

Top-down suppression of incompatible motor activations during response selection under conflict

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ARTICLE INFO

Article history:

Accepted 1 August 2013

Available online 9 August 2013

Keywords:

Top-down control

Conflict

Inhibition

Corticospinal excitability

Response selection

Transcranial magnetic stimulation

ABSTRACT

Top-down control is critical to select goal-directed actions in changeable environments, particularly when several options compete for selection. This control system is thought to involve a mechanism that suppresses activation of unwanted response representations. We tested this hypothesis, in humans, by measuring motor-evoked potentials (MEPs) elicited by transcranial magnetic stimulation (TMS) in a left finger muscle during motor preparation in an adapted Eriksen flanker task. Subjects reported, by a left or right button-press, the orientation of a left- or right-facing central arrow, flanked by two distractor arrows on each side. Central and peripheral arrows either pointed in the same (congruent trial) or in the opposite direction (incongruent trial). Top-down control was manipulated by changing the probability of congruent and incongruent trials in a given block. In the “mostly incongruent” (MI) blocks, 80% of trials were incongruent, producing a context in which subjects strongly anticipated that they would have to face conflict. In the “mostly congruent” (MC) blocks, 80% of trials were congruent and thus subjects barely anticipated conflict in that context. Thus, we assume that top-down control was stronger in the MI than in the MC condition. Accordingly, subjects displayed a lower error rate and shorter reaction times for the incongruent trials in the MI context than for similar trials in the MC context. More interestingly, we found that top-down control specifically reduced activation of the incompatible motor representation during response selection under high conflict. That is, when the central arrow specified a right hand response, left (non-selected) MEPs became smaller in the MI than in the MC condition, but only for incongruent trials, and this measure was positively correlated with performance. In contrast, MEPs elicited in the non-selected hand during congruent trials, or during all trials in which the left hand was selected, tended to increase more after the imperative signal in the MI than the MC condition. Another important observation was that, overall, MEPs were already strongly suppressed at the onset of the imperative signal and that this effect was particularly pronounced in the MI context. Hence, suppression of motor excitability seems to be a key component of conflict resolution.

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Introduction

At every moment, we are faced with a large choice of actions. A key question is therefore how one action is selected in favor of another. Models of decision making postulate that the motor representations associated with the potential actions are activated in parallel and compete for selection (Cisek, 2012; Doya and Shadlen, 2012; Klein et al., 2012; Oliveira et al., 2010). Selection occurs when the activation of one action representation reaches a given threshold (Domenech and Dreher, 2010; Roitman and Shadlen, 2002). In many variants of decision-making models, the accumulation of activity for each potential response is accompanied by mutual inhibitory interactions (Brown and Heathcote, 2005; Duque et al., 2008; Praamstra and Seiss, 2005; Usher and McClelland, 2004). That is,

each candidate not only accrues supporting “evidence”, but also inhibits the alternative options (Coles et al., 1985; Seeley et al., 2012). Consistently, the cortical representation of non-selected responses is systematically suppressed during action selection (Burle et al., 2004; Duque et al., 2005, 2007; Meckler et al., 2010; van de Laar et al., 2012; Wijnen and Ridderinkhof, 2007).

In the context of sensorimotor decisions, perceptual evidence can sometimes lead to a strong activation of action representations that are goal-irrelevant, because irrelevant information is very salient or because these inappropriate actions are strongly appealing by nature, sometimes even more than the relevant options (Cai et al., 2012; Chen et al., 2009; Mars et al., 2009; Mattler, 2003; Michelet et al., 2010; Praamstra et al., 1998; Taylor et al., 2007). In this situation, there is a “conflict” between the goal-directed and the irrelevant actions, as evidenced by an increased time needed to provide the appropriate response and a higher error rate (Hughes and Yeung, 2011; Ridderinkhof, 2002; Takezawa and Miyatani, 2005).

When selection occurs under situations of conflict, a specific brain network, including the anterior cingulate cortex, pre-supplementary

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motor area (pre-SMA), and lateral prefrontal cortex, is engaged to help resolve competition in favor of the relevant actions (Aron, 2007; Botvinick et al., 1999; Duque et al., in press; Lenartowicz et al., 2011; Siegel et al., 2011; Young and Shapiro, 2011). The recruitment of this “top-down” control network seems to depend on the degree to which conflict is expected in advance (Cohen and Ridderinkhof, 2013; Grandjean et al., 2012; King et al., 2012). Accordingly, the ability to overcome conflict is typically larger in situations where conflict can be anticipated than when it was unlikely (Botvinick et al., 2004; Gratton et al., 1992; Ridderinkhof, 2002). Importantly, it is usually assumed that conflict resolution relies on the strengthening of inhibitory influences directed at unwanted (incongruent) response representations (Stürmer et al., 2000; Verleger et al., 2009). However, there is only indirect evidence to support this idea, both in humans (Duque et al., in press; Neubert et al., 2010; Tandonnet et al., 2011; Taylor et al., 2007) and monkeys (Cisek and Kalaska, 2005; Lecas et al., 1986). Especially relevant to the current issue is the recent finding that a TMS-induced virtual lesion to the pre-SMA, an area known to play a critical role in conflict resolution (Nachev et al., 2007; Usami et al., 2013), reduces suppression of inappropriate motor representations, especially when response selection occurs under conflict (Duque et al., in press). This indicates a link between pre-SMA functioning, conflict resolution and suppression of irrelevant representations. However, the design used in that recent study did not allow us to relate directly the strength of the motor suppression during response selection with the goal to resolve conflict. The present study aimed at addressing this point directly.

We measured motor-evoked potentials (MEPs) in a left intrinsic hand muscle while participants performed the Eriksen flanker task (Eriksen and Eriksen, 1974). Subjects were required to indicate by a left or right button-press the orientation of a briefly presented left- or right-facing central arrow, flanked by distractor arrows on each side. The central and peripheral arrows either pointed in the same (congruent trials) or in the opposite – conflicting – direction (incongruent trials). The proportion of congruent and incongruent trials was manipulated to produce two different contexts in terms of conflict expectation. In one context, most trials (80%) were incongruent (“mostly incongruent” MI context) and thus subjects anticipated that they would have to face conflict in most trials; in contrast, in the other context, a majority of trials (80%) was congruent (“mostly congruent” MC context) and thus subjects barely anticipated that they would need to overcome conflict in that condition.

Based on many previous reports, we predicted that the activation of inappropriate response representations would be larger in incongruent compared to congruent trials, especially in the MC context, due to the higher conflict in the former trial type. More importantly, we expected that this activation of inappropriate response representations would decrease in the MI context, possibly reflecting further inhibition directed at unwanted representations to resolve conflict.

Methods

Participants

A total of twenty-one subjects participated in a behavioral experiment ($N = 9$), 6 women, mean age = 23.2 ± 0.72 years old) or in a TMS experiment ($N = 12$), 7 women, mean age = 26.1 ± 1.87 years old). None of the participants had any neurological disorder or history of psychiatric illness, drug or alcohol abuse, or were on any drug treatment that could influence performance or neural activity. All the subjects were right-handed according to the condensed version of the Edinburgh Handedness Inventory (Oldfield, 1971) and were financially compensated for their participation (~35 euros per session). They were all naive to the purpose of the study. The protocol was approved by the Ethics Committee of the Université catholique de Louvain (Belgium) and all subjects gave written informed consent for their participation.

Eriksen flanker task

In both experiments, we used a modified version of the Eriksen flanker task (Eriksen and Eriksen, 1974), which was implemented by means of Matlab 6.5 (The MathWorks, Natick, Massachusetts, USA) and the Cogent 2000 toolbox (Functional Imaging Laboratory, Laboratory of Neurobiology and Institute of Cognitive Neuroscience at the Wellcome Department of Imaging Neuroscience, London, UK). Subjects were asked to respond with a left or right button-press according to the orientation of a left- or right-pointing arrow (i.e., < or >, respectively) which was briefly presented at the center of a computer screen, positioned about 60 cm in front of them. This central arrow (which we will refer to as the “target”) was always flanked by a set of two distractor arrows on each side (referred to as the “flankers”); the target and the flankers either pointed in the same direction (congruent trial, “<<<<<” or “>>>>>”) or in opposite directions (incongruent trial, “>><<<<” or “<<>>>>”). Hence, subjects performed button-presses with the left or right hand in congruent and incongruent trials (4 conditions; see Fig. 1A, upper part).

As mentioned above, top-down control was manipulated by changing the probability of congruent and incongruent trials in a given block (see Fig. 1A, lower part). In the MI context, subjects had to face conflict in most trials (80% incongruent trials) whereas in the MC context, most trials did not require subjects to face conflict (80% congruent trials). Subjects were always told about the context (MI or MC) of the block they would start performing next. As a consequence, the degree to which subjects anticipated conflict, and thus the goal to resolve conflict, clearly varied in these two contexts (Ridderinkhof, 2002). Accordingly, we assume that the involvement of top-down control mechanisms recruited to overcome conflict was larger in the MI context, a condition where subjects strongly anticipated conflict, compared to the MC context, when subjects barely anticipated conflict, as previously shown (Grandjean et al., 2012; King et al., 2012).

