Neuropsychologia 109 (2018) 28–38

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Effects of intentionality and subliminal information in free-choices to inhibit

Tommaso Dall'Acqua[a], Chiara Begliomini[a,b], Raffaella Motta[c], Diego Miotto[c], Umberto Castiello[a,b,d,*]

[a] Dipartimento di Psicologia Generale, Università di Padova, Padova, Italy
[b] Center for Cognitive Neuroscience, Università di Padova, Padova, Italy
[c] Dipartimento di Medicina, Università di Padova, Italy
[d] Centro Linceo Interdisciplinare Beniamino Segre, Accademia dei Lincei, Roma, Italy

ARTICLE INFO

Keywords:
Voluntary action
Masked priming
Free-choice
Intentional inhibition
Rostral cingulate zone

ABSTRACT

Stopping an action at the very last moment is an important feature of human behavioural flexibility. Intentional inhibition has been defined as the ability to inhibit an action on the basis of an internal decision process. Without this ability, actions would be impulsive and would leave little space to correct misguided decisions. Previous research suggests that making a choice between action alternatives activates a specific "choice network" that includes the rostral cingulate zone (RCZ), the anterior insula (AI), the dorsolateral prefrontal cortex (DLPFC) and the inferior parietal lobe (IPL). The activity of this network has shown to be influenced by non-conscious (subliminal) stimuli. In this study, we tested whether the same regions are recruited by free-choices to inhibit and modulated by unconscious information as reported in the case of free-choices to act. Using functional magnetic resonance imaging (fMRI) we manipulated the degree of 'freedom' of the choice between acting and inhibiting an action by introducing explicit cues or leaving the participants free to choose between action alternatives. We included subliminal masked primes to test whether responses to targets were facilitated and/or obstructed by conditions of congruency and incongruency between primes and targets. Our findings confirmed higher activation of the "choice network" in free-choice trials when compared to cued choices. However subliminal priming failed to significantly influence participants' responses, in free-choice conditions.

1. Introduction

Choosing whether to perform an action or not is a fundamental process that allows people to flexibly interact within a complex, social environment. Sometimes that decision might be taken ahead of time, such as when planning whether to go for a run in the morning or deciding to sleep an extra hour. Often, however, one has to take an in-the-moment decision to accomplish or to stop a motor plan that has already partially implemented, such as when, during a football match, an opponent's moves requires a sudden change in motor planning. This inhibitory control has been investigated over the years employing paradigms that required participants to stop an ongoing behaviour in response to an external 'no-go' or 'stop' stimuli (van den Wildenberg et al., 2010). In 'Go/No-go' paradigms usually 'go' stimuli are presented in a sequence, in alternation with less frequent 'no-go' stimuli', triggering the inhibition of a tendency to respond ('action restraint'). Differently the 'Stop Signal' task (SST; Logan, 1994) requires an active search for the 'stop signal' to trigger inhibition of an already started action ('action cancellation'; Bari and Robbins, 2013). In these tasks, acting or desisting from action is a reactive response linked to the presentation of external stimuli, excluding any component of spontaneous choice of the individual but just to implement the 'go' or the 'stop' instructions. However, in everyday life such decisions are most likely taken on a voluntary basis and their origin is self-determined. In this respect, a recent line of research has proposed that along with the externally-driven inhibition, a more intentional mechanism might be recruited to withhold from executing a pre-potent action tendency (Brass and Haggard, 2007; Filevich et al., 2012). The so-called 'intentional inhibition' has been tested by means of specifically tailored experiments, in which participants were free to decide whether to execute or inhibit a particular behaviour (Kühn et al., 2009). A peculiarity of these experiments relies on the fact that such tasks do not result in any overt behavioural response to be explored (since the action has been inhibited) and, more importantly, there is no external imperative signal that time-locks the voluntary decision to a precise moment. Due to these factors, intentional inhibition has been widely investigated through neuroimaging techniques with the aim to define whether intentional and externally-driven control rely on the same neural

* Corresponding author at: Dipartimento di Psicologia Generale, Università di Padova, via Venezia 8, 35131 Padova, Italy.
E-mail address: umberto.castiello@unipd.it (U. Castiello).

https://doi.org/10.1016/j.neuropsychologia.2017.11.035
Received 10 May 2017; Received in revised form 7 November 2017; Accepted 29 November 2017
Available online 01 December 2017
0028-3932/

substrates and mechanisms or not (Schel et al., 2014). Externally-driven inhibition has been commonly associated with increased activity in the fronto-basal ganglia network including the dorsal prefrontal cortex (dPFC), the inferior frontal gyrus (IFG, mostly in the right hemisphere), the pre-supplementary motor area (preSMA) and the basal ganglia (most prominently the dorsal striatum and the sub-thalamic nucleus; Aron, 2011; Bari and Robbins, 2013). Although the activity related to intentional inhibition largely overlaps with the networks characterizing externally-driven inhibition (Schel et al., 2014), increased activity within the dorsal part of the frontomedian cortex (dFMC) has also been reported (Brass and Haggard, 2007; Kühn et al., 2009; Lynn et al., 2014). Initially thought of as a late '*veto area*', with the ability to halt voluntary motor commands (Kühn et al., 2009), the dFMC has been recently indicated as a key region for self-control, allowing to disengage from strong impulses and intentions (Lynn et al., 2014). A point worth noting, however, is that whereas some studies failed to identify inhibition-related activity over the dFMC (Hartwell et al., 2011; Kühn and Brass, 2009), others found dFMC activation confined to externally-driven inhibition (Lynn et al., 2016; Severens et al., 2012). These inconsistencies make the role and underlying functioning of dFMC quite controversial.

