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RESEARCH ARTICLE

Top-down modulation of brain activity underlying intentional action and its relationship with awareness of intention: an ERP/Laplacian analysis

Davide Rigoni · Marcel Brass · Clémence Roger · Franck Vidal · Giuseppe Sartori

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Abstract Intentional actions are executed with the peculiar experience of "I decide to do that." It has been proposed that intentional actions involve a specific brain network involving the supplementary motor areas (SMAs). Here, we manipulated the internal representation participants attended to (intention vs. movement) in order to (1) examine the activity of SMAs and of the primary motor cortex (M1) during intentional action preparation and execution, and (2) investigate the temporal relationship between activity in these structures and intention awareness. Participants performed self-paced key presses. After each key press, participants were asked to report either the time they had the first intention to press the key (W-condition) or the time they actually started the movement (M-condition). We then estimated surface Laplacians from brain electrical potentials recorded while participants were performing the task. Activity in SMAs was greater in the W-condition than in the M-condition more than 1 s before electromyographic (EMG) activation, suggesting that this region is indeed associated to the formation of conscious intention. Conversely, activity in primary motor cortex (M1) contralateral to the responding hand was larger in the M-condition than in the W-condition, revealing that this region is also modulated by top-down processes. In addition, waveforms time-locked to the W-judgement revealed that M1 as well as EMG activation preceded the time at which participants become aware of their intention by about 0.3 s. This observation argues against the possibility that the temporal delay between motor-related activation and intention awareness results from smearing artifacts.

Keywords Conscious intention · Readiness potential · SMAs · Action preparation · W-judgement · Laplacian

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D. Rigoni · G. Sartori
Department of General Psychology, University of Padova, Padua, Italy

D. Rigoni · F. Vidal
Laboratory of Cognitive Neuroscience, Aix-Marseille I Université, CNRS: UMR 7291, Marseille, France

D. Rigoni (✉) · M. Brass
Department of Experimental Psychology, Ghent University, 2 Henri Dunantlaan, 9000 Ghent, Belgium
e-mail: davide.rigoni@unipd.it

M. Brass
Behavioural Science Institute, Radboud University Nijmegen, Nijmegen, The Netherlands

C. Roger
Cognitive Neuroimaging Unit, CEA/DSV/I2BM NeuroSpin Center, INSERM U992, Gif-sur-Yvette, France

Introduction

Motor behavior can be seen as a *continuum* ranging from actions that are reflexive and automatic to actions that are intentionally guided (Brass and Haggard 2008; Krieghoff et al. 2011). An intentional action is perceived as a coherent stream of sensorimotor events, including the formation of the intention to act, the awareness of the action itself, and the evaluation of the action-effects. According to the model of intentional action proposed by Haggard (2008), each sensorimotor event arises from specific brain processes including motor preparation, motor execution, and monitoring of sensorimotor feedbacks. The brain binds together the representations of these different stages in order to produce a continuous and coherent experience of action (Haggard 2008; Haggard et al. 2002).

Although intentional actions are accompanied with such a distinct subjective experience, only recently research in cognitive neuroscience shed light on the functional neuroanatomy of intentional action preparation and execution (Brass and Haggard 2008; Desmurget and Sirigu 2009; Desmurget et al. 2009). A neuroanatomo-functional framework has been proposed in which prediction and selection of intentional actions (i.e., the intention to move) are reflected by the activity of the posterior parietal cortex (PPC), while the preparation of the imminent movement (i.e., the urge to move now) is related to the supplementary motor areas (SMAs), including the SMA proper and pre-SMA (Desmurget and Sirigu 2009).

The main objective of the current study was to examine the spatiotemporal dynamics of brain activity underlying intentional action preparation and execution. More precisely, we wanted to investigate how top-down processes, such as the focus of attention—i.e., attention to intention or attention to movement—influence the brain activity reflecting the preparation of an imminent intentional action. Another objective of the experiment was to investigate the relationship between awareness of the intention and the preparatory motor activity as measured by electrophysiological indexes (i.e., EEG and EMG).

The classical way to isolate processes related to intentional action is to compare internally guided behavior with externally triggered behavior (Krieghoff et al. 2011). However, such an approach causes several problems because it usually compares experimental conditions that differ in more respects than intention alone (but see Waszak et al. 2005). An alternative approach was introduced by Lau et al. (2004). They used an attentional spotlight paradigm to isolate the brain processes related to the representation of intentions. The *rationale* behind this method is to compare two conditions in which participants perform exactly the same motor task, but that vary regarding the internal representation they attend to. Previous studies have shown that paying attention to a sensory stimulus increases brain activity in the corresponding sensory part of the brain (e.g., Kastner and Ungerleider 2000). This method has been successfully used also for looking "inward." For instance, Griffin and Nobre (2003) showed that it is possible to investigate neural processes underlying the orientation of selective spatial attention to internal representations held in working memory. We therefore employed this procedure to modulate the activity of brain areas involved in the preparation and execution of an internally triggered action. The experimental procedure we employed in the current study was adapted from Lau et al. (2004). In an fMRI experiment, they measured brain activity while participants were performing voluntary finger movements in a variant of the well-known Libet task (Libet et al. 1983). Participants were asked to press a key at the time of their own choosing while watching a rotating clock hand. In the intention condition (W-condition), after each movement, participants were asked to report the time they had the intention to act (W-judgment). In the movement condition (M-condition), they had to report the time they actually executed the movement (M-judgment). Brain activity associated with the two conditions was then compared. The authors found that the activity of the pre-SMA was enhanced in the W-condition as compared to the M-condition (Lau et al. 2004). From these data, the authors concluded that pre-SMA is related to the representation of intentions.