Experimental procedure

The participants sat in front of the computer screen with both forearms in a semi-flexed position and resting on a pillow; the hands were placed palms down on a keyboard. The keyboard was turned upside-down so that subjects could press on the required buttons with the left or right index fingers (keys “F12” and “F5”, respectively). After each trial, subjects were asked to place their index fingers on two small rubber pads, which were positioned on the external side of the two target buttons (see Fig. 1B). Hence, each key press required subjects to perform a brisk flexion and abduction movement of the left or right index finger. Note that a strong emphasis was put on the execution of strictly unilateral movements. The experimenter monitored this aspect of behavior by continuously looking at the electromyography (EMG) of the left and right first dorsal interosseous muscles (FDI: muscle agonist of index finger flexion and abduction) during the experiments. He provided feedback to the participant to reduce muscle activity when necessary.

Each trial started with the presentation of a warning signal, a fixation cross (+), displayed at the center of the screen for 500 ms (Fig. 1B). This signal indicated the beginning of a trial and was followed, after a 500 ms fixed delay period, by the imperative signal which consisted of one of the four possible combinations of target and flankers (“<<<<<”, “>>>>>”, “>><<<<”, “<<>>>>”). Subjects were asked to respond as quickly as possible following this imperative signal; the latter disappeared after 400 ms or once a response key had been pressed. Reaction times (RTs) were computed by means of a homemade hardware (PSB). In brief, the PSB is a microcontroller (μ C; MSP430F249 – Texas Instrument) based system receiving VGA and keyboard events: a timer starts on specific VGA events (imperative signal) and stops on keyboard events (finger response). The μ C sends the pressed key code and the timer value (128 μ s resolution) to the main computer through a USB interface, providing RT measurements with very high temporal resolution. Once

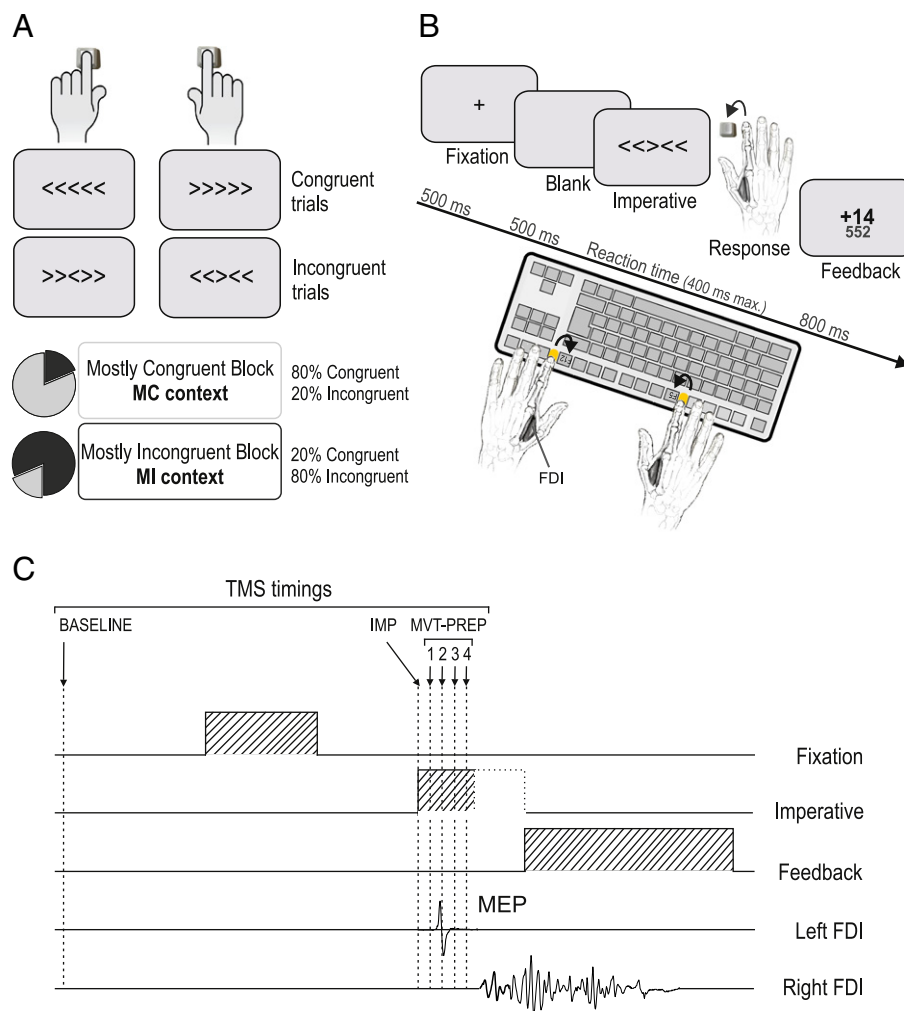


Fig. 1. A: Experimental conditions. Subjects were asked to respond with a left or right button-press according to the orientation of a left or right-pointing arrow displayed in the center of the screen. This target arrow was always flanked by a set of two distractor arrows on each side; the target and flankers either pointed in the same direction (congruent trial) or in the opposite direction (incongruent trial). The proportion of congruent and incongruent trials was manipulated within a block to produce the MC and MI contexts. B: Time course of a trial. Each trial started with a fixation cross. Then, after a blank screen, the imperative signal appeared indicating the required button press on a keyboard turned upside-down. A visual feedback was displayed after each response (see [Methods](#) section). C: Sequence and TMS timings. A single TMS pulse was applied over the right primary motor cortex at six possible timings ($TMS_{BASELINE}$, TMS_{IMP} , $TMS_{MVT-PREP1-4}$). FDI = first dorsal interosseous. TMS = transcranial magnetic stimulation. MEP = motor evoked potential. MVT-PREP = movement preparation. IMP = imperative onset.

subjects had given a response, a feedback was presented for 800 ms. This feedback consisted of a positive score depicted in green (following a correct response) or a negative score depicted in red (following a wrong response). Note that positive scores were always proportional to the RTs; the faster the response, the better the score (score = k/RT with $k = 5000$). For instance, a correct response provided with a 400 ms RT yielded a score of 12.5 points. Wrong responses were always followed by a fixed negative score (−10). The total amount of points accumulated from the beginning of each block was also presented following each trial, just below the current trial score. In order to increase their motivation, subjects were told that they would get a financial bonus in proportion to their scores (up to 5 euros per session). Finally, the feedback screen was followed by a blank screen which remained for a variable interval of 2400 to 2800 ms.

Behavioral experiment

Experiment goals

In this experiment, we aimed at assessing the subjects' performance in the congruent and incongruent trials of the MC and MI contexts. To do

so, we focused on two behavioral measures, that is, (1) the reaction times (RTs) and (2) the amount of errors (expressed in percentage of the total number of trials in the corresponding condition, %Errors). We predicted that subjects would be slower (longer RTs) and would make more errors (larger %Error scores) in the incongruent compared to the congruent trials, given the presence of conflict in the former trial type but not in the latter. In addition, performance in incongruent trials should depend on the context within which these trials are executed: we expected RTs to be shorter, and the %Errors to be lower, in the MI context than in the MC context, reflecting the operation of control mechanisms recruited to help overcome conflict.

Blocks and session

The behavioral experiment comprised one session of about 45 min. At the beginning of the experimental session, subjects performed a few trials in a neutral context (same amount of congruent and incongruent trials). This allowed them to become familiar with the basic procedure. Then, in the main phase of the experiment, they performed two blocks in a MC context and two blocks in a MI context; the order of the blocks (MC or MI blocks first) was counterbalanced between subjects. Subjects

were always told about the context of the blocks they would be doing next. Each block comprised 100 trials and lasted about 7 min. A break was made in between the two context conditions.

Statistical analyses

RTs and %Errors were analyzed by means of a three-way repeated-measure (RM) ANOVA with CONTEXT (MC, MI), TRIAL (congruent, incongruent) and HAND (left, right) as factors. Post-hoc comparisons were conducted using the Fisher's LSD (Least Significant Difference) procedure. All of the data are expressed as mean $\pm$ SE.

TMS experiment

Experimental goal

Results from the behavioral experiment confirmed that subjects recruited further control mechanisms when conflict was expected (MI context) compared to when conflict was unlikely (MC context), consistent with previous reports (e.g. Gratton et al., 1992; Ridderinkhof, 2002); RTs were shorter and %Error scores were lower when incongruent trials were performed in the MI context than in the MC context. Then, in the TMS experiment, we aimed at investigating whether conflict resolution in the MI context involved suppressing activation of incompatible motor representations, as often proposed in the literature (e.g. Duque et al., in press; Neubert et al., 2010; Tillman and Wiens, 2011). To do so, we measured corticospinal (CS) excitability during movement preparation following congruent and incongruent imperative signals in the MC and MI contexts. We hypothesized that if conflict resolution is associated with the strengthening of inhibitory influences directed at unwanted motor representations, then CS excitability related to these representations should be lower in the MI than in the MC condition, particularly in incongruent trials.