Despite the neuroanatomical correlates, the extent to which intentional – free – choices to act and to inhibit are linked with a conscious form of voluntary self-control is still a matter of debate. Importantly, with two-alternative forced choice paradigms, it has been demonstrated that stimuli presented below the threshold of awareness can systematically bias response decisions even when such choices appear to be internally generated and free (Schlaghecken and Eimer, 2004). In the same fashion, Teuchies et al. (2016), using masked arrows as subliminal primes, showed that activity over some areas of the 'voluntary choices network', specifically the rostral cingulate zone (RCZ), the left anterior insula (AI), the dorsolateral prefrontal cortex (DLPFC) and the supramarginal gyrus (SG), was modulated according to the congruency between the prime and the response. The study suggests an involvement of these areas in solving the conflict between the external unconscious information and the free response selection (Teuchies et al., 2016). As a matter of fact, intentional decisions to act might not be taken as freely as one might think: as a consequence, to what extent intentional decisions to inhibit are necessarily based on a deliberate choice remains an open question (Parkinson and Haggard, 2014). Testing whether subliminal clues in the environment are able to modulate neural activity in areas such as the dFMC or regions of the choice network would add invaluable information on the mechanisms by which we make intentional decisions whether to act or to inhibit.

Here we capitalized on a paradigm which has the ability to reveal that intentional inhibition can be unconsciously primed (Parkinson and Haggard, 2014) to demonstrate whether brain areas concerned with intentional inhibition are modulated by masked primes. In particular, the paradigm used is a modified version of the Go/No-go task implemented by Lingnau and Vorberg (2005). While laying in the scanner, participants were required to respond to three possible target stimuli (arrows) in three different conditions: (i) *cued action condition,* in which the choice to act is indicated by a cue (cued Go targets); (ii) a *cued inhibition condition,* in which the choice not to act is indicated by a cue (cued No-go targets); or (iii) a *free-choice condition,* in which participants were free to choose whether to act or not (free-choice targets). The targets were preceded by masked primes (arrows), whose orientation could be congruent or incongruent with the Go and No-go target (i.e., having the same or opposite orientation), or Neutral (i.e., without a specific orientation). Within the decision making' literature, choice performances for this type of tasks are commonly described by race or diffusion models (Gold and Shadlen, 2007; Leuthold and Kopp, 1998). These models assume that participants accumulate independent evidence to support one decision versus another (in our case action or inhibition) until a decision threshold is reached (Hanes and Schall, 1996). Since the rate at which cortical activity grew toward that threshold is determined in part by ongoing stochastic fluctuations of neural activity (Schurger et al., 2012), subliminal primes could influence the responses to Go and No-go stimuli in different ways: on the one hand primes could enhance the excitability of post-decisional motor pathways, having a direct impact in the actual implementation of the action and thus modulating reaction times (RTs) to Go trials (Smith, 2000). On the other hand, primes might also bias the actual neural "free decision" in favour of initiating or inhibiting the action: by managing the noise level within action decision circuits, primes would change the level at which the threshold is reached. Accordingly, while still modulating RTs to Go trials, subliminal primes would operate also on choices suggesting that the brain incorporates whatever information is available, even subliminal, into its decisions about whether to initiate an action or not. This interpretation is consistent with previous studies showing that the influences of subliminal primes at (low-level) automatic stages of motor processing are mediated by (high-level) current intentions and task set (the set of stimulus-response mappings imposed by task instructions; Schlaghecken and Eimer, 2004). In line with this interpretation, we expect RTs to action trials to be speeded up by congruent primes and slowed down by incongruent primes. Furthermore we predict accuracy to be reduced by incongruent, when compared to congruent, prime-target associations within cued conditions. By effect of the subliminal prime presented before the target, a comparable pattern of results should characterize response choices in the free-choice condition. More in detail, we expect Go primes to increase the proportion of choices to act, and No-go primes to increase the proportion of choices to inhibit the action, when compared to neutral primes.

Since we predict the present paradigm to be able to disentangle between forced and free components of action and inhibition in relation to subliminal processing, we focused on a network of brain regions described by previous studies dealing with the generation of free-choices (Forstmann et al., 2006; Kühn and Brass, 2009; Teuchies et al., 2016). At first, we expect that areas linked to the 'voluntary choice network', specifically the RCZ, that is the part of the medial frontal cortex extending posteriorly and dorsally from the anterior cingulate cortex (ACC), the DLPFC, the inferior parietal lobule (IPL) and the AI to be more involved in intentional rather than in cued conditions, in both action and inhibition trials. Further, since the concept of intentional inhibition is still poorly understood, we aim to investigate how specialized functional areas, such as the dFMC, can be related to the generation of free-choices to inhibit. To this end, we conducted a ROI analysis focused on this region. On the one hand, taking into account that the formulation of the present experimental design has been originally conceived for the exploration of intentional inhibition (Parkinson and Haggard, 2014), we expect to find dFMC activity when comparing free-choice inhibition trials with other conditions. On the other hand, it has been recently questioned whether paradigms combining 'go', 'no-go' and 'free-choice' trials could actually involve intentional inhibition mechanisms (Lynn et al., 2014). Accordingly, at the appearance of free-choice trials participants might first stop the prepotent response, and then decide whether to reinitiate the action or not. If so, the decision in free-choice trials would not be about the intentional inhibition of an ongoing action tendency, but rather about choosing between different response alternatives, namely action or non-action. As a consequence, the activity of the dFMC would not be expected.

To conclude, we conducted another set of ROI analyses to test whether information provided by subliminal information conveyed by the prime might modulate the activity in the same set of regions. Based on the aforementioned findings for intentional actions (Teuchies et al., 2016), we hypothesize that the RCZ, the DLPFC, the IPL and the AI would be affected by our manipulation: we expect these areas to be more involved in incongruent rather than congruent prime-response mappings, given their specific role in overcoming inconsistent sources of information (Teuchies et al., 2016). With regard to the specific

involvement of the dFMC we conducted a ROI analysis focused on this region, as we did for the first set of ROI analyses. We compared only free-choice inhibition trials among the three levels of congruency.