While this experimental manipulation provides an innovative way to isolate processes related to intentional action, fMRI lacks the temporal resolution to investigate the different stages of brain activity underlying the formation of a motor intention. It is not clear if the increased activity reported by Lau et al. (2004) in the W-condition is really related to action preparation, since there is empirical evidence showing that SMAs are also involved in monitoring the effects of an action. For instance, Lau et al. (2007) applied transcranial magnetic stimulation (TMS) over the pre-SMA *after* the execution of a simple spontaneous movement while participants were performing the Libet task. When the TMS pulse was applied 200 ms after movement execution, the perceived onset of the intention shifted backward in time, indicating that the experience of conscious intentions depends in part on neural activity of the pre-SMA taking place after the execution of action. Sirigu et al. (2004) provided partial evidence that the SMAs is indeed associated to the preparation of an intentional action. In a EEG study, they found that the readiness potential (RP; Kornhuber and Deecke 1965), a slow potential reflecting action preparation that is assumed to be generated by the SMAs (Shibasaki and Hallett 2006), started earlier in the W-condition than in the M-condition. However, data were collected on 5 subjects only, and no statistics were reported. These observations suggest that the formation of a conscious intention is associated with increased activity of SMAs, but the low spatial resolution of the EEG method makes the interpretation of these findings uncertain. It is known that volume conduction effects smear the distribution of the potentials at the scalp level, thereby producing overlapping effects both in space and, indirectly, in time (Nunez and Srinivasan 2005). Since the RP is not a unitary component and reflects early stages of action preparation as well as very late stages associated with movement execution (Shibasaki and Hallett 2006), it is difficult to say which part of the activity reflected by the RP is generated by which structure. To overcome this limitation, in the current study, we applied a Laplacian transformation to the monopolar EEG recordings (Perrin et al. 1989; Vidal et al. 2003). The Laplacian transformation acts as a high-pass spatial filter and removes the blurring effect of the diffusion of the currents through the skull. One advantage of the Laplacian transformation is that it increases the spatial resolution of the monopolar EEG recording up to 2–3 cm (Nunez 2000). It also reveals the time course of the activity corresponding to the different structures and thus indirectly enhances the temporal resolution of EEG signal (Law et al. 1993).

It has been shown that the Laplacian transformation allows to investigate the activity of the SMAs and that of the M1, separately (e.g., Vidal et al. 1995, 2003; Macar et al. 1999). Here, we specifically focused on the activity of the SMAs and that of the M1 contralateral to the responding hand. EEG activity was recorded while participants performed the Libet task (Libet et al. 1983; Lau et al. 2004) and were asked to report either the W-judgment or the M-judgment. Our prediction is that the specific "internal" representation participants attend to (i.e., intention or movement execution) would modulate the activity of the brain structure involved in the processes to which attention must be oriented to. The hypothesis was that the early stages of motor preparation, reflected by activity of SMAs, would be enhanced when participants attended to their intention. An opposite pattern was expected on M1, with enhanced activity when they attended to the movement execution.

A second objective of the current study was to examine the relationship between the awareness of intention, as measured by the W-judgment, and the EEG and EMG activity associated with movement preparation and execution. The previous observation that the onset of the RP occurs earlier than the time at which people report their conscious intentions to act (e.g., Libet et al. 1983; Haggard and Eimer 1999) inspired a scientific controversy concerning the role of intentions in the generation of behavior (see Haggard 2008 and Roskies 2010 for two overviews). Despite the criticism (e.g., Gomes 1998), these observations have been repeatedly confirmed by other studies. Haggard and Eimer (1999) observed that the W-judgment correlates with the lateralized-RP (LRP), an ERP component that is assumed to be more related than the RP to movement execution. This finding suggests that the W-judgment is linked to brain processes that specify which specific movement has to be performed, rather than to an unspecific *readiness* to act.

One important methodological concern about the interpretation of the delay between the W-judgment and the motor-related brain activity is that these observations may be produced by a smearing artifact. The smearing artifact is described in detail elsewhere (e.g., Trevena and Miller 2002) and is a well-known effect in EEG research (Callaway et al. 1984). It occurs when several EEG recordings are averaged, as the latency of an EEG component depends on whether it is measured from individual trials and then averaged, or measured from the averaged waveform. When it is measured from the averaged waveform, the latency of the EEG component is close to the earliest onset of that component in all the individual trials contributing to the average (Meyer et al. 1988). That means that the findings that the W-judgment is preceded by motor-related brain activity (Libet et al. 1983; Haggard and Eimer 1999; Rigoni et al. 2011) may be produced by comparing the W-judgement with the RP only after averaging the EEG traces. To exclude this possibility, Trevena and Miller (2002) looked at the full distribution of the W-judgments and compared the RP and the LRP only with the earliest W-judgments. Although the RP preceded the W-judgment in the majority of trials, they found that a portion of W-judgments (i.e., around the 20 %) were reported before the onset of the LRP. They concluded that the brain activity reflecting the specific movement to be produced may not start until after the conscious decision to move.