Blocks and sessions

The TMS experiment extended over two sessions (one for each context) performed on different days; the order of the sessions was counterbalanced across subjects. As in the behavioral experiment, subjects were told at the beginning of the session whether it would involve MC or MI blocks. Each session always began with two blocks in a neutral context (same amount of congruent and incongruent trials) performed in the absence of TMS. The first one served to familiarize the subjects with the task. The second block was used to compute the individual median RT. This value was used to determine the pre-movement TMS timings within that session (see "Stimulation procedure" section below). Then, in the main phase of the experiment, subjects performed six

blocks of 95 trials (about 7 min each). There was a 5 minute break every other block or whenever the subjects felt they needed to rest.

Stimulation procedure

A figure-of-eight coil (wing external diameter 70 mm) connected to a Magstim 200 magnetic stimulator (Magstim, Whitland, Dyfed, UK) was placed tangentially on the scalp over the primary motor cortex; the handle was oriented towards the back of the head and laterally at a 45° angle away from the midline, approximately perpendicular to the central sulcus. We identified the optimal spot for eliciting MEPs in the left FDI muscle and this location was marked on an electroencephalography cap fitted on the participant's head to provide a reference landmark throughout the experimental session. The resting motor threshold (rMT) was defined as the minimal TMS intensity required to evoke MEPs of about 50 μ V peak-to-peak in the targeted muscle in 5 out of 10 consecutive trials. It was measured at the beginning of each session. Across participants (and sessions), the rMT corresponded to $37 \pm 1.9\%$ ($n = 12$) of the maximum stimulator output. The intensity of TMS was always set at 120% of the individual rMT.

In order to assess CS excitability of the left FDI muscle during response preparation, we applied TMS at six different timings (see Fig. 1C); only one single TMS pulse was delivered in each trial. First, to establish a baseline of CS excitability, TMS pulses were applied during the inter-trial interval. More specifically, this timing of stimulation, referred to as TMS_{BASELINE} (5 MEPs/block, 30 MEPs in total for each context), occurred at random between 500 and 900 ms before the onset of the fixation cross. Second, TMS pulses were also applied at the onset of the imperative signal (TMS_{IMP}; 5 MEPs/block, 30 MEPs in total for each context). This timing was used to check for a possible effect of conflict expectation on CS excitability, which would occur even before the subjects perceive the imperative signal and hence even before they can detect the presence of conflict. Finally, TMS pulses could occur at one of four timings between the onset of the imperative signal and the motor response (less frequent trials [20%] = 2 MEPs/block, 12 MEPs total for each context; more frequent trials [80%] = 8 MEPs/block, 48 MEPs in total for each context). These timings, referred to as TMS_{MVT-PREP1}, TMS_{MVT-PREP2}, TMS_{MVT-PREP3} and TMS_{MVT-PREP4}, were determined on an individual basis, and corresponded to 25%, 50%, 75% and 90% of 66% of the individual median RT (see Table 1). This RT was measured at the beginning of each experiment in the second no-TMS block (see "Blocks and sessions" section above) and corresponded to the time elapsed between the onset of the imperative signal and the detection of the button press. Note that in the first three subjects, we used the same pre-movement TMS timings in both sessions, based on the median RT

Table 1

TMS_{MVT-PREP} timings and mean reaction times (RTs) in the TMS experiment.

Subject	MC context					MI context				
	TMS _{MVT-PREP1}	TMS _{MVT-PREP2}	TMS _{MVT-PREP3}	TMS _{MVT-PREP4}	RT	TMS _{MVT-PREP1}	TMS _{MVT-PREP2}	TMS _{MVT-PREP3}	TMS _{MVT-PREP4}	RT
#01	60	120	180	216	364	60	120	180	216	364
#02	50	100	150	180	303	50	100	150	180	303
#03	68	136	204	245	412	68	136	204	245	412
#04	80	160	240	288	485	73	146	219	263	442
#05	82	164	246	295	497	80	160	240	288	485
#06	63	126	189	227	382	66	132	198	238	400
#07	53	106	159	191	321	61	122	183	220	370
#08	62	124	186	223	376	68	136	204	245	412
#09	70	140	210	252	424	80	160	240	288	485
#10	68	136	204	245	412	74	148	222	266	448
#11	71	142	213	256	430	64	128	192	230	388
#12	72	144	216	259	436	69	138	207	248	418
Mean	67	133	200	240	404	68	136	203	244	411
SE	2.8	5.6	8.3	10.0	16.8	2.5	4.9	7.4	8.9	15.0

TMS_{MVT-PREP} (1–4) = Four TMS timings determined on an individual basis (0.25, 0.50, 0.75, 0.90 $\times$ 66% of RT) to assess corticospinal excitability during the preparation period following the imperative signal. Left and right hand RTs were pooled together across trial types to determine the TMS_{MVT-PREP} timings.

measured in the first session only (see Table 1). The value of 66% of the RT was chosen because it corresponds roughly to the onset of the FDI EMG activity preceding the key press, as observed in three different tasks using a similar response setup in the laboratory (e.g. Klein et al., 2012). Finally, the timing of the last TMS pulse ($90\% \times 66\%$) corresponded to the latest delay at which, in this experimental design, we could elicit MEPs without having too many TMS pulses falling after the EMG onset (Michelet et al., 2010). This is a critical point because when assessing CS excitability changes during response preparation, it is important to include only the trials in which the TMS falls before EMG onset (Chen and Hallett, 1999); trials in which the TMS pulse fell after EMG onset were removed from the data set. We believe that the four TMS_{MVT-PREP} (1–4) timings provide us with a representative sample of CS excitability changes during response preparation (Leocani et al., 2000; Reynolds and Ashby, 1999; Rossini et al., 1988) with only a marginal amount of data loss due to variations in RTs.

For the analysis of CS excitability during movement preparation, all MEPs evoked at TMS_{MVT-PREP} (1–4) were pooled together (on an individual basis) and sorted based on the actual interval between the time of the TMS pulse and “EMG onset” (estimated at 66% of the time of key-press). We then grouped these MEPs into three main time epochs (TMS_{MVT-200}, TMS_{MVT-120}, TMS_{MVT-40}), each covering an 80 ms period centered on 200, 120 and 40 ms before “EMG onset”, respectively. As a consequence, the interval between the TMS pulse and “EMG onset” ranged from 240 to 160 for TMS_{MVT-200} (mean interval = 190 ± 1.9 ms and 194 ± 1.1 ms in the MC and MI contexts, respectively), from 160 to 80 ms for TMS_{MVT-120} (mean interval = 120 ± 1.9 ms and 121 ± 0.7 ms), and from 80 to 0 ms for TMS_{MVT-40} (mean interval = 45 ± 2.4 ms and 47 ± 2.2 ms). On average, the MEPs included in each time epoch were elicited at a comparable interval from movement onset in the two contexts (all $F < 2.9$, all $p > 0.120$). Finally, the three pre-movement epochs (TMS_{MVT-200}, TMS_{MVT-120}, TMS_{MVT-40}) fell on average 88 ± 4 ms, 144 ± 7 ms and 221 ± 7 ms after the onset of the imperative signal, respectively.

In eight out of the twelve subjects, we also measured CS excitability at rest (outside the blocks) by applying 20 TMS pulses (TMS_{BASELINE-OUT}) at three different phases during the TMS experiment (before the first block, after the third block and after the last block). The mean value of MEPs elicited at TMS_{BASELINE-OUT} was compared with MEPs elicited at TMS_{BASELINE} (elicited during the blocks) in order to check for the occurrence of a global effect of context on CS excitability in the two block types, one that would extend to the baseline MEPs.

EMG recordings

EMG activity was recorded from surface electrodes (Neuroline, Medicotest, Oelstykke, Denmark) placed over the left and right FDI muscles. EMG data were collected for 2600 ms on each trial, starting at least 200 ms before the TMS pulse. The EMG signals were amplified and band-pass filtered on-line (10–500 Hz [Neurolog; Digitimer, Hertfordshire, UK]) and digitized at 2000 Hz for off-line analysis. The EMG signals were used to measure peak-to-peak amplitudes of the left FDI MEPs. Trials in which the TMS pulse fell after EMG onset or with a background EMG activity larger than 100 μ V in the 200 ms window preceding the TMS pulse were excluded from the analysis. This was done to prevent contamination of the MEP measurements by significant fluctuations in background EMG (Cavallo et al., 2012; Duque et al., 2005, 2007; Sartori et al., 2011). Finally, trials in which subjects pressed the wrong button were also removed from the data set. After trimming the data for errors, background EMG activity and outliers, a minimum of 10 MEPs remained to assess CS excitability in each condition. One subject had to be excluded for the analysis of CS excitability changes occurring during movement preparation ($n = 11$) because the number of MEPs gathered for each window (TMS epochs) was insufficient in that participant. This subject was nevertheless included for the analysis of CS changes occurring at the imperative signal onset ($n = 12$).