2. Method

2.1. Participants

A total of twenty-eight healthy volunteers participated in the study (17 female, mean age = 23.53 years ± 2.86), after giving oral and written consent. Data of four participants were discarded: one participant was discarded because of an excessive tendency to prefer inhibition in free-choice trials (3.64%, > 2.5 standard deviations from sample mean), and three participants for head motion exceeded tolerance (> 3.5 mm in translation, and 3.5 degrees in rotation). All analyses were conducted on the remaining twenty-four participants, whose mean age was 23.8 years (16 female, age range = 19–30 yrs). All participants had normal or correct-to-normal vision and were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971). None of the participants had a history of neurological or psychiatric disorder. The study was approved by the University of Padova Ethics Committee and carried out in accordance with the Declaration of Helsinki.

2.2. Stimuli

As shown in Fig. 1, the paradigm was composed of three distinct prime stimuli and three distinct target stimuli (panel a). Prime stimuli were small white arrows either pointing up, down or being neutral (overlapping up and down primes). The target stimuli followed the primes and were formed by the contour of either upward, downward or double headed pointing arrows. Targets surrounded a metacontrast mask that superimposing the primes obstructed their visibility. Primes subtended a visual angle of .6° × 1.8°, targets of 1.4° × 3.8° and the mask of 1° × 2.2° (Fig. 1a). The stimuli were presented over a black background and always appeared aligned to the fixation cross in the middle of the screen.

2.3. Procedure

During stimuli presentation, participants were lying down in the scanner and wore MR-compatible LCD video goggles (VisuaStim XGA, Resonance Technology Inc.) with a resolution of 800 × 600 and 60 Hz refresh rate. Responses were given with the index finger of the right (dominant) hand using an MR-compatible response box (Evoke Response Pad, Resonance Technology Inc.) positioned along the body midline of the participant. Every trial started with a small fixation cross (subtending .3°) in the center of the screen for 560 ms followed by a masked prime stimulus (from now on defined as 'prime') presented for 17 ms (1 frame at 60 Hz ≈ 16.7 ms). The prime was immediately succeeded by a fixation cross of 35 ms duration, followed by the target surrounding a meta-contrast mask. Both the target and the mask lasted for 136 ms (see Fig. 1b for the sequence of events). Having the same luminance as the prime, this backward stimulus sequence has been shown to effectively obstruct the visibility of the prime stimulus (Lingnau and Vorberg, 2005). Between trials a fixation cross was continuously displayed and interrupted only by a blank screen lasting the duration of a refresh of the monitor that signalled the beginning of the new trial. In contrast to previous studies, we decided to use upward/downward pointing arrows and right hand responses in right-handed participants to control for the possibility that No-go primes and targets might, in principle, produce spatial incompatibility effects of the Simon type (Simon, 1969). Participants were instructed to make 'cued Go', 'cued No-go' or 'free-choice' responses according to the orientation of the target stimuli (Fig. 1b). At the beginning of each scanning run, participants were informed regarding the Go target identity (upward or downward pointing arrow) they were about to see and were requested to react as quickly and accurately as possible to its appearance by pressing the response box button. Conversely, the target arrow having the opposite orientation was labeled as No-go target, and participants were instructed to refrain from giving an answer. The labeling of Go and No-go targets according to the orientation was counterbalanced between runs and between participants. The appearance of the double-headed target arrow always represented a free-choice target, where participants were instructed to freely decide whether to answer or inhibit their action (by pressing the key). Although they were asked to "diversify" their decision throughout the experiment, they were also asked to avoid using strategies like alternating between action and inhibition. For this reason, participants were encouraged to always prepare the action, but to decide at the very last moment whether to carry it out or not. The response window was set at 1000 ms, starting from the appearance of the target. Speed was stressed in order to lead participants preparing the action at the beginning of each trial. Primes stimuli were categorized according to their orientation in relation to the target. Go primes pointed in the same direction as Go targets; No-go primes pointed in the same direction as No-go targets; Neutral primes (formed overlapping up and down primes) served as control conditions. Accordingly, 'congruent cued' trials had primes and target pointing to the same direction, whereas 'incongruent cued' trials primes and target were pointing in opposite directions. In 'neutral cued' trials targets were preceded by a neutral prime. In free-choice trials, where no clear instruction was provided, the congruency depended on the choice made by the participant: when participants inhibited the response after a No-go prime, or when they performed the response after a Go prime, then

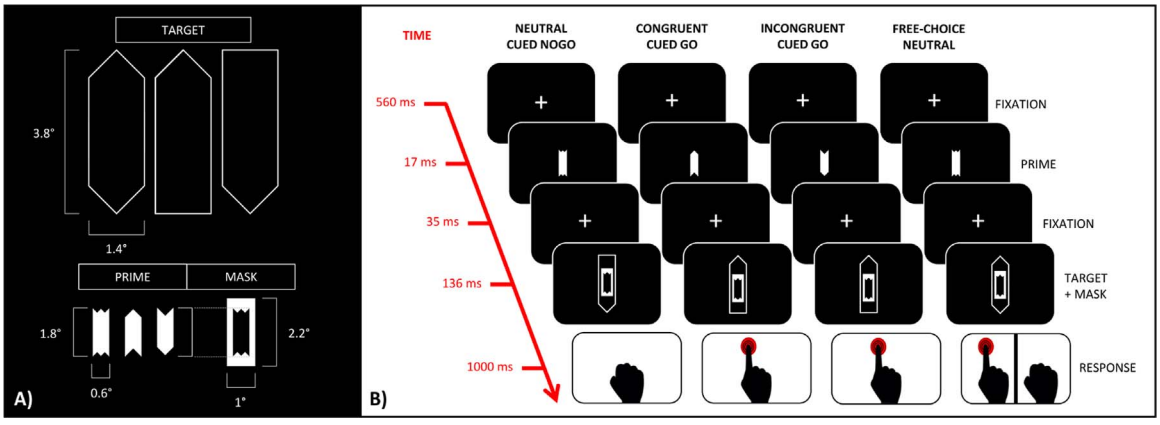

Fig. 1. Panel 'A' depicts the schematic representation of the elements considered in the paradigm. Values indicate the visual angle subtended. Panel 'B' depicts four examples of the possible masked prime/target combinations.

the trial was labeled as 'free-choice congruent'. Vice versa, when participants inhibited the response after a Go prime or when they performed the response after a No-go prime the trial was labeled as 'free-choice incongruent'. Free-choice targets preceded by a neutral prime were labeled as 'free-choice neutral'. Task presentation and response registration were controlled using E-prime 2.0 experimental software (http://www.pstnet.com/eprime.cfm).

