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RESEARCH ARTICLE

The volition, the mode of movement selection and the readiness potential

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Abstract
A growing body of evidence suggests that the mode of movement selection is relevant for the readiness potential, namely, internal (or free) selection of movements is associated with increased readiness potential amplitudes compared to predetermined or externally guided selection. It is little acknowledged, however, that this finding may be ascribed to the different expression of volition (i.e., conscious experience of choice) rather than to the mode of movement selection per se. To probe this issue, we conducted two experiments: in Experiment 1, a mental task was employed to distract sixteen volunteers from the selection and performance of incidental movements, which consisted of pressing one of two buttons according to either free or externally guided modes of movement selection; in Experiment 2, another sixteen individuals performed the same motor task, however, they were encouraged to attend to their intention to act. As result, the increased readiness potential amplitude before freely selected movements was found exclusively in Experiment 2. More detailed analysis suggested that the attention to the initiation of movements was associated with greater readiness potential in its medial and late portion, while the attention to the movement selection, with more global increase of the component. The study suggests that much of the higher demands on motor preparatory activities ascribed to the internal selection of movements in previous studies actually depends on individual's attention and, thus, probably corresponds to volitional processes.

Keywords Readiness potential · Bereitschaftspotential · Volition · Will · Mode of movement selection · Supplementary motor area

Introduction

Despite the controversy surrounding the existence of free will in human behaviour, it is an intriguing fact that people do have the experience of acting according to their own choices. In physiology, an important issue on the theme consists of understanding the neural processes involved in individual´s self selection of forthcoming actions. In this way, important advances stemmed from studies comparing brain activities associated with movements selected internally (by the individuals themselves) with those selected according to external rules—factor often called "mode of movement selection" (Dirnberger et al. 1998; Praamstra et al. 1995, 1996). Using this approach, functional neuroimaging studies suggested that self-determined (also referred as "free") selections of action plans are characterized by exuberant brain activities involving the supplementary motor, prefrontal, premotor, anterior cingulate and parietal cortices (Deiber et al. 1991, 1996; Frith Friston et al. 1991; Playford et al. 1992). These findings are in line with pre-existing

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theories proposing that the genesis of movements selected according to internal and external sources of information depend on macroscopically distinct neural circuits (Goldberg 1985; Passingham 1987).

Concerning electroencephalographic studies, the effect of mode of movement selection on motor preparatory processes have been evaluated by means of the readiness potential (RP or Bereitschaftspotential), a slow negative slope of cortical potentials widely spread over the vertex, starting up to two seconds prior to self-initiated movements (Kornhuber and Deecke 1965). Considering both morphological and physiological aspects, the readiness potential is commonly divided into two parts, the early Bereitschaftspotential (early BP) and the late Bereitschaftspotential (late BP) (Shibasaki and Hallett 2006). A growing body of evidence indicates that freely selected movements are preceded by increased amplitudes of the readiness potential compared to pre-determined movements (Dirnberger et al. 1998; Praamstra et al. 1995, 1996; Touge et al. 1995). Concerning the main activation sources of the readiness potential, several cross-references with neuroimaging studies suggest that such increased negativity reflects higher demands on supplementary motor cortices.

However, it is important to consider that externally and internally guided selections of movements may also differ with respect to volition. The present study explores how brain processes associated with volition influence the effect of the mode of movement selection on the readiness potential. Volition can be defined as the individuals' subjective experience of acting deliberately or according to their own will. In the context of motor actions, volition is present when determined movement command is selected consciously. With regard to conscious experiences, William James described two types of voluntary movements: first, the ideo-motor actions (referred as "automatic" in this text) which arise automatically in response to certain contextual demands, without the expression of any sort of "fiat, decision, consent, volitional mandate, or other synonymous phenomenon of consciousness" (James 1890); second, the volitional (also referred as willed) movements, which are experienced as a result of conscious choice between action plans (e.g., move or stand still, turning to the right or to the left) (Frith et al. 1991; James 1890). While the first type constitutes more fundamental and ordinary variety of human behaviour, the second one is observed in more specific situations, when solving the conflict between two or more action tendencies are difficult or subjectively relevant.

A thorough examination of the mode of movement selection suggests that the relatively simple condition-action mappings associated with externally guided movement conditions are susceptible to the automatization of movement selection processes (Isoda and Hikosaka 2011). Such automatization could hypothetically explain why individuals are less aware of the selection of their movements in ordinary goal-directed actions. In contrast, in the internally selected (or "free") movement conditions, movements would be more willed as individuals are explicitly instructed to make their own choices of how to act. Based on these observations, Lau et al. (2004a, b) conducted a fMRI study comparing different modes of movement selection on motor planning. In contrast with previous studies, they disrupted the putative automatization processes involved in the stimuli driven movement condition. According to their findings, at least part of the increased cortical activities previously associated with free selection of movements might actually be ascribed to attention to selection of actions. Although similar conclusion could be extrapolated to readiness potential studies, this hypothesis still needs empirical evidences.