A more straightforward method to compare the W-judgment and motor-related brain activity would be to time-lock the EEG waveform to the W-judgment on each trial, rather than to the motor activation (e.g., button press or EMG onset). As illustrated in Fig. 1, if the W-judgement precedes the activation of motor-related brain activity on each trial, there should be no activity preceding the W-judgement in the averaged waveform. In this case, the previous findings that the onset of the motor-related brain activity precedes the W-judgement (Libet et al. 1983; Haggard and Eimer 1999) would be produced by the smearing of the EEG traces. Conversely, if at least in some trials the W-judgement is preceded by motor-related brain activity, the averaged waveform will display motor-related brain activity preceding the W-judgement. This finding would suggest that, at least in some trials, motor-related brain activity starts before the conscious intention—as reported by the subject—to execute the movement. Here, we therefore time-locked the surface Laplacians to the W-judgement on each trial and then computed the averaged waveform. By employing this procedure, we could examine the activation of the SMAs and the M1 contralateral to the responding hand, as well as the muscular activity, as measured by the EMG.

Methods

Participants

Fifteen undergraduate students of the University of Padua, Italy, volunteered for this experiment. None of them suffered of neurological or psychiatric disease. All participants were right handed, had normal or corrected-to-normal vision, signed an informed consent form, and were debriefed at the end of the experiment. For one participant, recordings contained a large number of artifacts (artifact-free trials were less than 80 % of total trials), and the data were therefore

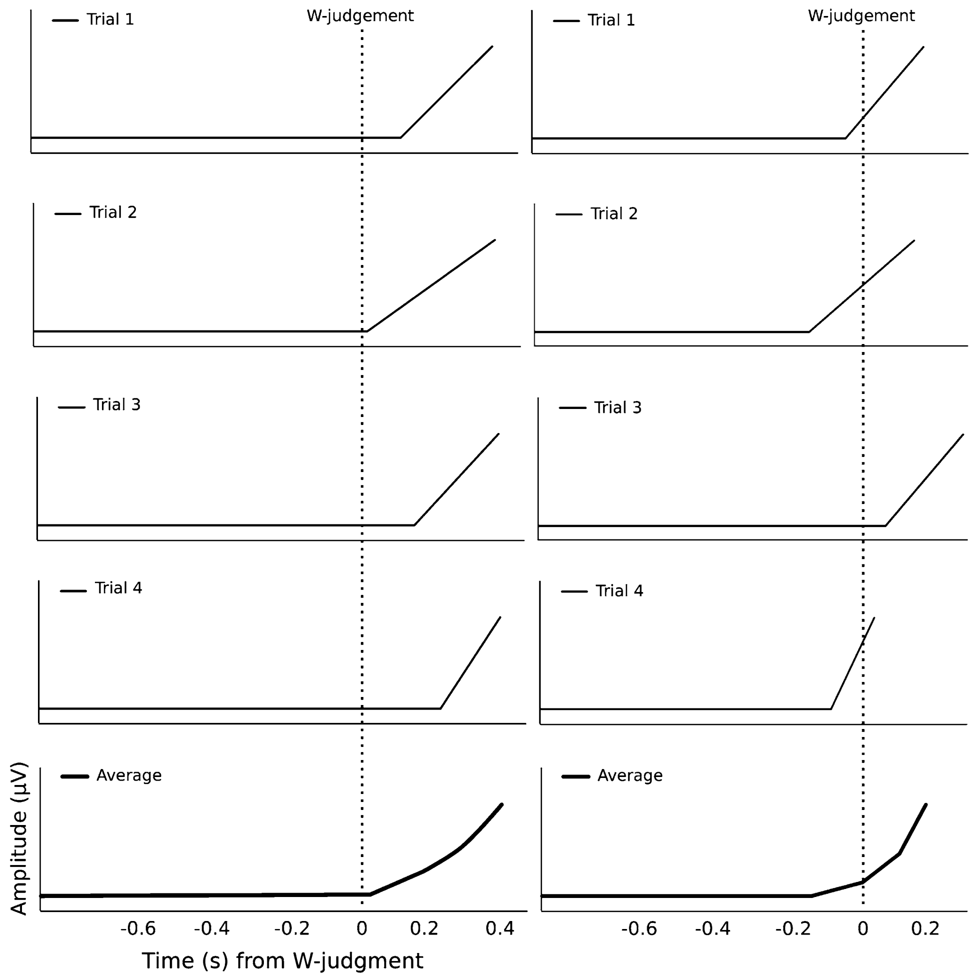

Fig. 1 Schematic illustration of the rationale behind the analysis time-locked to the W-judgment. On each trial, the EEG activity is represented by a linear increase in the EEG trace starting at a certain time relative to the W-judgment (*dashed vertical line*, time = 0). In the *left column*, the W-judgment always precedes the EEG activation, and therefore, there is no EEG activation before the W-judgment in the averaged waveform. In the *right column*, the EEG activity increases before the W-judgment in some trials, and it results in the W-judgment being preceded by EEG activity in the averaged waveform

excluded from the analyses. In sum, analyses on behavioral and EEG data were conducted on 14 participants (6 males and 7 females, age range from 21 to 26). The study was conducted according to the Declaration of Helsinki and was approved by the local ethical committee. Participants were paid 12 euro for participation.

Procedure

The experimental procedure was adapted from previous studies (Libet et al. 1983; Lau et al. 2004). Participants sat comfortably in a shielded room in front of a computer screen that was positioned about 1 m away in the line of eyes. Noise isolation headphones were employed to attenuate external environmental noise (e.g., button clicks). The experimenter encouraged participants to relax the muscles, especially those of the head, neck, and forearm. Each trial began with a red cursor on a black computer screen moving in a clockwise direction around a clock face at the speed of 2.56 s/cycle. The clock was 90 mm in diameter with 60 evenly spaced white spots. Participants were requested to fix the gaze on the center of the clock and to rest their right index finger on the response button—i.e., the "v" button of the keyboard. Participants were asked not to pre-plan the button press and were instructed to press the button at a time of their own choosing, following at least one rotation of the cursor. After each button press, the cursor rotated for a random interval between 800 and 1500 ms and then stopped. In the W-condition, participants were asked to report the position of the cursor on the clock at the instant they had the first intention to press the button—i.e., the W-judgement. In the M-condition, participants were asked to report the position of the cursor at the instant they actually started the movement—i.e., the M-judgement. In both conditions, after each button press, participants used the mouse with their left hand to position the cursor. When the cursor was placed in the appropriate position, participants clicked the left button of the mouse. Then, a blank screen was displayed for 500 ms, after which the following trial started.