Statistical analyses

To analyze behavior in the TMS experiment, we separated the trials in which TMS was applied far from movement onset (TMS_{BASELINE}, TMS_{IMP} and TMS_{MVT-PREP1}) from those in which TMS was applied close to movement onset (TMS_{MVT-PREP2}, TMS_{MVT-PREP3} and TMS_{MVT-PREP4}). Based on previous work, we assumed that the TMS pulse would affect behavior in the latter trials (TMS close) but not in the former ones (TMS far) (Davare et al., 2007; Duque and Ivry, 2009; Hallett, 2007; Rossini, 1988). The RTs and %Errors were then analyzed using four-way ANOVAs_{RM} with CONTEXT (MC, MI), TRIAL (congruent, incongruent), HAND (left, right) and TMS_{TIME} (TMS far, TMS close) as factors. To provide a comparison of the behavior between the two experiments, we conducted an ANOVA_{RM} on RTs and %Errors with CONTEXT (MC, MI), TRIAL (congruent, incongruent) and HAND (left, right) as within-subject factors and EXPERIMENT (Behavioral, TMS) as between-subject factor. Note that for this analysis, we only considered the trials in which TMS was elicited far from movement onset as we wanted to compare the two groups of subjects performing in a similar setting.

For the analysis of CS excitability, we considered MEPs falling into the different epochs described above (“Stimulation procedure” section). First, we focused on MEPs elicited at the onset of the imperative signal (at TMS_{IMP}). These MEPs were expressed in percentage of MEPs elicited at TMS_{BASELINE} and then compared between the MC and MI context using a paired-t-test. Second, we analyzed CS excitability changes during movement preparation. To do so, MEPs elicited at TMS_{MVT-200}, TMS_{MVT-120} and TMS_{MVT-40} were expressed in percentage of MEPs elicited at TMS_{IMP}. This normalization procedure provided us with a measure of MEP changes that were specific to the preparation period. The normalized MEP data were analyzed using a four-way ANOVA_{RM} with CONTEXT (MC, MI), TRIAL (congruent, incongruent), HAND (left, right), and TMS EPOCH (TMS_{MVT-200}, TMS_{MVT-120} and TMS_{MVT-40}) as factors. Third, we expressed the MEPs (normalized to MEPs elicited at TMS_{IMP}) in the MI context as a percent change with respect to the corresponding MEPs in the MC context. This provided us with an index of the context effect (%Context-effect: $[\text{MEP}_{\text{MI}} - \text{MEP}_{\text{MC}}] / \text{MEP}_{\text{MC}}$) for each experimental condition. A three-way ANOVA_{RM} was conducted on this %Context-effect with TRIAL (congruent, incongruent), HAND (left, right) and TMS EPOCH (TMS_{MVT-200}, TMS_{MVT-120} and TMS_{MVT-40}) as factors. All post-hoc comparisons were conducted using the Fisher's LSD procedure. All dependent variables were tested for non-sphericity using Mauchly's test. All of the data are expressed as mean $\pm$ SE.

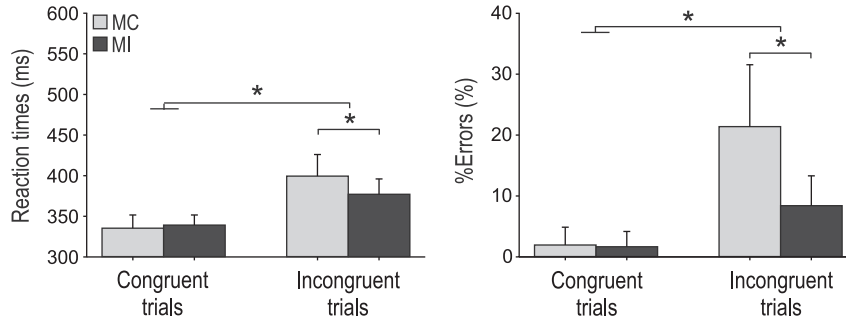
Results

Behavioral experiment

In congruent trials, the mean RT was 335 ± 5.4 ms and 339 ± 4.2 ms in the MC and MI contexts, respectively ($n = 9$); in incongruent trials, the mean RT was, respectively, 399 ± 8.8 ms and 377 ± 6.3 ms in the MC and MI contexts. The ANOVA_{RM} revealed a significant main effect of the factor TRIAL ($F_{(1,8)} = 80.7$, $p < 0.0001$): RTs were shorter in congruent (on average 337 ± 4.8 ms) than in incongruent trials (on average 388 ± 7.6 ms; Fig. 2A, left side). More interestingly, the ANOVA_{RM} showed a significant CONTEXT $\times$ TRIAL interaction ($F_{(1,8)} = 40.7$, $p < 0.0001$) on these data: RTs were influenced by the context within which the trials were performed but in a way that depended on the compatibility of the target and flanker arrows. Indeed, RTs in incongruent trials were shorter in the MI context than in the MC context ($p < 0.0001$) whereas RTs in congruent trials were comparable in the two contexts ($p > 0.231$; see Fig. 2A, left side).

Similar conclusions can be drawn from the analyses of the %Error scores. In congruent trials, the mean %Errors was $1.9 \pm 0.9\%$ and $1.7 \pm 0.8\%$ in the MC and MI contexts, respectively; in incongruent trials, the mean %Errors was $21.4 \pm 3.4\%$ and $8.4 \pm 1.6\%$ in the MC and MI contexts. There was a main effect of factor TRIAL on the %Errors

A: Behavioral Experiment



B: TMS Experiment

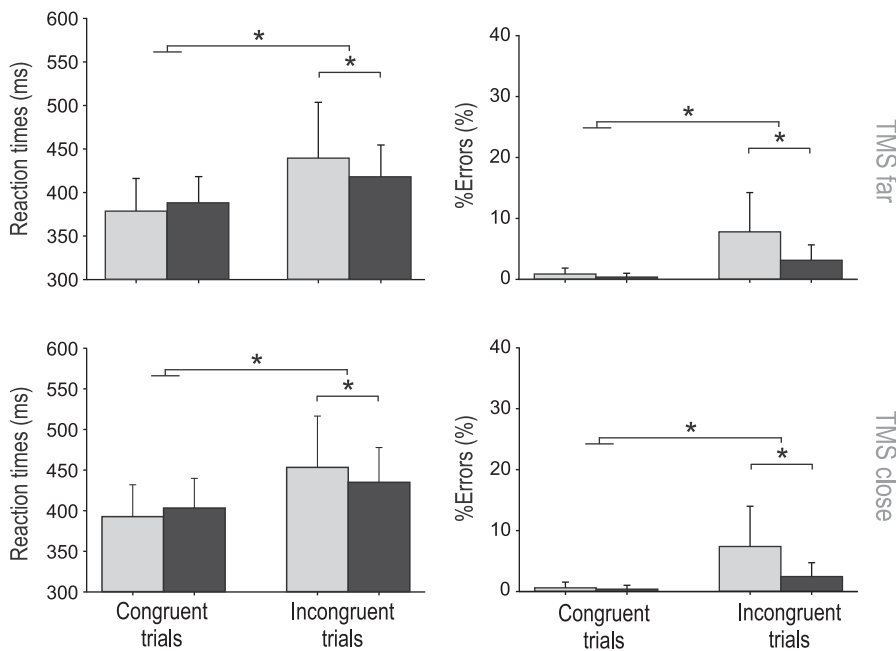


Fig. 2. Illustration of the reaction times (RTs, left side) and the error rate (%Errors, right side) for the two types of trials (congruent, incongruent) in the two contexts (MC, MI) for the behavioral experiment (A, $n = 9$) and the TMS experiment (B, $n = 12$). For the TMS experiment, the upper panel depicts data from trials where TMS was applied far away from movement (TMS far; TMS_{BASELINE}, TMS_{IMP}, TMS_{MVT-PREP1}) whereas the lower panel includes trials in which TMS was applied close to movement onset (TMS close; TMS_{MVT-PREP2-4}; see [Methods](#) section). Note the consistently shorter RTs and lower %Errors for incongruent trials in the MI context than in the MC context. * = p -value < 0.05.

($F_{(1,8)} = 38.5$, $p < 0.0002$): on average, subjects made more errors (higher %Error scores) in incongruent than in congruent trials. In addition, ANOVA_{RM} revealed a significant $\text{CONTEXT} \times \text{TRIAL}$ interaction ($F_{(1,8)} = 16.8$, $p < 0.003$; see [Fig. 2](#), right side): the %Error scores were lower in the MI than in the MC context for incongruent trials only ($p < 0.0003$; congruent trial $p > 0.902$).