The objective of the present study is to compare the effect of mode of movement selection on the readiness potential in situations in which spontaneous movements are performed under different levels of volition. For this, the readiness potential associated with the selection of movements determined internally or externally was compared in two experiments. In Experiment 1, the participants' volition was putatively attenuated by distracting them from their intention to act using a mental task. The volunteers were asked to select and initiate spontaneous movements incidentally to an introspection exercise which, according to a fictitious instruction, was considered the focus of the study. As a control, in Experiment 2, the mental task was omitted. The participants were asked to initiate a movement when they wanted to do so according to the basic instruction of the traditional self-paced movement paradigm. Using this paradigm, previous studies show that while attending to their intention to act, individuals tend to experience some sort of volition in the execution of movements (e.g., Haggard and Eimer 1999; Libet et al. 1983). This experimental design was based on our previous study on the effect of conscious intention to act on the readiness potential (Takashima et al. 2018, 2019).

Methods

Participants and experimental set-up

The experimental protocol was approved by the University Research Ethics Committee. Forty volunteers took part in the experiment after providing informed consent in written form. The first twenty individuals were recruited for Experiment 1 (AUTOMATIC group), and the remaining twenty, for Experiment 2 (WILLED group). Four individuals from the AUTOMATIC group and four from the WILLED group were excluded from analyses due to excessive EEG artifacts. No individual had history of drug abuse, neurological or psychiatric disorders or head trauma. Three individuals from the AUTOMATIC group and two from the WILLED were left handed according to self-report. The groups (which consisted of 16 individuals each) were not different in terms of age [23.13 ± 3.81 (mean ± standard deviation) years; $t(30) = 1.42$, $p = 0.167$] or sex (in each group, nine were female).

Each participant was seated in a dark and silent room using earphones and facing an LCD screen (22 inches, 60 Hz) at a distance of about 60 cm. The responses (button presses) were collected using a computer mouse attached to a plastic support comfortably held with both hands. The stimuli were generate with the Psychtoolbox version 3 (Brainard 1997). The EEG was recorded using the actiCHamp (BrainVision^R) system with 64 electrodes.

Stimuli and procedures

The experimental design was generated to investigate the interaction between the mode of movement selection and volition to move with respect to the readiness potential. The study consisted of two experiments (Experiment factor), each one divided in two conditions (Condition factor). The Condition factor established whether determined movement selection was imposed by external cues or made by the participants themselves (i.e., mode of movement selection). The Experiment factor consisted in modulating the individual's attention to their intention to move. The conceptual relation between the Experiment factor and volition is based on the assumption that the degree of explicit attention to the intention to move is directly proportional to the degree of awareness of movement selection, which is subjectively experienced as volition.

Experiment 1 (AUTOMATIC)

The experiment performed by the AUTOMATIC group consisted of two conditions, named CUED and NONCUED, which were presented in separate blocks of 50 trials each. Each participant performed a total of four blocks (two of each condition, total of 200 trials) alternating the conditions (order of the conditions was counterbalanced across participants). Before the onset of each block, participants were allowed to talk, relax and drink a glass of water.

Experiment 1: CUED condition All visual stimuli were displayed in the centre of a black screen. The sequence of events is shown in Fig. 1a. First, two white rings (radius 18′) were presented side-by-side for a random interval from 850 to 1150 ms. Then, a magenta disc (radius 18′) gradually appeared (appearance lasted for 333 ms) behind one of the rings (50% right, 50% left, randomized) and only disappeared (during another 333 ms) if the corresponding button of the mouse (left button for the disc on the left, right button for the disc on the right) was pressed and held for at least 700 ms. If, by mistake, the contralateral button was pressed for 700 ms, an auditory tone (superposed sinusoidal waves at 725, 747 and 799 Hz) was presented until button release and the disk did not disappear until the opposite button was pressed and held.

The participants were instructed that during all blocks they should: keep their eyes on the visual elements by the centre of the screen; hold the mouse device with both hands with the right thumb on the right button and the left thumb on the left button; and avoid moving, except for performing the instructed responses. In addition, the participants were informed that a continuous infrasound tone could be presented by the earphones in half of the trials while the magenta disc was on the screen. This information was fictitious since no infrasound tone was actually played. This instruction aimed to engage participants' attention away from their motor actions by suggesting that that a subliminal stimulus randomly presented could impact on their performance in the main task. At the end of the experiment, all the false statements provided during the instructions were disclosed.

Before the experiment, the participants received a fictitious explanation that the objective of the experiment was to test their sensibility to infrasounds, which consisted in subliminal stimuli that could not be perceived consciously as an auditory stimulus, but mighty evoke subtle changes in their feelings. As the main task, participants were instructed that during presentation of the magenta disc (when participants would be possibly exposed to an infrasound stimulus), they should pay careful attention to their own feelings and after a subjective judgement that the introspection was enough, they should press and hold the correct mouse button (of the same side of the magenta disc) until disappearance of the disc. Noteworthy, the participants were encouraged to perform a thorough introspection because the putative influence of infrasounds on one´s feeling would be very subtle. After 900–1100 ms from the complete disappearance of the magenta disc, the stimuli were replaced by the text "Adivinhe se estava ligado" ("Make a guess whether it was played" in Portuguese) and the following trial could be started by the experimenter. The participants were asked to answer aloud "sim" or "não" ("yes" or "no" in Portuguese), trying to guess whether the infrasound tone was presented to them. The participants were not instructed about how long they should perform the act of introspection. Only in few cases, when in the first trials participants exhibited very long introspection periods (larger than 20 s), we encouraged them to respond more quickly.