Participants performed a brief practice session in order to familiarize with the task. Then, the experimental session started. There were 30 trials for each condition, for a total of 60 trials, administered in two separate blocks. The order of the two conditions was counterbalanced across participants.

Presentation of the experimental stimuli and recording of responses was controlled by E-Prime 1.1 software.

Electrophysiological recordings

EEG, electrooculogram (EOG), and electromyogram (EMG) were recorded using Synamps amplifiers (NeuroScan, El Paso, Texas, USA) and analyzed off-line with Brain Vision Analyzer software (Brainproducts, Munich, Germany). Scalp EEG voltages were recorded using a 58-channel electro-cap with Ag/AgCl-incorporated electrodes arranged according to the 10–20 international system (Jasper 1958). A frontal electrode (AFz) was connected to the ground, and all the electrode recordings were referenced online to the average of the left and right mastoids. Vertical and horizontal EOG were recorded with two electrodes situated above and below the left eye and two electrodes at the outer canthi. The EMG activity of the responding hand was recorded with paired Ag–AgCl electrodes placed about 3 cm apart at the dorsal part of the right forearm overlying the extensor muscles of the index finger. EEG, EOG, and EMG were digitized at a sampling rate of 500 Hz (16 bit AD converter, accuracy 0.08 μV/bit) and stored on a Pentium IV computer. Electrode impedance was kept under 5 kΩ for all recordings. For the EEG and EOG signals, a 0.1–100 bandpass filter was used.

Signal processing

EEG and EMG signals were filtered off-line (bandpass: 0.016–70 Hz and 10–250 Hz, respectively; 24 dB/octave attenuation). Ocular artifacts were subtracted through the algorithm implemented in Brain Vision Analyzer (Gratton et al. 1983), and visual inspection was performed in order to reject trials containing global or local artifacts (i.e., at one site only).

The onset of the EMG burst was detected manually for each trial, on the basis of visual inspection. This method has been proved to be more accurate than automated algorithms (Van Boxtel et al. 1993; Staude et al. 2001). EEG traces were segmented with respect to the EMG onset into periods of 2.5 s, from −2.0 s prior the EMG onset to 0.5 s after the EMG onset, and EMG trace was rectified before averaging. For each participant, recordings contained at least 24 artifact-free trials (i.e., 80 % of total number of trials) for each condition.

For the W-locked analysis, each trial was segmented from −1.5 to 1.0 s, relative to the reported W-judgement. The objective of this analysis was to test whether the reported time of intention was preceded by muscular and motor-related brain activity. Trials in which the W-judgement was reported after the key press were therefore excluded from this analysis, as we reasoned that in those trials the W-judgements were obviously preceded by some activity reflecting the motor response. On average, there were 20.28 trials for each participant (range from 10 to 27) in the W-locked analysis.

Surface Laplacians were estimated from the averaged individual monopolar EEG trace, with the method implemented in Brain Vision Analyzer (Perrin et al. 1989). First, the signal was interpolated with the spherical spline interpolation procedure, and then, the second derivatives in the two dimensions of space were computed (degree of spline = 3, maximum degrees the Legendre polynomial = 15). The brain structures underlying the recording sites were identified on the basis of the information provided by Steinmetz et al. (1989). In the monopolar recordings, the RP is usually maximal at electrode Cz, as a result of volume conduction effects. Since the Laplacian transformation reduces the volume conduction effects, it is preferable to look at the electrodes that are closer to each region of interest. Therefore, statistical analyses were conducted on the electrodes FCz and C3, reflecting the activity of the SMAs and the contralateral M1, respectively (Steinmetz et al. 1989). The areas under the brain potentials in specific time windows were used as indices of the activation of the underlying structure.

Results

Behavioral data

W- and M-judgments time-locked to the onset of the EMG activation were entered as dependent variables into a mixed ANOVA with *condition* (W, M) as within-subjects factor and *order* (W–M, M–W) as between-subjects factor. Overall, W-judgements were reported earlier than M-judgements (−74.19 ms ± 252.76 vs. 112.55 ms ± 232.19, respectively), as revealed by the main effect of *condition* ($F(1,12) = 14.48$, $p < 0.01$, $\eta_p^2 = 0.55$). This finding indicates that participants actually reported two distinct internal events. Neither the *order* nor the *condition* × *order* interaction reached or approached significance (all ps > 0.1).

To exclude that the W- and the M-condition differed regarding other aspects, we also measured the response time and the decision time. The response time was computed as the interval between the onset of the trial and the onset of the EMG activation. The decision time was computed as the interval between the time at which the cursor stopped rotating and the subjective W- or M-judgment. This measure reflects the time taken by the subject to judge where was the cursor when they decided to move (W-condition) or when they actually performed the movement (M-condition). We reasoned that if one condition implies a more difficult judgment than the other, this should be reflected in longer decision time for that condition. Individual response and decision times were entered as dependent variables into two separate mixed ANOVA with *condition* (W, M) as within-subjects factor and *order* (W–M, M–W) as between-subjects factor. The response time did not differ between the W-condition (4.19 s ± 0.73) and the M-condition (4.31 s ± 0.73; $p > 0.1$). The decision time was equal to 2.67 s ± 0.78 for the W-judgment and to 2.74 s ± 0.93 for the M-judgement, with no significant differences between the two conditions ($p > 0.1$). For both measures, there was neither effect of *order* nor interactions (all $ps > 0.1$).