2.4. Design

An event-related design was adopted and the entire task was split in 4 scanning runs, each of them lasting approximately 9 min and 40 s. A total of 384 trials was administered, divided into: 25% Go targets, 25% No-go targets and 50% free-choice targets. Each target was preceded by Go, No-go or Neutral primes, with equal probability (33.3%). An equal number of Go and No-go stimuli was considered, since a fundamental requirement of our priming manipulation was to avoid any confounds on the choice of the participants aside the effect induced by the primes. A higher proportion of cued 'Go' trials with respect to cued 'No-go' or 'Free-choice' trials would have produced a tendency toward choosing to act in free-choice trials that would have been indistinguishable by the effect of the primes. Since there are also fMRI studies reporting inhibitory activity using equal probabilities for Go and No-go stimuli consistent with studies using lower probability inhibitory cues (Konishi et al., 1999; Roth et al., 2007), we opted to use the same frequency for Go and No-go trials. The inter-trial-interval (ITI) was jittered including duration from 3000 to 9000 ms, and the software Optseq. 2 (http://surfer.nmr.mgh.harvard.edu/optseq) was used to optimally randomize the order and spacing between stimuli in order to ensure orthogonality of our stimulus conditions. ITI duration was independently randomized within each single experimental run. For the entire duration of the experimental session, participants remained unaware of the presence of the prime. After the experimental session was completed, participants were informed regarding the presence of the masked primes, and were then asked to take part in a short testing session to verify whether primes could be consciously discriminated. A total of 30 testing trials was administered (10 repetitions for each of the three prime stimuli): testing trials were identical to free-choice trials, but participants were asked to focus on prime appearance and ignore the target, trying to decide whether the prime was an up, down, or neutral arrow. The three primes were assigned to different buttons of the response box and the index finger of the dominant hand was used to respond by making unspeeded but forced choices. The shape and the position of the prime were described to the participants prior to the beginning of the discrimination task. Participants did not receive feedback regarding their success or failure of detecting the prime. In case of uncertainty, they were instructed to simply guess. During this last brief session the scanner acquired images, with the purpose of reproducing the same experimental conditions of the experimental session (images were not analyzed). Participants were trained to familiarize with the task instructions during a training session before scanning.

2.5. MRI data acquisition and preprocessing

Data were acquired with a 1.5 T Siemens Avanto MRI scanner (Siemens Medical Systems, Erlangen, Germany) equipped with a standard Siemens eight channels coils. Participants were positioned head-first and supine in the magnet bore. The head was held in place with clamps to avoid head motion. Functional images were acquired with a gradient-echo, echo-planar (EPI) T2*-weighted sequence in order to measure blood oxygenation level-dependent (BOLD) contrast throughout the whole brain (37 contiguous axial slices acquired with ascending interleaved sequence, matrix size = 56 × 64 voxels, 3.5 mm × 3.5 mm × 4.0 mm resolution, FOV = 196 mm × 224 mm, flip angle = 90°, TE = 49 ms). Volumes were acquired continuously for each run with a repetition time (TR) of 3 s 196 volumes were collected in each single scanning run, resulting in 4 functional runs of 9 min and 48 s duration (39 min and 12 s of acquisition time in total). High-resolution anatomical images were then acquired for each subject using a T1-weighted 3D MPRAGE sequence (176 axial slices without interslice gap, matrix size = 256 × 256 voxels, 1 mm isotropic voxels, TR = 1900 ms, TE = 2.91 ms, flip angle = 15°). Data were preprocessed and analyzed using SPM12 (Wellcome Trust Center for Neuroimaging, London, UK) working in Matlab environment (MathWorks, Natick, MA, USA). The first three scans of each individual time series were removed because of the non-equilibrium state of the magnetization in order to allow for stabilization. The ArtRepair toolbox for SPM was used to detect slices corrupted by motion artifacts and/or signal spikes (Mazaika et al., 2007). Then the data was slice time corrected taking the central slice as reference, realigned to the mean image by rigid body transformation, coregistered with the image of the gray matter obtained from the structural image segmentation, normalised to the Montreal Neurological Institute (MNI) template, and smoothed using a 7 mm × 7 mm × 8 mm full-width-at half-maximum (FWHM) Gaussian Kernel. Finally, the ArtRepair toolbox was applied again to detect outlier volumes concerning global intensity or large scan-to-scan movement (Mazaika et al., 2007).