During the experiment, rejected trials corresponded to those in which the first button push after the introspection period: occurred before 2300 ms from the complete

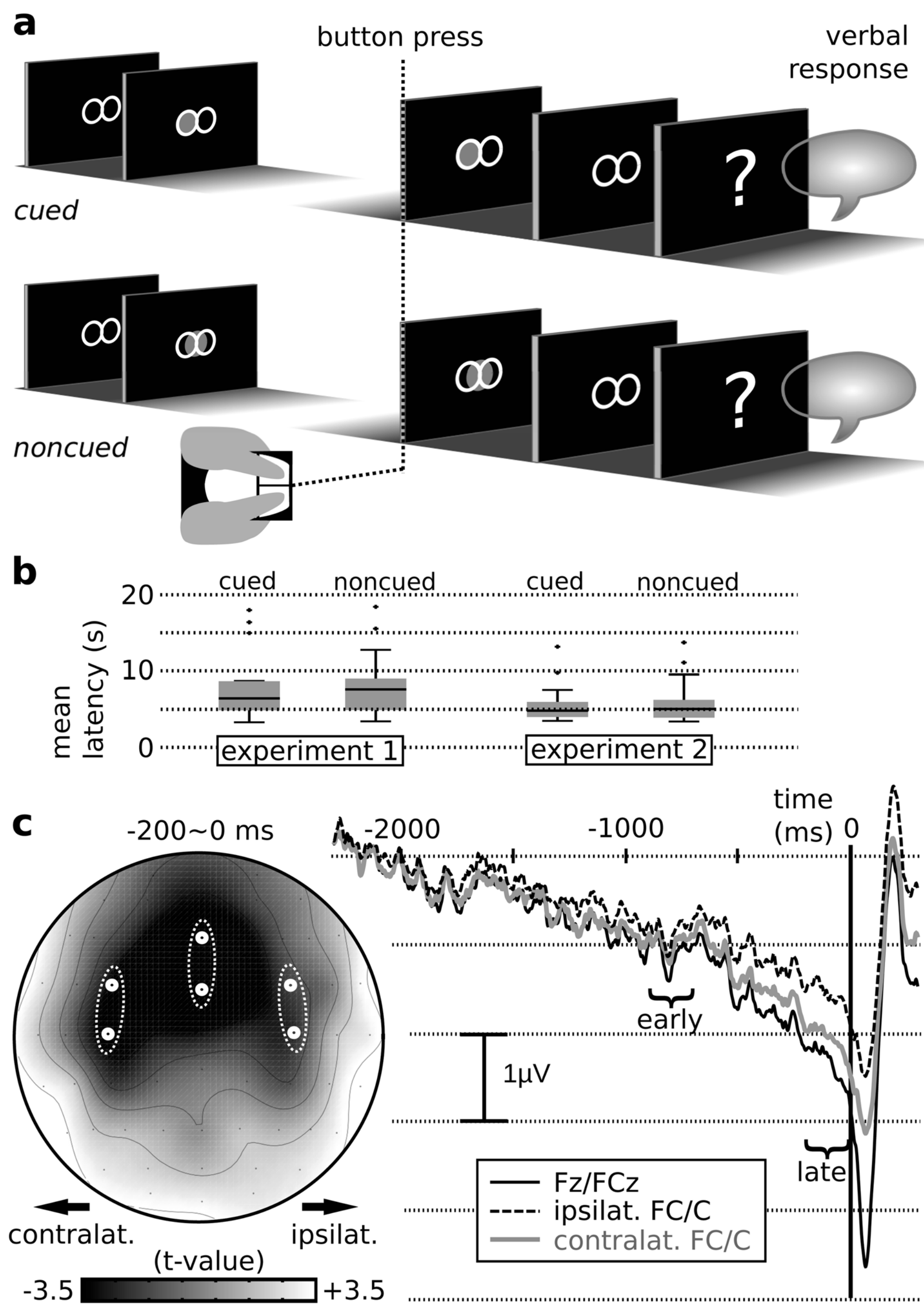

Fig. 1 Scheme of the behavioural task. **a** Sequence of trial events in CUED and NONCUED conditions. **b** Boxplots of the mean latencies of button press in each Experiment and Condition. **c** Overall features of the readiness potential (Experiments and Conditions merged): topography within – 200–0 ms at left; time course from each selected region at right

appearance of the magenta disc; was not held for at least 700 ms; or was not of the same side of magenta disk. Each rejected trial was replaced after a random number of trials.

Experiment 1: NONCUED condition The sequence of stimuli presented in the NONCUED condition was the same as the described in the previous condition, except by position of the magenta disc that was always presented the same spot, in the centre of the screen between the white rings as shown in Fig. 1a. So, the participants were not cued about which button they should press in order to continue the experiment. After the introspection period, they should choose one of the buttons randomly and hold it for 700 ms. If the disc did not disappear and the auditory feedback was played, they should try the other button. Differently from the CUED condition, the trial was not rejected if the wrong button was pressed at first. Before the experiment, the participants were informed that the reason why they were not cued about which button to press was associated with technical problems with the computer software.