Electrophysiological data

Electromyographic activity

To test whether the motor activity of the responding hand differed between the two conditions, the area under the EMG activation was computed in the time window from the onset of the EMG to the following 0.5 s. This time window was selected to measure the increase of the muscular activity leading to the motor response. Paired *t* tests revealed no differences between the two experimental conditions ($t(13) = 0.44$, $p = 0.66$), suggesting that the muscular activity of the responding hand did not differ reliably between the W- and the M-condition.

Pre-movement SMAs activity

Figure 2 presents the surface Laplacians prior movement execution in SMAs for the W- and the M-conditions. At visual inspection, the activation appears to be more pronounced for the W-condition than for the M-condition. The activity of SMAs was quantified as the total area—the positive area was subtracted from the negative area—under the brain potential in the time window from −1.5 s to −0.5 s, with prior 0.2 s as baseline (Fig. 2). This time window was chosen to capture brain activity reflecting motor preparation that precedes motor execution processes (i.e., early RP; Shibasaki and Hallett 2006). Paired *t* tests revealed a significant difference ($t(13) = 4.25$, $p = 0.0009$), with the total area being more negative for the W-condition than for the M-condition. This finding indicates that pre-motor SMAs activity differs between the two conditions at an early stage of motor preparation—i.e., before the activation of the M1 contralateral to the responding hand.

Executive motor M1 activity

Figure 3 shows the surface Laplacians in the primary motor cortex contralateral to the responding hand for the W- and the M-conditions. To measure the movement-related activation of the contralateral M1, a time window was selected around the EMG onset, from −0.35 s to +0.35 s (Fig. 3). This time window was meant to capture M1 activity related to the preparation and the execution of the imminent motor response. The total area was computed within this time window, with the preceding 0.2 s as baseline. Paired *t* tests revealed a significant difference (one-tailed $t(13) = 2.45$, $p = 0.029$), with the total surface being more negative for the M-condition than for the W-condition. This finding shows that activity in contralateral M1 was overall more pronounced for the M-condition than for the W-condition.

Awareness of intention and movement-related electrophysiological activity

Figure 4 shows the EMG activity for the responding hand and the surface Laplacians in SMAs and M1, time-locked

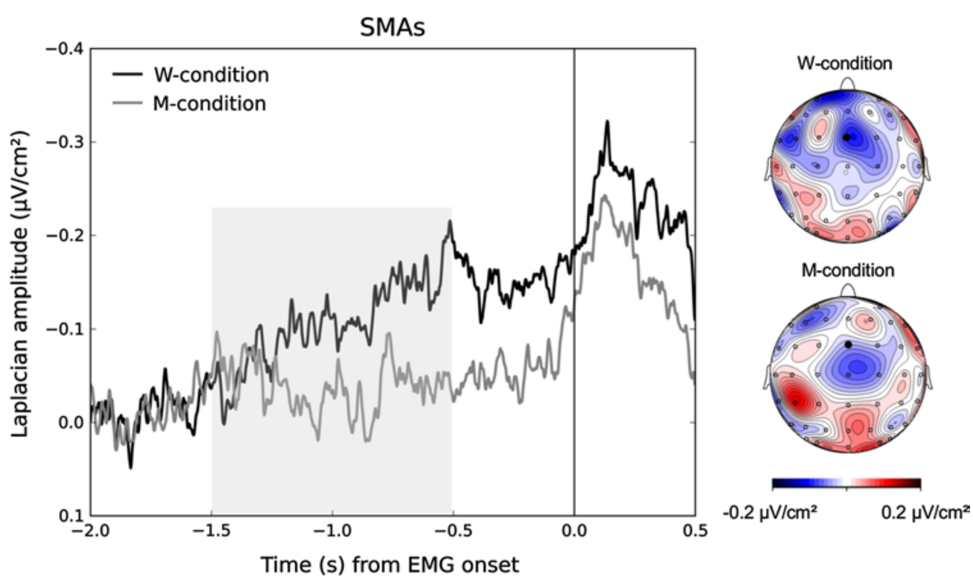

Fig. 2 Surface Laplacians over SMAs (electrode FCz) for the W-condition (*black line*) and the M-condition (*gray line*). Traces are time-locked to the EMG onset (*vertical black line*). The surface Laplacian maps show mean scalp brain activity in the selected time window (i.e., from −1.5 to −0.5 s prior EMG onset, *pale gray box*). Electrode FCz is marked in the scalp maps (*black dot*)