TMS experiment

In the TMS experiment, the mean RT in congruent trials was 388 ± 11 ms ($n = 12$) and 396 ± 10 ms in the MC and the MI contexts, respectively; in incongruent trials, the mean RT was 446 ± 19 ms and 426 ± 12 ms in the MC and the MI contexts. There was a main effect of the TMS_{TIME} ($F_{(1,11)} = 27.4$, $p < 0.0003$; see [Fig. 2B](#), left side). That is, RTs were globally longer when TMS was applied close to movement onset (TMS close: 421 ± 15 ms) compared to when TMS was applied far from movement (TMS far: 406 ± 15 ms). This observation is consistent with previous observations that TMS can postpone movement initiation when applied at the end of a preparation period ([Burle et al., 2002](#)). In addition, the ANOVA_{RM} revealed a significant main effect of the factor TRIAL ($F_{(1,11)} = 84.9$, $p < 0.0001$). RTs were shorter in

congruent (on average 391 ± 11 ms) than in incongruent trials (on average 436 ± 15 ms; [Fig. 2B](#), left side). Finally, similar to the behavioral experiment, the ANOVA_{RM} showed a significant $\text{CONTEXT} \times \text{TRIAL}$ interaction ($F_{(1,11)} = 12.1$, $p < 0.005$) on these data, regardless of the TMS_{TIME}. RTs were shorter in the MI context compared with the MC context for incongruent trials only ($p < 0.004$; congruent trial $p > 0.110$).

When considering accuracy in the TMS experiment, we found that the mean %Errors in congruent trials was $1.0 \pm 0.4\%$ and $0.5 \pm 0.3\%$ in the MC and MI contexts, respectively; in incongruent trials, the mean %Errors was $7.7 \pm 2.1\%$ and $3.4 \pm 0.9\%$ in the MC and MI contexts. The ANOVA_{RM} revealed a significant main-effect of the TRIAL factor ($F_{(1,11)} = 17.4$, $p < 0.001$). %Error was lower in congruent ($0.72 \pm 0.3\%$) than in incongruent trials ($5.6 \pm 1.5\%$). Additionally, the $\text{CONTEXT} \times \text{TRIAL}$ interaction was significant ($F_{(1,11)} = 11.1$, $p < 0.007$). Subjects made more errors (higher %Errors) in incongruent than in congruent trials ($p < 0.006$) but again, this %Error score was reduced for incongruent trials when performed in the MI context ($p < 0.0008$; congruent trial $p > 0.610$). The TMS_{TIME} did not influence the %Errors (all $F_{(1,11)} < 2.5$, all $p > 0.141$).

Factorial ANOVAs were used to compare directly the performance of the subjects involved in the behavioral and TMS experiments. These tests revealed a main effect of the factor EXPERIMENT on the RTs ($F_{(1,19)} = 9.3$,

$p < 0.007$) without any interaction (all $F_{(1,19)} < 0.52$, all $p > 0.48$). RTs were globally slower in the TMS experiment than in the behavioral experiment. This result could be due to the fact that the TMS pulse delayed RTs. However, we believe this is unlikely because we only considered, for this analysis, trials in which TMS was applied far from movement onset (see [Methods](#) section), a condition which is usually associated with a shortening rather than a lengthening of RTs ([Davare et al., 2007; Duque and Ivry, 2009](#)). Regarding the %Errors data, the ANOVA_{RM} revealed a significant EXPERIMENT $\times$ CONTEXT $\times$ TRIAL interaction ($F_{(1,19)} = 8.3$, $p < 0.010$). As evident in [Fig. 2](#) (right side), this effect was due to the larger amount of errors in incongruent trials of the MC context in the behavioral compared with the TMS experiment ($p < 0.0002$). Hence, it appears that the subjects involved in the TMS experiment emphasized accuracy over speed, possibly in anticipation of a potentially

interfering effect of the TMS pulse. All other conditions were comparable between the two experiments (all $p > 0.20$).

[Fig. 3A](#) displays the amplitude of MEPs (expressed in percentage of baseline) elicited at all timings for each experimental conditions. In the following paragraphs, we report the analyses performed on these data. The mean amplitude of left FDI MEPs applied during the inter-trial interval (at TMS_{BASELINE}) was 2.34 ± 0.5 mV and 2.26 ± 0.4 mV in the MC and MI contexts, respectively. These baseline values in the two contexts were comparable ($t_{(11)} = 0.16$, $p > 0.872$). However, because the two contexts were tested on different days, the direct comparison of MEPs elicited at TMS_{BASELINE} might be biased by several uncontrolled aspects which may have changed between sessions (e.g. position of the electrodes, level of alertness of the subjects, location of TMS coil, etc.), precluding us from observing any global effect of the context. Hence, to

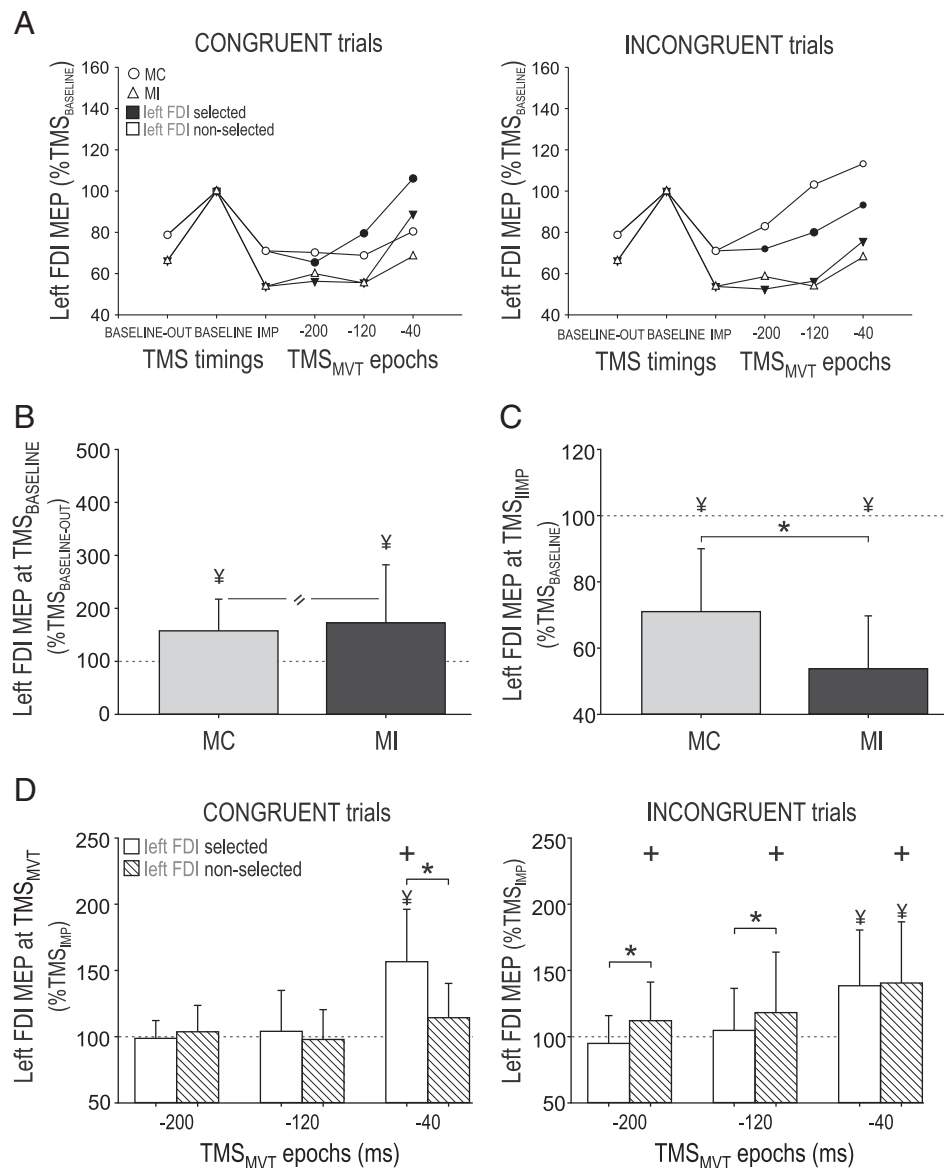


Fig. 3. A: Illustration of left FDI MEPs elicited at the TMS timings and TMS_{MVT} epochs (expressed in percentage of MEPs elicited at TMS_{BASELINE}, $n = 11$) for the two sessions of the TMS experiment (MC and MI contexts) in incongruent (left side) and congruent trials (right side). Note that the TMS_{BASELINE-OUT} was assessed in 8 participants. B: Left FDI MEPs elicited at TMS_{BASELINE} (expressed in percentage of MEPs elicited at TMS_{BASELINE-OUT}) for the two sessions of the TMS experiment (MC and MI contexts, $n = 8$; see [Methods](#) section). ¥ = significantly different (p -value < 0.05) from MEPs elicited at TMS_{BASELINE-OUT}. C: Left FDI MEPs at TMS_{IMP} (expressed in percentage of TMS_{BASELINE}) elicited in the MC and MI contexts. Note that MEPs are pooled across hands and trials at TMS_{IMP} given that, at that time, participants don't know yet which trial they will be involved in ($n = 12$; see [Methods](#) section). ¥ = significantly different (p -value < 0.05) from MEPs elicited at TMS_{BASELINE}. D: Left FDI MEPs (expressed in percentage of TMS_{IMP}) for the three TMS_{MVT} epochs (see [Methods](#) section) when the imperative signal indicated that the left FDI was selected or non-selected ($n = 11$; see [Methods](#) section). MEPs are pooled across contexts on this figure. ¥ = significantly different (p -value < 0.05) from MEPs elicited at TMS_{IMP}. + = significantly larger than homologous condition in the other trial type. * = p -value < 0.05 on all figures.