Experiment 2 (WILLED)

Participants in the WILLED group also performed four experimental blocks (50 trials each) intercalating the two conditions, CUED and NONCUED (which order was also counterbalanced across individuals).

Experiment 2: CUED condition The sequence of stimuli was exactly the same as in the CUED condition of Experiment 1 but the instructions provided were different. No information about infrasound and no instruction of introspection were given. Instead, after the presentation of the magenta disc, participants were instructed to press the button at will, that is, when an urge to move feeling is experienced after at last three seconds from the complete presentation of the magenta disc. During the waiting intervals, they should avoid estimating the time by counting or planning in advance the moment of their movements, trying to be "as spontaneously as possible". As in Experiment 1, the correct side of the button was cued by the magenta disk. When the question was displayed on the screen, they should speak aloud either "caneta" ("pen" in Portuguese) or "relógio" ("clock") randomly.

Experiment 2: NONCUED condition In this condition, the stimuli presentation was the same as in the NONCUED condition of Experiment 1 and, because side of button press was not cued, they should also try to press one of the buttons randomly. However, with respect to the stand still period before the button press, the instructions were the same as in the CUED condition of Experiment 2, i.e., no information about the infrasound was given and the individuals were asked to move at will.

EEG acquisition and preprocessing

EEG electrode impedances were reduced below 20 kΩ and recordings were performed in direct current mode at a sampling rate of 1000 Hz. The 64 EEG electrodes were placed according to the 10–10 system. Superficial electrodes for electromyograph (EMG) were placed over the ventral and dorsal surface of both hands, surrounding the flexor pollicis brevis muscle.

Preprocessing and data analysis were performed in Matlab^{R} R2009a (The MathWork^{R}). The EEG electrodes were referenced to averaged earlobe electrodes and the EEG signal was filtered with low-pass and high-pass cut-offs at 0.05 and 40 Hz (2nd order, Butterworth filter, double-pass to void phase shifting). The resting intervals between blocks were excluded. Ocular artifacts were removed using independent component analysis (ICA, infomax method available in EEGLAB) (Delorme and Makeig 2004). Because the method relies on stationarity assumption, the ICA decomposition matrix was calculated from a copy of the EEG data which was high-pass filtered at 1 Hz.

The EMG signal was filtered with a high-pass cut-off at 10 Hz (2nd order, double-pass) and a 60 Hz notch filter, and represented as unsigned values. The movement onset was determined as the moment at which the cumulative EMG signal, calculated from 250 ms before the instant of the button press, reached 80% of its maximum value. The EEG data was epoched from − 2300 ms to 500 ms in relation to the movement onsets.

For each participant, the EEG signal from each trial and electrode was rejected whenever its *z*-scored peak-to-peak amplitude or kurtosis was higher than 1.8. This rejection threshold corresponded to 90.34 ± 20.54 μV for peak-to-peak amplitude and 3.97 ± 0.29 for kurtosis. Trials with more than 8 rejected electrodes were entirely rejected. In the remaining trials, rejected electrodes were interpolated using spherical spline interpolation (Perrin et al. 1989).The proportion of rejected trials corresponded to 15.92% ± 6.68% and the rate of interpolated electrodes per trial was 2.94% ± 0.62%. The individual ERP curves from each condition were drawn by averaging the EEG epochs across the trials.

Data analysis

The movement onset was adopted as the zero reference on time axis and was determined based on the EMG (see "EEG acquisition and preprocessing"). The baseline interval was from − 2300 to − 2000 ms. For the main readiness potential analysis, three pairs of electrodes (medial, ipsilateral and contralateral to the movement) were selected based on the scalp topography of the component. The amplitudes of the early and late BP were calculated as the averaged potential within two 200 ms intervals which were selected according to the morphological aspect of the readiness potential. The amplitudes of the readiness potential were compared with a repeated-measures ANOVA with one between-subject factor, the experimental group (Experiment: AUTOMATIC and WILLED), and three within-subject factors, scalp region (Region: medial, ipsilateral and contralateral), time interval (Time: early BP and late BP) and condition (Condition: CUED and NONCUED). *p* values were corrected according to the Greenhouse–Geisser method. In post hoc analysis, simple main effects were tested using the Tukey procedure.

Results

Behavioural performance

The button presses did not show differences across experiments and conditions with respect to mean EMG amplitude [considering the 100 ms window centred at the movement onset, $F(1, 30) < 0.01$, $p = 0.950$ for Experiment effect; $F(1, 30) = 0.39$, $p = 0.537$ for Condition effect; $F(1, 30) = 0.76$, $p = 0.392$ for interaction] and latency (from the complete appearance of the magenta disc), both in terms of mean [7.03 ± 3.81 s, $F(1, 30) = 2.87$, $p = 0.101$ for Experiment effect; $F(1, 30) = 0.66$, $p = 0.425$ for Condition effect; $F(1, 30) = 0.09$, $p = 0.765$ for interaction] or standard deviation [$F(1, 30) = 0.20$, $p = 0.658$ for Experiment effect; $F(1, 30) = 0.34$, $p = 0.566$ for Condition effect; $F(1, 30) = 0.05$, $p = 0.826$ for interaction]. The distributions of individual mean latencies in each experiment and condition are represented by boxplots in Fig. 1b.