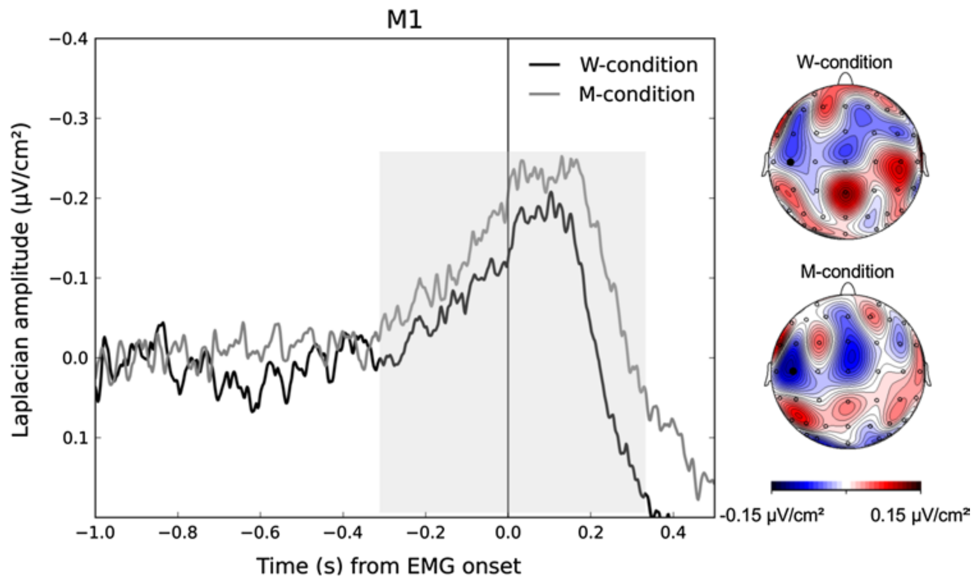

Fig. 3 Surface Laplacians over M1 (electrode C3) for the W-condition (*black line*) and the M-condition (*gray line*). Traces are time-locked to the EMG onset (*vertical black line*). The surface Laplacian maps show scalp brain activity in the relevant time window (i.e., from −0.35 to +0.35 s, *pale gray box*). Electrode C3 is marked in the scalp maps (*black dot*)

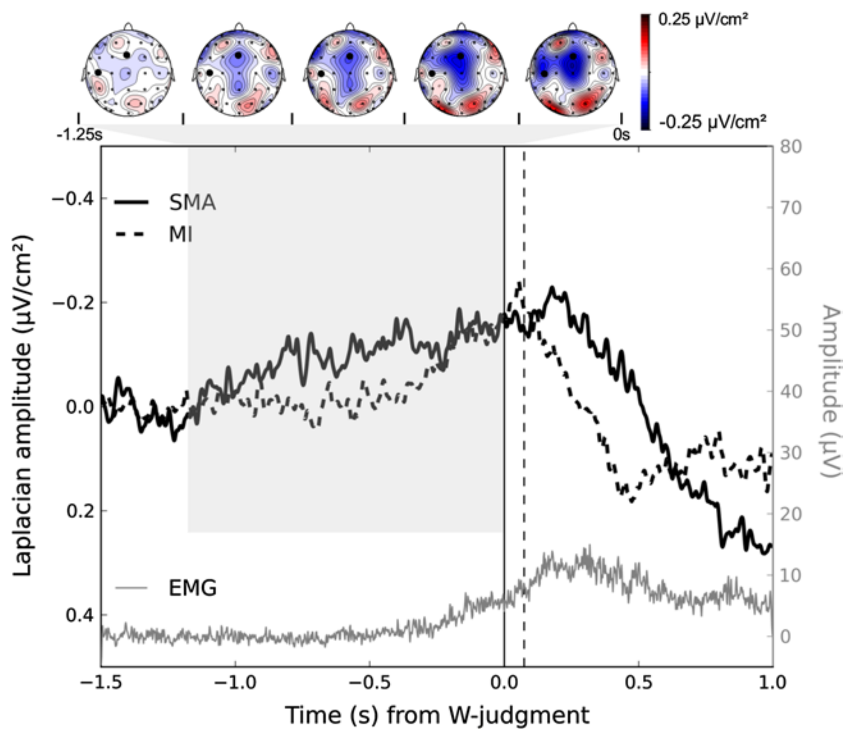

Fig. 4 Surface Laplacians over SMAs (i.e., electrode FCz, *black solid line*) and M1 (i.e., electrode C3, *black dashed line*), and EMG activity for the responding hand (*gray solid line*). Traces are time-locked to the W-judgement (*vertical black line*). The *vertical dashed line* indicates the average EMG onset relative to the W-judgment. Baseline is from −1.5 to −1.3 s. The left *y*-axis (*black*) reflects the amplitude of the surface Laplacians over the SMAs and M1; the right *y*-axis (*gray*) reflects the amplitude of the EMG activation. The surface Laplacian maps show scalp brain activity in the 1.25 s preceding the W-judgment, with each map referring to the average amplitude over a 0.25 s time period. Electrodes FCz and C3 are marked in the scalp maps (*black dots*)

to the W-judgment. The main interest of this analysis was to examine whether the reported time of conscious intention was preceded by non-zero EMG and/or EEG (i.e., SMAs and M1) activity. To do so, the area under the EMG and EEG traces was calculated for each 0.25 s non-overlapping time window from −1.25 to 0 s. The area for each time window was then compared to zero through one-sample *t* tests. Activity in SMAs started to be significantly different from zero in the time window from −1.0 to −0.75 s before the W-judgment (one-tailed $t(13) = 2.29$, $p = 0.04$). Non-zero activity was clearly visible at visual inspection before the W-judgment also in both contralateral M1 and EMG traces (Fig. 4). Surface Laplacians for M1 differed from zero in the time window from −0.25 to 0 s ($t(13) = 2.19$, $p = 0.04$). The area under the EMG activity was significantly different than zero in the same time window ($t(13) = 3.1$, $p = 0.008$). These results indicate that, on average, estimated Laplacians for contralateral M1, as well as muscular activation of the responding hand, differed reliably from zero up to 0.25 s before the reported time of conscious intention (see also Figure S1 in the supplementary material).