2.6. Behavioural data analyses

Reaction Times (RTs) were obtained from participants' responses to Go targets (cued Go trials) and to free-choice targets when participants chose to press the button to answer (free-choice Go trials). Mean response times of each participant for each condition were submitted to a 3 × 2 repeated-measures ANOVA, with PRIME (Go, No-go, Neutral) and TARGET (cued Go, free-choice Go) as within-subjects factors. Free-choice trials were further analyzed in order to uncover how masked priming influenced participants' choices to execute or inhibit the response. The proportion of choices to act (or inhibit) in free-choice congruent trials, free-choice incongruent trials and free-choice neutral trials was calculated and submitted to a one-way ANOVA with PRIME (Go, No-go, Neutral) as within-subjects factor. Statistical analyses on error rates within each cued condition (omissions in cued Go trials and false alarms in cued No-go trials) were computed by fitting a generalized mixed-effects (GLME) model with a binomial link function, with PRIME (Go, No-go, Neutral) as fixed effect (Pinheiro and Bates, 2000). Random effects consisted of participants and scanning runs. Models were fitted using Restricted Maximum Likelihood (REML) and *p*-values were estimated by likelihood ratio tests of the full model with the effect in question against the model without the effect in question. The strength of evidence in favour of one model over the other is reported as the relative likelihood based on the models' Akaike Information Criterion (AIC) computed as $AIC_{RL} = \exp((AIC_{M1}–AIC_{M2})/2)$, where '$AIC_{RL}$' represent the relative likelihood of the model with the effect in question, and 'AIC_{M1}' 'AIC_{M2}' the comparison between the two models (Akaike, 1987; Burnham and Anderson, 2010; Wagenmakers and Farrell, 2004). Based on our strong prior hypotheses on how priming would affect the response to targets, post-hoc analyses were performed on the effects of interest by means of planned pair-wise comparisons (*t*-tests) and the α level was set at .05 prior to Bonferroni correction. Finally the results from the prime discrimination test performed in the scanner were calculated as the mean percentage of primes correctly discriminated compared against the chance level of 33.3% accuracy.

2.7. fMRI analyses

For first-level analyses, the preprocessed images were analyzed with a General Linear Model (GLM; Friston et al., 1994a) for each subject. Trials were modeled according to the combination of CONGRUENCY (Congruent, Incongruent, Neutral) and the response to the TARGET (cued action, cued inhibition, free-choice action, free-choice inhibition), producing twelve different regressors of interests (see

Supplementary Table 1). Trials on which an error was made (omissions in cued Go trials and false-alarms in cued No-go trials) were included as an additional nuisance variable (≈ 3.5% of all trials) and realignment parameters were modeled as regressors of no interest to account for motion artifact in the data. For each participant, the four runs were modeled as separate session in the GLM. The fMRI time series were then analyzed by convolving a canonical hemodynamic response function (HRF) to the onset of the target and the duration of the events in the GLM was set to 0 s. One-sample *t*-tests were performed in order to produce images for each single condition for each participant. First, a whole brain analysis has been conducted, to explore the specific role of intentionality on the response or in response inhibition. For this analysis primes were collapsed and the resulting matrix is a 2 × 2 factorial design with RESPONSE (action, inhibition) and INTENTIONALITY (free-choice, choice) as factors (see Supplementary Table 2). Images for each of the four conditions were entered into a second level random effect analysis (RFX). First, at the whole brain level, cued vs free-choice trials were compared in order to reveal whether the 'voluntary choices network' was significantly involved in the present task. As a second step, a region of interest (ROI) analysis was implemented in those areas commonly reported to be involved during voluntary choices. ROI analysis were performed using the MARSBAR toolbox (http://marsbar.sourceforge.net; Brett et al., 2002) considering the following anatomical ROIs: RCZ, bilateral AI, bilateral IPL and bilateral DLPFC (as Brodmann area 46 – BA46) as key areas of the 'voluntary choice network' (Brass and Haggard, 2010; Mueller et al., 2007). In this analysis we first compared free-choice action and inhibition trials with cued action and inhibition trials respectively. Then the two free-choice conditions were mutually compared. For the definition of the RCZ, given no anatomical map was available, the average of coordinates reported in other studies comparing free-choices to cued choices was considered (Demanet et al., 2013; Forstmann et al., 2006; Kühn and Brass, 2009; Lynn et al., 2016; Mueller et al., 2007; Teuchies et al., 2016; Wisniewski et al., 2016). A 10-mm radius sphere was built around the resulting coordinates according to the Montréal Neurologic Institute (MNI) stereotaxic space (MNI *x, y, z*: 0 27 38). In addition, in order to test whether our task elicited intentional inhibition mechanisms as reported in previous work (Kühn et al., 2009), a ROI analysis focusing on the dFMC was conducted comparing cued and free choice inhibition trials. To this extent we created a spherical ROI with 10 mm radius around the MNI coordinates for dFMC taken from on Kühn et al. (2009; MNI x, y, z: −7 42 21). Finally, to verify our a priori hypotheses focusing on how masked priming should influence free-choices, the four ROIs related to the 'voluntary choice network' (RCZ, AI, DLPFC and the IPL) and the dFMC were entered in a 3 × 4 factorial design with factors: CONGRUENCY (Congruent, Incongruent, Neutral) and TARGET (cued action, cued inhibition, free-choice action, free-choice inhibition). The congruence between primes and the response given to each different target produced twelve different conditions (see Supplementary Table 1). For the dFMC analysis we focused on the effect of primes on free-choice inhibition trials only. We hypothesized that a Go prime presented before a free-choice trial would produce an even stronger action tendency. In particular, this increase would require the activation of the neural mechanisms specifically related to intentional inhibition (e.g., the dFMC) in those trials that were effectively inhibited (incongruent free-choice inhibition trials). Finally, to disentangle the possible mechanisms by which priming would affect choices and not just the motor state of responses, we conducted an exploratory ROI analysis on primary motor cortex (M1). If primes affect participants' responses by increasing preparatory activity of the motor neurons involved in producing the action, one would expect to find significant differential activity for incongruent vs congruent trials even in absence of an actual motor response. Alternatively if primes affect the activity of the neural representations of choices but not directly the motor processes one could predicts no differences within motor cortices. To this purpose we contrasted congruent versus neutral versus incongruent No-go trials (cued and free-choice) within M1. For the definition of the ROI we computed the contrasts 'action > inhibition' at the whole brain level in conjunction with Brodmann area 4 (BA4) as defined by the brain atlas Automated Anatomical Labeling (AAL; Tzourio-Mazoyer et al., 2002). For all ROI analyses, planned contrasts were performed using paired sample *t*-tests in order to test for the effect of interests, adopting a significant level of $\alpha = .05$ prior to Bonferroni correction. For whole brain analysis all reported effects were thresholded at $p < .05$, family-wise error (FWE) corrected with cluster-extent based thresholding method with a low cluster-defining primary threshold, $p < .001$. Cluster-extent threshold was estimated by Gaussian Random Field method (Friston et al., 1994b; Woo et al., 2014) implemented in SPM12.