With respect to the side of button presses, the mean proportion of trials in which the right button was selected was 52.44% ± 8.19%. Participants in the NONCUED conditions (regardless experiment) presented a tendency to produce shorter streams of repetitions of side (runs test's z-score = 1.83 ± 1.86) than in the CUED conditions [z-score = 0.08 ± 1.08; $F(1, 30) = 20.70$, $p < 0.001$ for Condition effect], in which the side of movements were pseudorandomized by the computer. The randomness of the sequences of buttons produced during the NONCUED conditions was not different across experiments [$F(1, 30) = 0.04$, $p = 0.854$; for Experiment effect; $F(1, 30) = 0.11$, $p = 0.744$ for interaction]. Regarding the verbal responses, participants responded "yes" in 51.94% ± 7.53% of the trials in AUTOMATIC and "pen" in 50.34% ± 3.87% of the trials in WILLED. The randomness of the responses was not affected by condition [$F(1, 30) = 0.06$, p = 0.792 for Condition effect; $F(1, 30) = 0.87$, $p = 0.359$ for interaction]. Although participants' responses in WILLED tended to show relatively short streams of repetitions (test's z-score = 1.95 ± 2.44), this behaviour seemed to be reduced in AUTOMATIC (test's z-score = 0.67 ± 1.12), as shown by a marginally significant Experiment effect [$F(1, 30) = 3.99$, $p = 0.055$].

Readiness potential analysis

For topographic display, the electrodes contralateral and ipsilateral to the motor act were represented, respectively, at left and right sides of the scalp map (Fig. 1c, at left). The readiness potential was widely distributed over the frontocentral region, from which the three pairs of electrodes were selected for analysis: Fz/FCz (medial), C3/FC3 and C4/FC4 (contralateral and ipsilateral, depending on the side of the movement). Based on the time course of readiness potential from the selected electrodes (Fig. 1c, at right), the time intervals selected to calculate the early and late BP amplitudes were from − 900 to − 700 and from − 200 to 0 ms. The BP amplitudes were compared with the repeated-measures ANOVA and the results are displayed in Table 1. As shown in Fig. 1b, the increase of readiness potential amplitudes from the early to the late interval [$F(1, 30) = 22.12$, $p < 0.001$ for Time main effect] was asymmetric, being less pronounced at the ipsilateral region [$F(2, 60) = 14.17$, $p < 0.001$ for Time × Region interaction].

Table 1 Result of the repeated-measures ANOVA with Experiment as between subject factor, and Region, Time and Condition as within subject factors

	d. f	F	p (Greenhouse–Geisser)
Experiment	1, 30	1.31	0.262
Region	2, 60	1.92	0.162
Condition	1, 30	1.37	0.251
Time	1, 30	22.12	< 0.001**
Experiment × Region	2, 60	3.26	0.053
Experiment × Condition	1, 30	6.40	0.017**
Experiment × Time	1, 30	0.78	0.386
Region × Condition	2, 60	0.29	0.737
Region × Time	2, 60	14.17	< 0.001**
Condition × Time	1, 30	1.74	0.198
Experiment × Region × Condition	2, 60	0.22	0.794
Experiment × Region × Time	2, 60	15.54	< 0.001**
Experiment × Condition × Time	1, 30	2.72	0.109
Region × Condition × Time	2, 60	2.59	0.085
Experiment × Region × Condition × Time	2, 60	3.45	0.039**

**p values less than 0.05

Probing the main result of the study, the Experiment × Condition interaction on the overall readiness potential amplitudes [$F(1, 30) = 6.40$, $p = 0.017$], the post hoc analysis indicated that in Experiment 2, the BP was greater in NONCUED than in CUED condition ($p = 0.014$); in Experiment 1, the BP amplitudes in NONCUED were numerically lower than in CUED, but the difference was not significant ($p = 0.334$) (Fig. 2a, error bars at left). The pairwise comparisons also showed that with regard to the NONCUED condition, the readiness potential in Experiment 2 was greater than in Experiment 1 ($p = 0.030$). The readiness potential curves from each experiment and condition are displayed in Fig. 2a (right graphic).