test for the occurrence of such a change in CS excitability at the context level, we compared the MEPs obtained at TMS_{BASELINE} to those elicited at TMS_{BASELINE-OUT} (outside the block) within the same session in eight subjects, by means of an ANOVA_{RM} with the factors CONTEXT (MC, MI) and TMS EPOCH (TMS_{BASELINE}, TMS_{BASELINE-OUT}). MEPs elicited during the block (TMS_{BASELINE}) were globally larger ($165.1 \pm 30\%$) than MEPs elicited outside the block (TMS_{BASELINE-OUT}; $F_{(1,11)} = 13.5$, $p < 0.007$), a finding consistent with previous reports (Labruna et al., 2011). However, this facilitation of MEPs was similar for the two contexts (CONTEXT $\times$ TMS EPOCH interaction: $F_{(1,7)} = 1.09$, $p > 0.331$, see Fig. 3B). This indicates that MEPs elicited at TMS_{BASELINE} within each context were not modulated in a distinctive way with respect to MEPs elicited outside the blocks, at TMS_{BASELINE-OUT}. Hence, the different degree of conflict expectation in the two contexts did not impact on baseline motor excitability of the left FDI muscle.

We then analyzed CS excitability changes occurring during the task. First, we focused on MEPs elicited at TMS_{IMP}. MEPs were strongly suppressed at the onset of the imperative signal, reaching $62.4 \pm 3.4\%$ of the baseline value when averaged across the two contexts (both $t_{(11)} < -5.3$, both $p < 0.0003$ when compared to baseline). However, the strength of this effect differed in the two contexts ($t_{(11)} = -2.23$, $p < 0.041$; Fig. 3C), with the MEP suppression reaching more profound values in the MI ($53.8 \pm 4.6\%$) than in the MC ($71 \pm 5.5\%$) context.

To identify CS excitability changes occurring after the imperative signal, we expressed MEPs at TMS_{MVT-200}, TMS_{MVT-120} and TMS_{MVT-40} with respect to MEPs at TMS_{IMP}. This allowed us to eliminate from our measures the main context effect that was observed at TMS_{IMP}. ANOVA_{RM} revealed a significant TRIAL $\times$ HAND $\times$ TMS EPOCH interaction ($F_{(2,20)} = 3.8$, $p < 0.040$) on these normalized MEPs. In congruent trials (see Fig. 3D, left side), the amplitude of left MEPs increased when the imperative signal indicated a left hand response (“<<<<<”: left FDI selected) but remained unchanged ($p = 0.088$) when the imperative signal indicated a right response (“>>>>>”: left FDI non-selected). As a consequence, close to movement onset (at TMS_{MVT-40}), left MEPs were significantly larger before left hand responses when compared with right hand responses ($p < 0.0001$), reflecting the specific preparation of the required motor response. Notably, we did not find any further suppression of left MEPs when the imperative signal had indicated that the left hand should not be selected (right hand response), suggesting that no further inhibition occurred after the appearance of the imperative signal, consistent with a previous finding (Duque et al., 2010).

The pattern of MEP changes was different following incongruent imperative signals (see Fig. 3D, right side). In these trials, left MEP amplitude increased during movement preparation, regardless of whether the imperative signal had indicated a left (“>>>>>”: left FDI should be selected) or a right (“<<<<<”: left FDI should not be selected) hand response. As a consequence, close to movement onset (at TMS_{MVT-40}), the amplitude of left MEPs was found similarly augmented preceding left and right hand responses ($p > 0.700$), both significantly different from MEPs at TMS_{IMP} (both $p < 0.016$). At the two earlier epochs (TMS_{MVT-200} and TMS_{MVT-120}), left MEPs were even larger in the non-selected compared with the selected condition ($p < 0.012$ and $p < 0.049$, respectively). This finding suggests that the presentation of incongruent flankers substantially modified CS excitability during movement preparation, despite the fact that the task required ignoring these stimuli. Consistently, a comparison between the two trial types revealed that non-selected MEPs were always larger in incongruent compared with congruent trials (all $p < 0.049$). However, notably, at the last TMS epoch (TMS_{MVT-40}), selected MEPs were in fact smaller in incongruent when compared with congruent trials ($p < 0.014$; see below), although MEPs considered in this last epoch were elicited at the exact same time with respect to movement onset in incongruent and congruent trials.

The CONTEXT $\times$ TRIAL $\times$ HAND interaction was also significant for MEP amplitudes ($F_{(1,10)} = 6.1$, $p < 0.033$). Fig. 4A illustrates the changes in left MEPs during movement preparation, averaged across the three TMS_{MVT} epochs (the quadruple interaction was not significant), for

each experimental condition. When the imperative signal indicated a left hand response (Fig. 4A, left side), in congruent trials, left MEPs increased more in the MI than in the MC context ($p < 0.017$); a similar trend was found for incongruent trials ($p = 0.14$). The right side of Fig. 4A illustrates changes in left FDI MEPs when the imperative signal indicated a right hand response; that is, when the left FDI was not selected for the forthcoming response. In the MC context, these non-selected MEPs remained unchanged following congruent imperative signals ($t_{(10)} = -0.4$, $p > 0.690$, when compared to MEPs at TMS_{IMP}), consistent with the fact that the imperative signal had indicated that the response should be provided with the other hand. However, despite this, the amplitude of non-selected MEPs increased following incongruent imperative signals ($t_{(10)} = 2.1$, $p > 0.089$, when compared with MEPs at TMS_{IMP}); as a result, MEPs recorded in the left, non-selected, FDI were significantly larger in the incongruent than in congruent trials ($p < 0.0001$). This is consistent with the view that irrelevant information can lead to inappropriate motor activations when it calls for an incompatible response, producing a conflict at the level of the motor system (e.g. Verleger et al., 2009). Interestingly, this inappropriate activation of non-selected MEPs disappeared in the MI context. As such, in this context, the amplitude of MEPs in the left, non-selected, FDI was comparable in incongruent and congruent trials ($p > 0.976$; black histograms in Fig. 4A). As a consequence, MEPs elicited in the incongruent trials of the MI context were found significantly smaller than those elicited in the same type of trial but in the MC context ($p < 0.008$). In contrast, MEPs elicited in congruent trials became larger (with respect to MEPs elicited at the imperative onset) in the MI than in the MC context (all $p < 0.018$). These findings support the idea that conflict resolution entails the recruitment of control mechanisms that help to decrease the activation of the inappropriate motor representations. Note that all the reported interactions respected the sphericity assumption (all $W > 0.66$, all $p > 0.150$).

In addition, an ANOVA_{RM} was used to compare the %Context-effect (see Methods section) for the MEPs elicited in the selected and non-selected FDI muscle (selected MEPs and non-selected MEPs, respectively) in the two trial types. Fig. 4B illustrates this %Context-effect for the three TMS_{MVT} epochs. The analysis revealed a significant HAND $\times$ TRIAL interaction ($F_{(1,10)} = 6.8$, $p < 0.026$). When considering the selected MEPs, the %Context-effect was similar in congruent and incongruent trials; as mentioned above, selected MEPs tended to become larger (with respect to MEPs elicited at the imperative onset) in the MI than in the MC context, regardless of the type of trial ($18.2 \pm 12.6\%$ increase on average, see Fig. 4B left traces). In contrast, when considering the non-selected MEPs, the %Context-effect was significantly different between the two trial types ($p < 0.002$). Whereas it was positive (>0) for congruent trials ($19.6 \pm 12.0\%$), indicating a larger non-selected MEP increase in the MI than in the MC context, it was negative (<0) in incongruent trials ($-4.9 \pm 10.8\%$), indicating smaller non-selected MEPs in MI than in MC context.