3. Results

3.1. Behavioural results

3.1.1. Prime discrimination test

A prime discrimination test was performed by computing the mean percentage of trials correctly discriminated, and comparing this value against the chance-level using single sample *t*-tests. Results show that primes were not consciously detected, $t(23) = .485$, $p = .632$, (mean correct = 32.08% ± 9.26; tested against the 33.3% chance level). As a measure of discriminability, *d'* was computed for each prime/participant. The obtained *d'* values were not significantly different from '0' (no discrimination possible), $t(23) = .485$, $p = .632$ (mean $d' = .32 \pm .09$).

3.1.2. Subliminal primes modulate RTs on Go trials

The repeated measure ANOVA (PRIME × TARGET) on RTs showed a significant main effect of PRIME, $F(1.57, 36.19) = 61.992$, $p < .001$, and TARGET, $F(1, 23) = 5.289$, $p = .031$. The main effect of target type indicated that cued trials are 20 ms faster than free-choice trials. The reported effect of the PRIME factor has been Greenhouse-Geisser corrected since it violated the ANOVA assumption of sphericity. Since the interaction between factors was not significant, $F(2, 46) = 2.464$, $p = .096$, we looked at the post-hoc comparisons for Go RTs (cued Go, free-choice Go combined) between 3 prime conditions (Go, No-go, Neutral). As expected response timing to Go trials were faster if preceded by Go primes when compared to Neutral, $t(23) = 6.07$, $p < .001$, $d = .45$, or No-go, $t(23) = 9.11$, $p < .001$, $d = .69$, primes. Conversely, No-go primes slowed down the response to the Go trials compared to Neutral, $t(23) = 6.38$, $p < .001$, $d = .55$, primes (Go: 416 ms ± 97; Neutral: 438 ms ± 89; No-go: 465 ms ± 79). Fig. 2 summarizes the mean RTs for each type of prime.

3.1.3. No effect of primes on free-choices

In the free-choice condition we also looked at how primes influenced participants' choices. The response bias was defined as the percentage of free-choice trials in which each participant chose to respond as a function of the congruency with the preceding masked prime. The total proportion of actions in free-choice trials was 51%. Results showed that in free-choice trials the response was not influenced by the presentation of the prime, $F(2, 46) = 1.449$, $p = .245$. Participants did not choose to act significantly more often after a Go prime (congruent trials – 53% ± 11), neither when compared to neutral, $t(23) = 1.973$, $p = .061$, nor as expected by chance, $t(23) = 1.329$, $p = .197$. Similarly, participants did not show a significant reduction (49% ± 14) in the proportion of free-choice responses after a No-go prime (incongruent trials) when compared to neutral trials, $t(23) = .171$, $p = .865$, or to chance level, $t(23) = .181$, $p = .858$.

3.1.4. Incongruent primes increased false alarms

Within cued No-go trials the mean rate of false alarms was 8.6%. The GLME model on false alarms yielded a significant main effect of

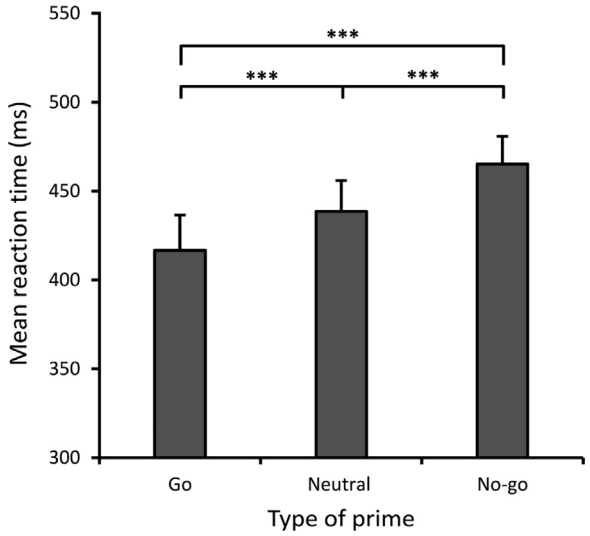

Fig. 2. Mean Reaction Time (RT) in milliseconds (ms) for Go trials (cued and free-choice trials combined). Error bars show standard error of mean. ***$p < .001$; **$p < .01$; *$p < .05$.

Table 1
Reaction times (RT) and Standard Deviations (SD) in milliseconds of both free-choice and cued trials, percentage of errors in cued Go and No-go conditions, percentage of responses in free-choice condition, split for each prime (upper part), and collapsed across primes (lower part).

Prime	Target	RTs (± SD)	% Errors	% Go responses
Go	Cued Go	410.6 (± 17.5)	5.21	
Neutral	Cued Go	425.9 (± 15.9)	5.99	
No-go	Cued Go	453.8 (± 14.5)	5.60	
Go	Cued No-go		12.8	
Neutral	Cued No-go		8.07	
No-go	Cued No-go		7.94	
Go	Free-choice Go	422.6 (± 23.1)		53.9
Neutral	Free-choice Go	451.1 (± 21.3)		49.9
No-go	Free-choice Go	476.8 (± 19.1)		49.5
Cued Go trials		430.1 (± 9.42)	5.60	
Cued No-go trials			9.49	
Free-choice Go trials		450.2 (± 12.3)		50.8