According to the post hoc analysis, the significant Experiment × Region × Time interaction [$F(2, 60) = 15.54$, $p < 0.001$] could be ascribed to a simple effect of Experiment on the late BP in medial electrodes ($p = 0.027$). This difference consisted of higher amplitudes in Experiment 2 in relation to Experiment 1 (Fig. 2b, error bars at left). The readiness potential curves from Experiment 1 and 2 (conditions merged) at medial sites are contrasted in Fig. 2b (graphic at right). Furthermore, the significant Experiment × Condition × Region × Time interaction [$F(2, 60) = 3.45$, $p = 0.039$] suggests that the effect of Experiment on specific components of the readiness potential was not the same across conditions. As a matter of fact,

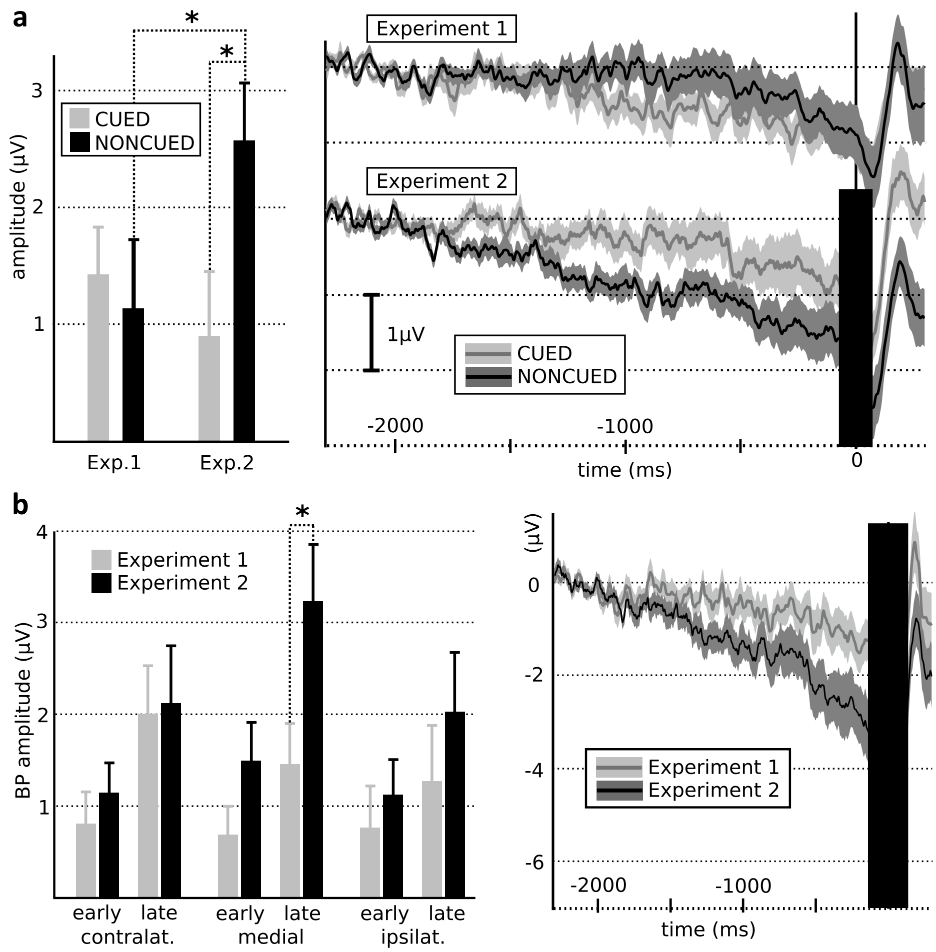

Fig. 2 Readiness potential analysis. **a** Experiment × Condition interaction: error bars of the BP amplitudes (Regions and Time intervals merged, at left) and the readiness potential curves (Regions merged, at right) from each Experiment and Condition. The asterisks indicate significant difference according to post hoc analysis. **b** Experiment × Region × Time interaction: error bars of the BP amplitudes from each Experiment, Time and Region (at left) and the readiness potential curves at medial sites (Conditions merged) from each Experiment (at right). The asterisks indicate significant difference according to post hoc analysis

the simple Experiment effect on medial late BP mentioned previously was more pronounced in NONCUED ($p = 0.025$), condition in which the early BP also showed greater amplitudes in Experiment 2 compared to Experiment 1 in both medial and lateral regions ($p = 0.004$ in medial, $p = 0.020$ in contralateral, $p = 0.033$ in ipsilateral) (Fig. 3, error bars at left). The readiness potential curves from each experiment, condition and time are shown in Fig. 3 (at right).

One can also hypothesize that the significant interactions involving the Region factor (Experiment × Region × Time and Experiment × Condition × Region × Time) could be actually ascribed to differences in the lateralized readiness potential (LRP) amplitudes across Experiments and Conditions. To rule out this possibility, we conducted a separate ANOVA comparing the LRP amplitudes (calculated as the difference of late BP amplitude between contralateral and ipsilateral regions) with Experiment (AUTOMATIC and WILLED) as between-subject factor and Condition (CUED and NONCUED) as within-subject factor. The amplitudes of LRP were affected by neither Experiment nor Condition [$F(1, 30) = 2.68$, $p = 0.112$ for Experiment effect; $F(1, 30) = 0.08$, $p = 0.778$ for Condition effect; $F(1, 30) = 1.13$, $p = 0.296$ for interaction].