Discussion

At behavioral level, participants reported the W-judgment on average −74 ms earlier than the onset of EMG activation, while the averaged M-judgment was reported 112 ms after the EMG activation. The fact that W- and M-judgments differed significantly confirms that participants were actually attending to two distinct events. The judgments in the current experiment are later than those reported previously (Keller and Heckhausen 1990; Libet et al. 1983; Lau et al. 2004). However, it must be noted that other studies time-locked the W-judgment to the button press, rather than the EMG onset, thus making the W-judgment appear later. In addition, averaged W-judgments vary considerably across different studies (e.g., Rigoni et al. 2010; Trevena and Miller 2002), thus making it difficult to argue that any particular value should be considered as the standard reference. Neither the response time (i.e., latency of the motor response relative to the trial onset) nor the decision time (i.e., time taken by the subject for reporting W- and M-judgments) differed between the two conditions.

Top-down modulation of brain activity underlying intentional action

The Laplacian transformation was applied to the monopolar EEG recordings in order to investigate separately the activity of SMAs and that of the M1 while participants attended either to the intention to move or to the movement itself. As predicted, we found larger SMAs activity in the W-condition than in the M-condition (Fig. 2). This finding is in line with previous research showing that pre-movement activity of SMAs is enhanced for actions initiated by a conscious intention (Waszak et al. 2005; Keller et al. 2006). In addition, the observation that the difference between the W- and the M-condition was statistically reliable well before muscular activation (Fig. 1) supports the interpretation that increasing the salience of the abstract representation of the intention influences early stages of action preparation related to SMAs (Rigoni et al. 2011; Lau et al. 2004).

We tested whether attending to the movement itself influenced the activity of the M1 involved in movement execution. Surface Laplacians for M1 contralateral to the responding hand are thought to reflect the activation of the primary motor cortex involved in the preparation and execution of the specific movement (e.g., Vidal et al. 2003). Here, we found increased M1 activity for the M-condition—i.e., when participants attended to the movement (Fig. 3)—as compared to the W-condition. This activity differed between the two conditions in the last 0.25 s time window before the EMG onset. Thus, although the muscular activation did not differ in the two conditions, as indicated by EMG recordings, the activity of the contralateral M1 did show an effect of the focus of attention—it should be recall that a one-tailed *t* test was used. This may indicate that the activation of the M1 contralateral to the responding hand is not modulated only by the type of movement that has to be executed, but also by high-order cognitive functions such as whether we pay attention to the movement itself.

One potential limitation of the current experiment is the relatively small number of trials included in the statistical analysis. Yet, there were at least 24 artifact-free trials for each participant in the analysis time-locked to the EMG onset. It has been previously reported that the average amplitude of the RP increases in the first 20 experimental trials, but tends to decrease afterward (Taylor 1978). In addition, our data showed that all participants have a negative going potential at some time before EMG onset in one or both experimental conditions. Taken together, these observations made us quite confident that the low number of trials should not constitute a major caveat and that the data are sufficiently reliable to support our conclusions.

The observation that the RP is enhanced in the W-condition as compared to the M-condition can be interpreted as the consequence of attention being allocated to this particular area when required to report the W-judgment. In other words, SMAs would be the region targeted by attentional resources when participants are asked to focus on their intention to perform a movement. If allocating attention to a specific internal or external process increases activity of the brain region responsible for that process—as demonstrated elsewhere (e.g., Kastner and Ungerleider 2000; Griffin and Nobre 2003)—then it is reasonable to conclude that early stages (i.e., up to around 0.5 s before movement execution) of SMAs activity, as measured by the RP, may reflect processes that are involved in the formation of the motor intention.

The question whether the RP reflects brain processes related to movement preparation has been recently questioned by several authors (Gomes 1998; Danquah et al. 2008; Matsuhashi and Hallett 2008; Trevena and Miller 2010; Miller et al. 2011; Schurger et al. 2012). For instance, Miller et al. (2011) proposed recently that the RP does not reflect intentional motor preparation, as it would be induced by the Libet-type experimental procedure. In their experiment, they asked participants to perform spontaneous key presses under two conditions. In one condition, participants had to monitor a clock while waiting to press the key and then they were asked to report when they formed the intention to move. In the other condition, there was no clock and participants simply made spontaneous key presses.

The authors found that the RP was greatly reduced in the no-clock condition and therefore argued that the "much or all of the pre-movement negative EEG shift can be attributed to the participants' observation of the clock used to report event times" (Miller et al. 2011, p. 104). Here, we cannot exclude that the RP was influenced by the Libet-type procedure, because a real control situation—i.e., without a rotating clock—was not included in the experiment. Also, introspection involved in the determination of internal events makes the interpretation of the early part of the RP quite problematic (Guggisberg et al. 2011). However, the presence of a rotating clock cannot account for the finding that early RP is larger in the W-condition than for the M-condition, since both conditions involved observing a clock and reporting a subjective event—either the W-judgment or the M-judgment. In addition, it should be noted that a very large RP starting more than 1.5 s before movement onset has been repeatedly reported even when participants were not monitoring a clock display and were not asked to determine subjective events (Shibasaki et al. 1980; Kitamura et al. 1993; Cui et al. 1999). This suggests that the RP may not be entirely induced by the presence of rotating clock and by the requirement to report subjective events.