PRIME, $\chi^2(2) = 14.259$, $p < .001$, $AIC_{RL} > 100$, indicating that false alarms were more numerous after a Go prime was presented (12.8.%) if compared to Neutral (8.1%) or No-go primes (7.94%) intuitively reflecting the incompatibility between the response suggested by the prime (go) and the response required by the target (no-go). Within cued Go trials participants were more accurate (mean rate of omissions: 5.6%) and the GLME model on omissions did not yield a significant main effect of PRIME, $\chi^2(2) = .454$, $p = .796$, $AIC_{RL} = .16$, indicating that in cued action trials the incompatibility between primes and target did not affect the general level of accuracy. Mean values for each condition, percentage of errors in cued trials and percentage of responses in free-choice trials are reported in Table 1. In summary, congruent primes had the ability to shorten RTs when compared to neutral primes. The incongruent, when compared to neutral primes, determined longer RTs. Overall, RTs for the cued 'Go' conditions were shorter than those for the free-choice 'Go' conditions, reflecting the possible underlying decision process. In addition to this, incongruent prime-target associations produced more errors in the cued No-go condition. In contrast to our hypotheses, primes were unable to bias participants' choices towards either acting or inhibiting the response.

3.2. fMRI results

3.2.1. Whole brain activation of the choice network

At the whole brain level we looked at the brain regions that showed significant activity when contrasting free-choice and cued trials (see Supplementary Table 3 and Supplementary Fig. 1 for the main contrast of RESPONSE type). Concerning the main effect of INTENTIONALITY, the direct comparison 'free-choice > cued' conditions highlighted activity within the 'voluntary choice network' (Brass and Haggard, 2008; Forstmann et al., 2006; see Fig. 3 and Table 2a), including the bilateral IPL, a large cluster extending from the preSMA to the ACC (defining the RCZ), the left AI, the right premotor cortex and the bilateral DLPFC (minimum k > 69, height threshold $t = 3.119$). These activations closely resemble previous findings in which free-choices and cued choices were contrasted (Demanet et al., 2013; Lynn et al., 2016). The opposite contrast (cued > free-choice) returned activity on the Precuneus and Angular gyri bilaterally (minimum k > 109, height threshold $t = 3.119$; see Table 2b).

3.2.2. Increased ROIs activity for free-choices

Since we were primarily interested in the activity related to the 'voluntary choice network', we looked at the specific comparisons between the levels of the two factors within the five ROIs selected on the basis of our prior hypotheses: the RCZ, the AI, the IPL, the DLPFC and the dFMC. The main effect of RESPONSE (action, inhibition) was significant in the bilateral AI, left: $F(1,23) = 17.72$, $p < .001$; right: $F(1,23) = 4.83$, $p = .029$, and left IPL, $F(1,23) = 10.64$, $p = .001$, whereas the main effect of INTENTIONALITY (free-choice, cued)

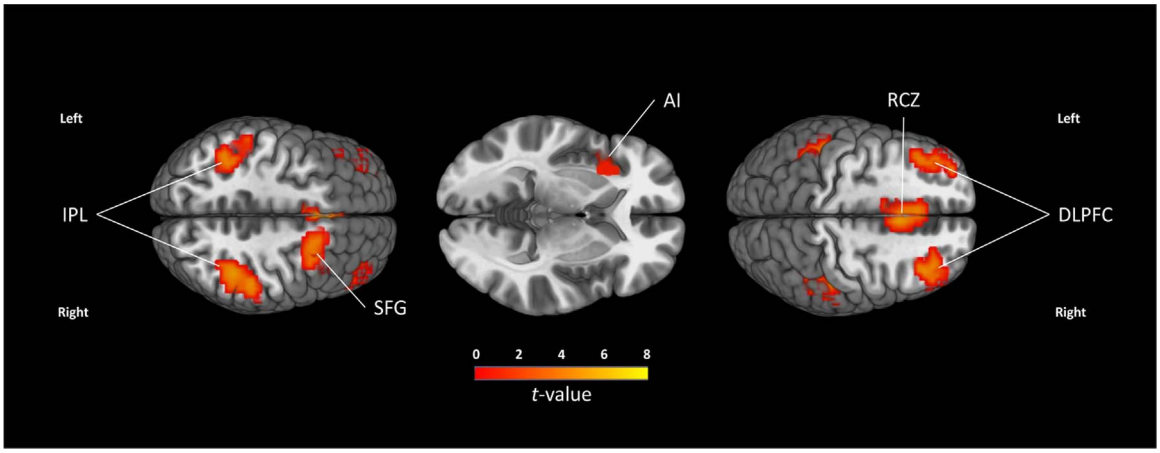

Fig. 3. Renderings of the whole-brain contrasts, comparing free-choice versus cued trials (Table 2a). Activation maps were thresholded at p < .05, family-wise error rate (FWE) corrected with cluster-extent based thresholding method with a low cluster-defining primary threshold, p < .001. The color bar represents *t* values. IPL: Inferior Parietal Lobule; SFG: Superior Frontal Gyrus; AI: Anterior Insula; RCZ: Rostral Cingulate Zone; DLPFC: DorsoLateral PreFrontal Cortex.

Table 2
Results of the whole-brain analysis for free-choice > cued trials (a), cued > free-choice trials (b) and free-choice action > free-choice inhibition trials (c). *p* value < .05, corrected for multiple comparisons (FWE; Family Wise Error). Side: L: Left, R: right; k: cluster extent; MNI: Montréal Neurological Institute. The cluster extent adopted varies according to the reported comparison.