Discussion

General considerations

The main objective of the current study was to examine the effect of mode of movement selection on the readiness potential in situations in which movements were executed with different demands of volition. In the experiment, the strategy to modulate the participants' conscious experience of selecting their movements (i.e. volition) was to increase or decrease their attention to the intention to move. Noteworthy, the degree of volition concerning the motor task could not be objectively measured and its modulation across the experimental groups was presumed based on following pragmatic premises: First, repetitive and simple goal-directed movements (pushing the button in Experiment 1) tend to be initiated with reduced awareness, especially when the participants are distracted by random stuffs; Second, when

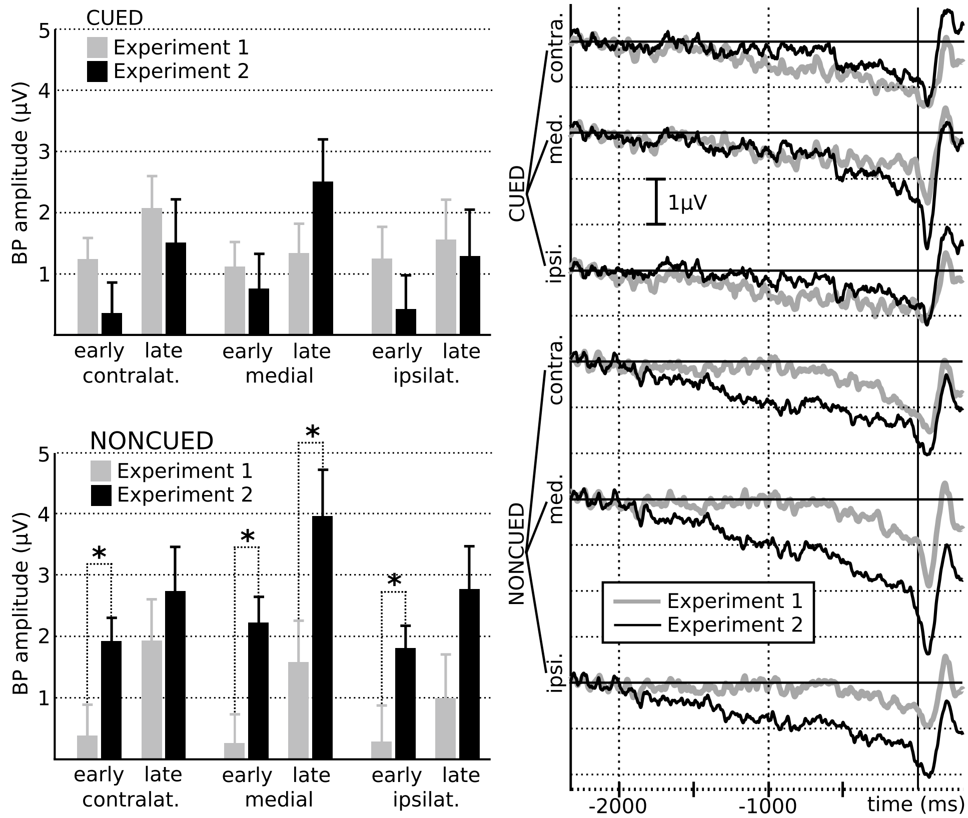

Fig. 3 Experiment × Condition × Region × Time interaction: at left, graphics with the error bars of all BP amplitudes; at right, the readiness potential curves from each Experiment, Condition and Region. The asterisks indicate significant difference according to post hoc analysis

encouraged to attend to their intentions to act (as in Experiment 2), individuals tend to become aware of the mental commands which determine the selection of free parameters of their motor actions (when or how to move).

The behavioural results suggest that differences in motor-related potentials across experiments and conditions can not be ascribed to physical aspects of the button presses, such as latency or muscular intensity. With respect to the side of the movements in NONCUED conditions, our results are in agreement with previous observations that while trying to produce sequences of random choices, individuals tend to produce shorter streams of consecutive repetitions than the expected from a truly random process (Bakan 1960; Ross 1955). Although similar tendency to respond with shorter sequence of repetitions was also observed with the verbal responses, in AUTOMATIC, individuals' responses tended to be more random, that is, less influenced by their previous responses. This finding might suggest that in general, individuals in AUTOMATIC were actually trying to make guesses concerning the infrasound task instead of trying to produce a random sequence of responses.

Mode of movement selection, volition and the readiness potential

Regarding the effect of the mode of movement selection on the readiness potential, previous studies concluded that self-determined movements are preceded by readiness potential with increased amplitudes in relation to predetermined movements (Dirnberger et al. 1998; Praamstra et al. 1995, 1996; Touge et al. 1995), possibly reflecting enhanced medial frontal activities involved in the endogenous selection of action plans (Deiber et al. 1991, 1996; Playford et al. 1992). The current study takes the investigation one step further by showing that such effect depends on individuals' attention to their intention to act. As shown by the results summarized in Fig. 2a, no increase of readiness potential prior to internally selected movements was found when individuals were distracted by the introspection task. This finding leads to the main conclusion of the study, that the enhanced expression of readiness potential related to the so called "free mode" of movement selection can not be ascribed to the endogenous selection of movements per se, but is probably related to volitional processes.