Awareness of intention and movement-related EEG and EMG activity

Surface Laplacians and EMG recordings were time-locked to the W-judgment in order to test directly whether the temporal delay of intention awareness with respect to motor-related EEG and EMG activity (e.g., Libet et al. 1982; Trevena and Miller 2002) is due to a smearing artifact (Callaway et al. 1984; Trevena and Miller 2002) (Fig. 1). We found that the W-judgment was preceded by both EEG and EMG activation (Fig. 4). Activity in SMAs started up to 1 s before the participants' reported time of intention. This result confirms the findings obtained in previous studies (Libet et al. 1983; Haggard and Eimer 1999; Rigoni et al. 2011; Trevena and Miller 2010) and provides evidence that the temporal delay of the W-judgment with respect to SMAs activity does not result from a smearing artifact. Notably, activity in M1 was different from zero in the last 0.25 s prior the W-judgment. This observation suggests that, on average, brain activity reflecting motor commands for the specific movement started before conscious intentions, so as they are reported by participants (Fig. 4). Also, EMG activation preceded the W-judgment by a similar temporal delay (Fig. 4). Taken together, these results indicate that, at least in some trials, the specific motor command was delivered by the M1 to the effector up to 0.25 s before intention awareness was reported by participants.

Schurger et al. (2012) recently proposed an accumulator model account of the RP that challenges the idea that the RP is specifically related to movement preparation processes. The main idea is that uncued voluntary movements, like those observed in a Libet-type task, arise when spontaneous ongoing fluctuations in the brain reach a certain activity threshold. The RP would not be specifically linked to movement preparation and execution processes. The fact that it precedes spontaneous movements would be a methodological artifact resulting from back-averaging-only trials in which a movement was produced. Spontaneous activity contributing to the threshold crossing would in that case be recovered in the average, leading to the erroneous conclusion that the RP corresponds to the onset of movement-directed brain processes. According to the authors, "the neural decision to move coincides in time with average subjective estimates of the time of awareness of intention to move" (p. 7). Our observation that averaged W-judgments are preceded by a RP starting 1 s earlier might therefore result from a back-averaging artifact and would be silent to the question whether W-judgments are preceded by movement-related brain activity. However, the fact that reported conscious intentions are preceded by both M1 and EMG activation—i.e., two clear indexes of movement execution—starting up to 0.25 s earlier would challenge this conclusion and would support the hypothesis that intention awareness is a latecomer in motor execution (e.g., Hallett 2007). At least in some trials, the reported time of conscious intention is preceded by the activation of the primary motor cortex contralateral to the responding hand, as well as muscle activation. One possible interpretation is that the W-judgments result from proprioceptive and/or sensorial experiences activated by the muscular activation. However, the W-judgment was not preceded by EMG activity for all participants (see Figure S1), suggesting that the relationship between EEG/EMG activation and the reported time of intention may be subject to important inter-individual differences. In addition, participants were not very accurate in reporting the movement onset in the M-condition—i.e., on average, 112 ms after the real EMG onset. The large inter-individual variability—i.e., standard deviation is equal to 232 ms for the M-judgments—suggests that participants may have used different subjective criteria for determining the time at which they started to move. This high variability may in principle extend to the W-judgment; thus, the finding that the W-judgment is preceded by M1 and EMG activity should be taken very cautiously.

Another concern regarding the Libet task is the reliability of participants' estimations of when they formed the intention to perform a movement—the so-called W-judgment. Pockett and Miller (2007) provided empirical evidence that the Libet clock method for timing subjective events is overall accurate. However, Danquah et al. (2008) asked participants to report when a stimulus was presented and demonstrated that participants are systematically affected by exogenous events, like the sensory modality of the presented stimulus. This finding questions, by extension, the reliability of the Libet procedure for measuring when participants form their intention to move. Also, the W-judgment is influenced by events occurring after action execution (Banks and Isham 2009; Rigoni et al. 2010), indicating that this measure may not reliably indicate *when* people are aware of their intention to move. Our results show that EEG activity in contralateral M1 as well as muscular activation preceded the W-judgment, on average, by up to 0.25 s. It is difficult to interpret this delay as the result of a systematic error in the subjective timing, as it is quite larger than the magnitude of bias induced by the experimental procedure reported in previous studies (e.g., Danquah et al. 2008; Banks and Isham 2009; Rigoni et al. 2010). However, inter-individual variability was very large, as for some participants there was no significant EEG and EMG activity prior the W-judgment (Figure S1). The temporal delay between the onset of movement-directed activity and the reported W-judgment should not be taken, in our opinion, as a confirmation that movements are always initiated unconsciously.

Conclusion

The current experiment shows that attending to the intention enhances the activity of SMAs preceding a finger movement. It also shows that paying attention to the movement increases the activity of the M1 contralateral to the responding hand. No differences regarding movement execution, as measured by EMG and by the response and decision time, could be reported. These findings provide further empirical support to the hypothesis that SMAs are specifically involved in the formation of an intention (Eagleman 2004; Lau et al. 2004; Sirigu et al. 2004). Also, we argued that this interpretation is not incompatible with recent proposals that the RP does not reflect the onset of specific movement-directed processes. The observation that activity recorded in the M1 contralateral to the responding hand is enhanced by the "attention to movement" manipulation shows that this area can be influenced by top-down processes such as the focus of attention.

By time-locking the waveforms to the W-judgment, we excluded the hypothesis that the temporal delay between the motor-related brain activity and the awareness of intention is due to a smearing artifact. At least in some trials, the conscious intention to "act now," so as reported by participants, is preceded by both muscular and brain activity that are specifically related to movement execution. This result should be taken cautiously given the large inter-individual variability and the questioned reliability of the Libet method to determine subjective events.

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