In order to investigate the relationship between the effect of the context on non-selected MEPs in incongruent trials and the associated changes in performance, we computed a correlation coefficient between the %Context-effect on non-selected MEPs and the %Context-effect on RTs ($[RT_{MI} - RT_{MC}] / RT_{MC}$) for each of the three TMS epochs (TMS_{MVT-200}, TMS_{MVT-120}, TMS_{MVT-40}). Interestingly, we found that the %Context-effect on RTs in incongruent trials was correlated with the %Context-effect on non-selected MEPs elicited at the beginning of the preparation period (TMS_{MVT-200}; $r = 0.74$, $p < 0.010$, Fig. 4C); the more the amplitude of non-selected MEPs was reduced in incongruent trials of the MI compared with the MC context, the more RTs became faster in the MI compared with the MC context. Such a correlation was not found for MEPs elicited closer to movement onset (TMS_{MVT-120} and TMS_{MVT-40}; both $r < 0.35$, both $p > 0.30$). The correlation found for non-selected MEPs at TMS_{MVT-200} passed a Bonferroni correction for multiple comparisons ($\alpha = 0.012$). This finding was confirmed by a multiple regression analysis with the

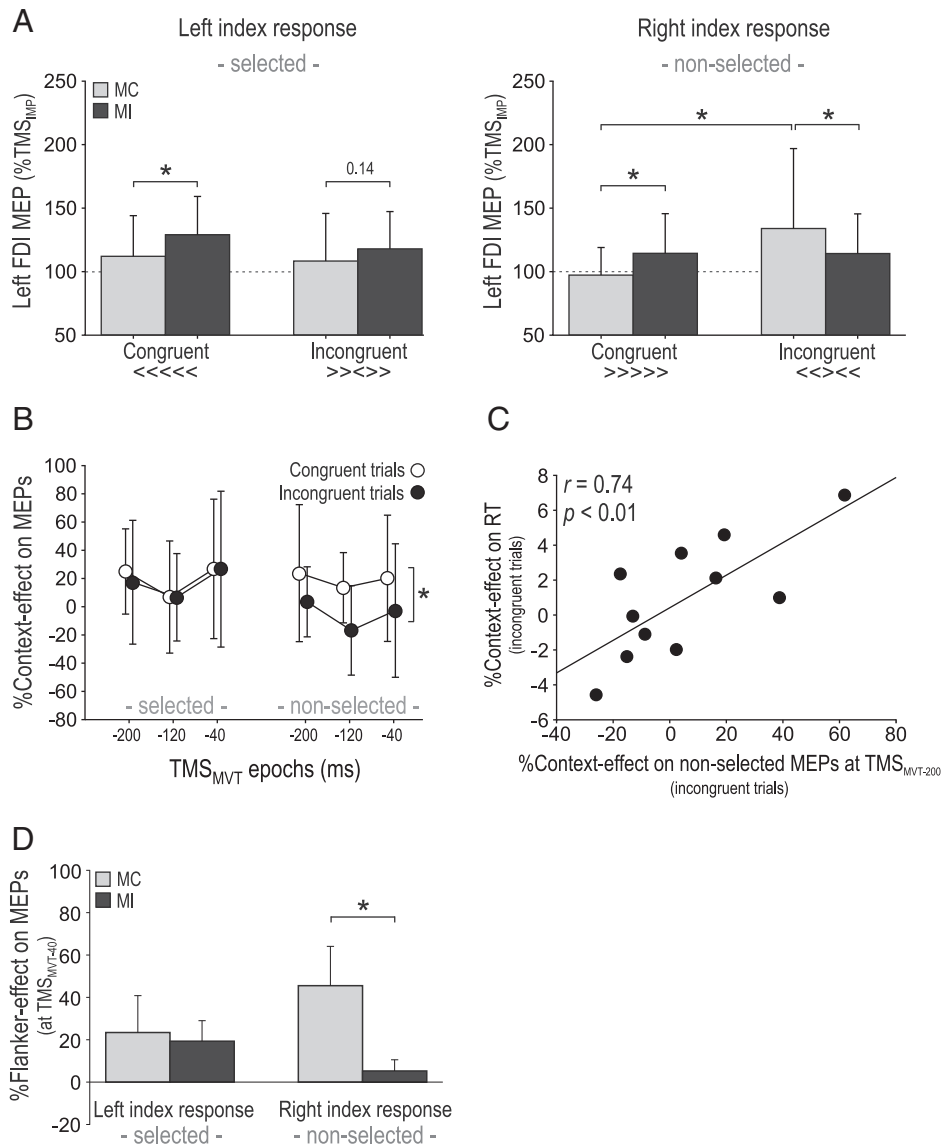


Fig. 4. Illustration of the effect of the context on left FDI MEPs in the TMS experiment ($n = 11$). A: Amplitude of left FDI MEPs (expressed in percentage of TMS_{IMP}), averaged across all the TMS epochs, following an imperative signal indicating a left (left side) or a right hand response (right side) in congruent or incongruent trials of the MC or MI context. B: %Context-effect ($MEP_{MI} - MEP_{MC} / MEP_{MC}$) for left (left FDI selected) and right (left FDI non-selected) hand responses in congruent and incongruent trials. C: The %Context-effect on MEPs elicited in a non-selected hand (at TMS_{MVT-200}) in incongruent trials was positively correlated with the %Context-effect on RTs ($RT_{MI} - RT_{MC} / RT_{MC}$) in incongruent trials. D: %Flanker-effect on left MEPs elicited at TMS_{MVT-40} ($MEP_{LEFT FLANKERS} - MEP_{RIGHT FLANKERS} / MEP_{RIGHT FLANKERS}$) for left (selected) and right (non-selected) hand responses in the MC and MI context. * = p -value < 0.05 .

three TMS epochs as factors. Only the regression coefficient associated with the earlier timing (TMS_{MVT-200}) reached significance ($\beta = 0.73$; $t_{(7)} = 2.7$, $p < 0.037$); the regression coefficients associated with the two other timings were not significant (all $t < -0.4$, all $p > 0.69$).

Importantly, the TRIAL $\times$ HAND $\times$ TMS EPOCH interaction described above revealed that at TMS_{MVT-40}, left MEPs associated with a selected or non-selected response were influenced in an opposite way by the congruency of the imperative signal. When the left hand was selected for the forthcoming movement, left MEPs were larger in congruent (flankers pointing to the left) compared with incongruent trials (flankers pointing to the right); in contrast, when the left hand was non-selected, left MEPs were larger in incongruent (flankers pointing to the left) than in congruent trials (flankers pointing to the right). Hence, left MEPs were always larger when the flankers pointed to the left compared with when they pointed to the right, whether the left hand was selected or non-selected for the forthcoming response. This effect is consistent with the view that the flankers increase activity of

the related response representation in the primary motor cortex, even if the task requires ignoring them. In a final post-hoc analysis, we intended to assess whether top-down control involved in conflict resolution entails inhibition of the flankers at the sensory level. If so, then the facilitatory effect of the flankers should be lower in the MI than MC context, regardless of whether the left hand is selected or non-selected for the forthcoming response. To address this point, we computed a %Flanker-effect at TMS_{MVT-40} by expressing left MEPs elicited when the flankers pointed to the left with respect to when the flankers pointed to the right ($MEP_{LEFT FLANKERS} - MEP_{RIGHT FLANKERS} / MEP_{RIGHT FLANKERS}$), both for the selected and non-selected trials in the MC and MI contexts. Consistent with the fact that flankers induced activation of the related motor representation, the %Flanker-effect was larger than 0 in all conditions (see Fig. 4D). More importantly, the %Flanker-effect was lower in the MI than MC context for non-selected MEPs only ($t_{(10)} = 2.3$, $p < 0.045$); they were similar in the two contexts for selected MEPs ($t_{(10)} = 0.2$, $p > 0.818$). This result suggests

that the %Context-effect on non-selected MEPs cannot be accounted for by a global decrease in the %Flanker-effect in the MI context.

Discussion

A prevalent idea in motor control is that response selection under conflict is associated with the operation of top-down control mechanisms that suppress activation of incompatible (unwanted) motor representations to assist selection of goal-directed actions (Burle et al., 2004; Praamstra and Seiss, 2005; Ridderinkhof et al., 2004). However, so far, there has only been indirect evidence to support this view (Duque et al., *in press*; Neubert et al., 2011; Taylor et al., 2007). The goal of the present study was to address this point precisely. To do so, we measured CS excitability associated with selected and non-selected (unwanted) responses during a modified version of the Eriksen flanker task in which motor preparation was associated with different amounts of conflict (congruent and incongruent trials) and top-down control (MC and MI contexts). We found that the activation of unwanted response representations was larger in incongruent compared with congruent trials, consistent with a larger conflict level in the former type of trials (Michelet et al., 2010; Verleger et al., 2009). Yet interestingly, this effect was only present in the MC context, a condition in which the recruitment of control mechanisms was probably marginal because conflict was not anticipated (Botvinick et al., 1999; Ridderinkhof, 2002). Importantly, when top-down control was increased because conflict was strongly expected (MI context), the activation of inappropriate response representations during incongruent trials was reduced; it was no longer larger than that found in congruent trials, possibly reflecting further inhibition directed at the unwanted representation to avoid its inappropriate activation. In addition, our results indicate that the presentation of the imperative signal in the MI context is associated with a much larger suppression of CS excitability than in the MC context.

