor intention but without movement in space (Blocked group), the other with spatial movement but without motor intention (Passive group). Our results are in line with the central role of the intentional and predictive operations for the occurrence of bimanual coupling.

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