It is important to acknowledge that when comparing our results with the previous studies above mentioned, one can observe that the NONCUED condition did not correspond exactly to the so called "free mode of movement selection". More precisely, if the wrong button was pressed and held, the participants were in certain way penalized with the obligation of repeating the action with the other hand motivating them to be more concerned about their choices comparing with the condition where either button could be selected freely. Thus, the participants could be actually guessing the side of the movements instead of merely freely choosing them. The main reason of accepting one correct button in NONCUED was to prevent the participants in Experiment 1 from pressing always the same button and forgetting the other one. This strategy was also considered useful in Experiment 2 because while guessing, individuals would be more motivated to pay attention to the selection of their movements.

It is important to note that, at first glance, the results from Experiment 2 seems to contradict a previous study showing that the readiness potential magnitude is not affected by the mode of movement selection when only two alternative movements are available (Haggard and Eimer 1999). However, combined with the current results, this finding may suggest that concerning the amplitude of the readiness potential, what really matters is not the mode of movement selection per se, but the degree of attention toward the selection of the movements. In the Haggard and Eimer (1999) study, the attention to the movement selection might not be increased from the "fixed" to the "free" condition because in both conditions, participants were cognitively busy timing their intention to move. Alternatively, it can be proposed that the existence of only two alternative movements might not be sufficient to keep the individuals' attention to their random choices, unless they were motivated by some sort of reinforcement (as in NONCUED condition).

ERP correlates of volitional control concerning when and how to move

In both experiments, the initiation of the movements was spontaneous, i.e., the choice of moving at certain instant was determined by the participants themselves rather than triggered or cued by external events. Nevertheless, in Experiment 1, the conscious component of the experience of initiating the movements was presumably reduced as the individuals were distracted from their intention to act by the introspective task. Considering these characteristics, the increased late BP amplitude at medial sites in WILLED compared to AUTOMATIC group is in agreement with our previous studies (Takashima et al. 2018, 2019) and supports the hypothesis that the attention to (and the awareness of) the initiation of motor acts accounts for a significant part of the late BP manifested in medial frontocentral regions. Accordingly, Keller and collaborators (Keller 1990) compared conscious and unconscious muscular hands' contractions and found that conscious movements were preceded by relatively increased readiness potential amplitude at medial frontocentral regions. Based on a functional magnetic resonance imaging studies (Deiber et al. 1999; Lau et al. 2004a, b), it can be proposed that at least part of the brain activities associated with the conscious experience of choosing whether to move or not originates from the pre-supplementary motor area.

Probing specifically the NONCUED condition, the simple effects of Experiment summarized in Fig. 3 showed that when individuals made their own choices of which hand to move, the attention to the intention to act accounted for increased expression of the late BP at medial sites and the early BP at both medial and lateral sites. This result suggests that concerning the conscious experience of initiating the action, the volitional choice of moving hand is associated with more exuberant cortical activities in terms of duration and spatial distribution. Considering previous neuroimaging studies (Deiber et al. 1991, 1996; Playford et al. 1992), it can be proposed that the increase of BP amplitude in question involves mainly the supplementary motor areas, as well as nearby structures such as the anterior cingulate and dorsal premotor cortices.

The phenomenon of consciousness has been conceptualized as an integrative workspace whereby motor processes can interact with several cognitive processes such as decision making, timing, reasoning, working memory (Baars 2005; Dehaene and Naccache 2001; Tononi and Edelman 1998). Nevertheless, the involvement of conscious processes has been largely underestimated in studies on the readiness potential. A number of studies has associated higher amplitudes of readiness potential with several factors such as strength, complexity or discreteness of the movements (Becker and Kristeva 1980; Benecke et al. 1985; Kitamura et al. 1993; Masaki et al. 1998), novel movements (Dirnberger et al. 2004), arousal (Bortoletto et al. 2011), motivation (McAdam and Seales 1969) and free mode of movement selection (Dirnberger et al. 1998; Praamstra et al. 1995). These studies, however, do not consider the possibility that these independent factors probably covary with attention to motor intentions. According to the present study, these multifaceted findings can be at least partially ascribed to brain processes involved in volitional motor control.

Such perspective is in line with the theory of Nachev and his collaborators (Nachev et al. 2007) on the functional role of the supplementary motor areas, one of the main activation sources of the readiness potential. According to them, "one of the problems in trying to model the supplementary motor complex is that a large array of highly disparate functions has been attributed to it, often with little concern about the nature of the mutual relations between such proposals". In search of a more integrative theory, they observed that several brain processes associated with the recruitment of the supplementary motor areas subserve the ultimate function of establishing a top-down action control whenever associations between contextual demands and forthcoming behaviours are found to be relatively complex.

Conclusion

Previous studies have consistently supported that movements selected internally are associated with increased readiness potential in comparison with those selected according to external rules. The current study corroborates the hypothesis that this finding can be ascribed to higher expression of volition concerning internally selected movement conditions. By studying spontaneous movements in situations with different demands on volition, we showed that the increased readiness potential prior to self-selected movements depends on the agents' attention to intention to move. Volitional processes involved in both initiation and selection of movements were shown to be accountable for increase of the readiness potential amplitudes. The study indicate that the degree of attention that individuals invest in the selection and execution of their actions accounts significantly for the expression of the readiness potential and should not be overlooked.

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