In congruent trials, the target and the flankers of the imperative signal always pointed into the same direction, all indicating the required response consistently. In that condition, left hand MEPs specifically increased following an imperative signal indicating that the left hand should be selected (all arrows pointing to the left); as a consequence, prior to the movement-related increase in EMG, MEPs in that condition became significantly larger than when the imperative signal had indicated that the left hand should not be selected (all arrows pointing to the right). This result is consistent with an abundant literature showing a specific activation of the motor cortex involved in the control of the forthcoming movement (Leocani et al., 2000; Michelet et al., 2010). However, the pattern of MEP changes was different in incongruent trials. In that condition, the flankers always pointed in the opposite direction to the target arrow, thus continually indicating the incorrect response. These trials were associated with slower reaction times and a larger probability of errors compared with congruent trials, consistent with many previous reports of behavior under situations of conflict (Cohen et al., 1990; Haddon and Killcross, 2007; van den Wildenberg et al., 2010). In addition, following such incompatible signals, left hand MEPs initially became larger when the target arrow indicated a right hand response (yet the flankers pointed to left) than when it indicated a left hand response (but the flankers pointed to the right). That is, left MEPs were larger when the left hand was not to be selected (but was called by the flankers) compared to when it had to be selected. Hence, MEPs initially increased in the muscle corresponding to an incorrect response to the flankers. Then, closer to movement onset, the amplitude of left MEPs became comparable in the selected than in the non-selected conditions. These results indicate that the perceptual conflict elicited by the incongruent arrows influenced CS excitability, inducing an inappropriate activation in the motor system, as already reported several times in the past (e.g. Michelet et al., 2010). This is consistent with the view that sensory information is used to specify, in parallel, representations of several potential actions which compete for selection

(Cisek and Kalaska, 2010). Neural studies have shown correlates of multiple potential actions in parietal, premotor and motor areas (Cisek and Kalaska, 2005; Michelet et al., 2010; Oliveira et al., 2010; Scherberger and Andersen, 2007), suggesting that the competition underlying action selection plays out across a large distributed system, including motor areas.

Importantly, when considering the MEP data obtained in the MC and MI contexts separately, we found that the conflicting effect of incongruent arrows on motor excitability was only present in the former but not in the latter context. That is, in the MI context, the incompatible signals of incongruent trials did not elicit a larger MEP increase in the “non-selected” than the “selected” condition. In fact, the amplitude of non-selected MEPs was comparable in congruent and incongruent trials of the MI context, despite the occurrence of incongruent flankers in the latter but not in the former trial type. Behaviorally speaking, subjects were also more proficient in incongruent trials of the MI context than the MC context, displaying shorter reaction times and a smaller proportion of errors in that condition. Such an improvement was not found for congruent trials; RTs and errors were similar in MI and MC contexts in these trials. Interestingly, the specific behavioral gain in incongruent trials of the MI context was correlated with the extent to which top-down control reduced activation of the inappropriate response representation following incompatible signals. That is, the smaller the non-selected MEPs in incongruent trials of the MI context (compared to the MC context), the faster the subjects in incongruent trials of the MI context (compared to the MC context).

These results indicate that the operation of top-down control mechanisms recruited to resolve conflict (Botvinick et al., 2001; Grandjean et al., 2012; King et al., 2012; Ridderinkhof, 2002) in the MI context diminished the effect of the incongruent arrows on action representation excitability. The question is then through which process(es) this could occur? One possibility is that top-down control strengthened inhibitory influences directed at unwanted action representations, presumably to sharpen the selectivity of motor activations in a competitive setting. Recently, such a function was proposed for the pre-SMA, in concert with the lateral prefrontal cortex (Cai et al., 2012; Duque et al., 2012, *in press*; Mars et al., 2009; Neubert et al., 2010; Zandbelt et al., 2013). It was suggested that these two areas may reinforce mutual inhibitory interactions between competing motor representations (Burle et al., 2004; Praamstra and Seiss, 2005; Vidal et al., 2003) or alternatively, that they may directly control the exertion of additional top-down inhibitory influences over unwanted representations (Chatham et al., 2012; Nigbur et al., 2012), possibly through cortico-basal ganglia loops (Aron and Poldrack, 2006; Hikosaka and Isoda, 2010; Isoda and Hikosaka, 2011). Notably, the decreased activation of the non-selected response in the MI context was only found for incongruent trials, despite the fact that conflict was also expected at the onset of congruent trials in the MI context. This suggests that the implementation of further inhibitory influences resulting in the suppression of the non-selected motor representation was triggered by the detection of conflict in the imperative signal.

A non-exclusive alternative is that the expectation of conflict in the MI context induced a sharpening of processes involved in selective attention (King et al., 2010; Luks et al., 2007) during presentation of the imperative signal. Selective attention processes can bias competitive interactions between sensory stimuli by favoring processing information that is relevant to specific behavioral goals while ignoring irrelevant stimuli (McMains and Kastner, 2011). Visual attention has been shown to favor the processing of relevant information using location-based, but also feature-based or object-based selection mechanisms (Andersen et al., 2008; Egner et al., 2008; Schoenfeld et al., 2007). Hence, it is plausible that in the MI context, because the irrelevant flankers were expected to be incongruent on most trials, attention was more selectively directed at the target arrow, decreasing the impact of irrelevant information conveyed by flankers on motor representations (Beck and Kastner, 2009; Egner and Hirsch, 2005). This is an

interesting issue to address in future investigations. However, note that such a phenomenon cannot by itself explain all our data. Based on this idea, we would have predicted a specific reduction in left MEP amplitudes in all conditions in which the flankers pointed to the left, with respect to when flankers pointed to the right, in the MI compared to the MC context. To assess this point, we computed a %Flanker-effect on left MEPs for the selected and non-selected trials in the MI and MC contexts (see [Results](#) section). Our data indicate a specific reduction in the %Flanker-effect when the left hand was an inappropriate respondent (non-selected trials) but not when it was the appropriate one. Hence, a higher selective attention in the MI context is possible but, if present, it is likely to occur in concert with the implementation of inhibitory influences specifically directed at incompatible response representations in motor areas.

Another important finding of the present study is that the expectation of conflict modulated the amplitude of MEPs at the onset of the imperative signal (TMS_{IMP}). At that time, we found that MEPs were suppressed compared to baseline MEPs. Such an effect has been reported in many previous studies and is thought to reflect inhibitory influences recruited in anticipation of the imperative signal ([Sinclair and Hammond, 2009](#); [Tandonnet et al., 2010](#)). More interestingly, this MEP suppression was more pronounced in the MI context when compared with the MC context. That is, MEPs were generally smaller at the onset of the imperative signal when subjects expected a conflicting signal compared to when they thought conflict was less probable. Hence, in addition to avoiding inappropriate motor activations after presentation of the imperative signal, top-down control appears to reduce CS excitability in anticipation of conflict. Two inhibitory mechanisms are known to operate in anticipation of an imperative signal and could thus possibly account for this effect. The first mechanism, referred to as inhibition for “impulse control”, helps to avoid the occurrence of premature responses. It is usually assumed that the presentation of a warning signal triggers the activation of all potential actions in anticipation of the imperative signal. Such motor commands then need to be withheld until the imperative signal is presented, probably through inhibitory influences directed at subcortical structures, including the spinal cord ([Cohen et al., 2010](#); [Duque and Ivry, 2009](#); [Duque et al., 2010, 2012](#)). A modulation of this impulse control mechanism could theoretically be responsible for the differential MEP suppression in our two contexts. However, we believe that the second inhibitory mechanism, referred to as inhibition for “competition resolution”, is associated with a function which is more relevant to the current issue. That is, it is thought to help sharpen selection processes, involving inhibitory interactions between candidate responses. In fact, similar to what occurs after an imperative signal, the activation of action representations during a warning period produces inhibition of the other options. Hence, if several potential action representations are activated in parallel, they should mutually inhibit each other. We believe that the reduced MEP amplitudes found in anticipation of the imperative signal in the MI context could be due to a strengthening of these inhibitory interactions. In other words, we believe that the MEP changes evidenced before and after the imperative signal could both reflect a strengthening of inhibitory interactions directed at unwanted response representations.

Future experiments are required to understand fully the functional significance of the effects observed in the present study. First, it would be interesting to relate our work to decision-making models and to investigate the possibility that the stronger MEP suppression observed at the onset of the imperative signal in the MI context could reflect a change in the degree of accumulation required to reach the selection threshold ([Domenech and Dreher, 2010](#)). In addition, the impact of experience (sequential effect of trials) should be investigated as it may contribute to the contextual effect reported in the present study ([Schlaghecken and Martini, 2012](#)). Finally, throughout the manuscript we have supposed that the suppression of incompatible activations in the MI context is a “top-down effect”. As mentioned in the [introduction](#), this assumption is based on previous neuroimaging studies which have shown the

involvement of a specific top-down control network in an MI context compared to an MC context, including the prefrontal, medial frontal and parietal cortex ([Grandjean et al., 2012](#); [King et al., 2012](#)). Yet, further studies are required to relate the effect observed in the present study with specific areas of the top-down control brain network.

Acknowledgments

This work was supported by grants from the ARC («Actions de Recherche Concertées» – Communauté Française de Belgique), the “Fonds Spéciaux de Recherche” (FSR) of the Université catholique de Louvain and the “Fonds de la Recherche Scientifique Médicale” (FRSM). P.A. Klein was a doctoral research fellow at the Belgian National Funds for Scientific Research (FRS – FNRS).

Conflict of interest

The authors have no conflict of interest to declare.

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