Region	*Side*	*Cluster level*		*Peak level*	*MNI*		
		p(FWE)	*k*	*t-value*	*X*	*Y*	*Z*
a) – Free-choice > Cued (k > 69)							
Rostral Cingulate Zone (RCZ)	R	.000	173	6.36	1	18	42
Anterior Cingulate Cortex (ACC)	L			5.13	−6	32	22
Superior Frontal Gyrus (SFG)	R	.000	81	5.78	19	14	62
Superior Frontal Gyrus (SFG)	R			4.27	29	11	54
Inferior Parietal Lobe (IPL)	R	.000	116	5.40	43	−46	46
Supramarginal Gyrus (SG)	R			5.10	54	−32	46
Dorsolateral Prefrontal Cortex (DLPFC)	R	.000	98	5.30	36	32	26
Middle Frontal Gyrus (MFG)	R			4.64	33	42	18
Middle Frontal Gyrus (MFG)	R			4.23	47	42	18
Anterior Insula (AI)	L	.000	77	5.03	−48	14	−6
Anterior Insula (AI)	L			4.78	−34	14	2
Dorsolateral Prefrontal Cortex (DLPFC)	L	.000	114	4.90	−38	49	6
Middle Frontal Gyrus (MFG)	L			4.46	−41	32	30
Middle Frontal Gyrus (MFG)	L			4.38	−41	39	18
Inferior Parietal Lobe (IPL)	L	.000	69	4.74	−38	−49	46
b) – Cued > Free-choice (k > 109)							
Angular Gyrus (AG)	L	.000	175	5.32	−38	−77	30
Angular Gyrus (AG)	L			4.22	−41	−56	22
Precuneus	L	.000	139	5.31	−3	−63	22
Precuneus	R			4.84	8	−60	22
Angular Gyrus (AG)	R	.000	109	5.12	40	−63	14
Angular Gyrus (AG)	R			5.06	40	−77	26
c) – Free-choice Action > Free-choice Inhibition (k > 56)							
Parietal Operculum (PO)	L	.000	234	5.93	−59	−18	14
Postcentral Gyrus (PoG)	L			5.49	−48	−32	54
Anterior Insula (AI)	L	.000	99	5.70	−41	−4	6
Parietal Operculum (PO)	L			4.99	−55	7	10
Cerebellum (I → IV Lobules)	R	.000	260	5.66	26	−60	−22
Cerebellum	R			4.48	8	−70	−14
Cerebellum (VIII → X Lobules)	R	.001	56	4.52	12	−63	−50
Cerebellum	L	.000	82	4.36	−38	−74	−22

highlighted significant results in the left AI, $F(1,23) = 5.07$, $p = .025$, the RCZ, $F(1,23) = 22.71$, $p < .001$, right IPL, $F(1,23) = 5.04$, $p = .026$, and the bilateral DLPFC, left: $F(1,23) = 5.07$, $p = .025$; right: $F(1,23) = 5.47$, $p = .020$. The interaction RESPONSE × INTENTIONALITY yielded no significant results in any of the considered ROIs. The post-hoc analysis concerning inhibition effects revealed that the RCZ, $t(23) = 4.52$, $p < .001$, the left AI, $t(23) = 2.68$, $p = .004$, the right IPL, $t(23) = 1.98$, $p = .024$ and the left DLPFC, $t(23) = 1.83$, $p = .041$, were significantly more engaged by free-choices inhibition trials (free-choice inhibition > cued inhibition). In general, the considered ROIs appeared to be more engaged in action than in inhibition trials: concerning the effect of intentionality, free-choice action trials appeared to elicit higher activity in respect to cued action trials (free-choice action > cued action) within the bilateral DLPFC, left: $t(23) = 1.72$, $p = .044$; right: $t(23) = 2.16$, $p = .016$, and the RCZ, $t(23) = 2.21$, $p = .014$. The comparison between free-choice trials (free-choice action > free-choice inhibition) highlighted significant increased activity within the bilateral AI, left: $t(23) = 2.61$, $p = .005$; right: $t(23) = 1.98$, $p = .037$, and left IPL, $t(23) = 2.78$, $p = .003$, however no further results were observed in the opposite contrast (all performed contrasts for this analysis are reported in Supplementary Table 4). The main findings of the ROI analysis are reported in Fig. 4. In summary, free-choice conditions systematically produced activation on both the RCZ and the bilateral DLPFC. This pattern emerged more clearly when the two conditions were mutually compared (free-choice action versus free-choice inhibition): both RCZ and DLPFC showed a similar activation level for both conditions (see Fig. 4). This evidence was further supported when the contrast 'free-choice action > free-choice inhibition' was conducted at the whole brain level: the analysis yielded activation of motor (bilateral cerebellum) and somatosensory areas (parietal operculum extending to the postcentral gyrus and to the AI), as expected given the implementation of the response in free-choice action trials (minimum k > 56, height threshold $t = 3.119$; Table 2c), however no other decision-related clusters of activation survived. On these bases, the two free-choice conditions seem to rely on an overlapping network of activity. Notably, the ROI analysis over the dFMC did not reveal significant higher activity relative to free-choice inhibition trials when compared to cued inhibition trials (free-choice inhibition > cued inhibition; see Fig. 4c and Supplementary Table 6).

3.2.3. Primes did not modulate the choice network

To further examine our predictions on how the masked priming modulates the activity on the ROIs during free-choices, we conducted a second set of ROI analyses. The regions related to the 'voluntary choice network' (RCZ, AI, DLPFC and the IPL) were submitted to a factorial design based on the CONGRUENCY (Congruent; Incongruent; Neutral) and the TARGETS (cued action; cued inhibition; free-choice action; free-choice inhibition). Neither the main effect of CONGRUENCY nor the interaction CONGRUENCY × TARGET revealed significant effects within any of the four ROIs, indicating that subliminal prime stimuli were unable to modulate the activity within this areas, neither by increasing the activity for incongruent trials nor reducing the activity for congruent trials (all performed contrasts for this analysis are reported in Supplementary Table 5). Furthermore, masked primes were unable to modulate the activity of the dFMC within free-choice inhibition trials. Incongruent primes (Go prime) did not engage dFMC more than congruent, $t(23) = .53$, $p = .701$, or neutral, $t(23) = 1.33$, $p = .908$, primes (see Supplementary Table 6). To conclude, the ROI analysis on the activity of M1 in No-go trials (cued and free-choice combined) did not reveal a significant increase of activity for incongruent primes when

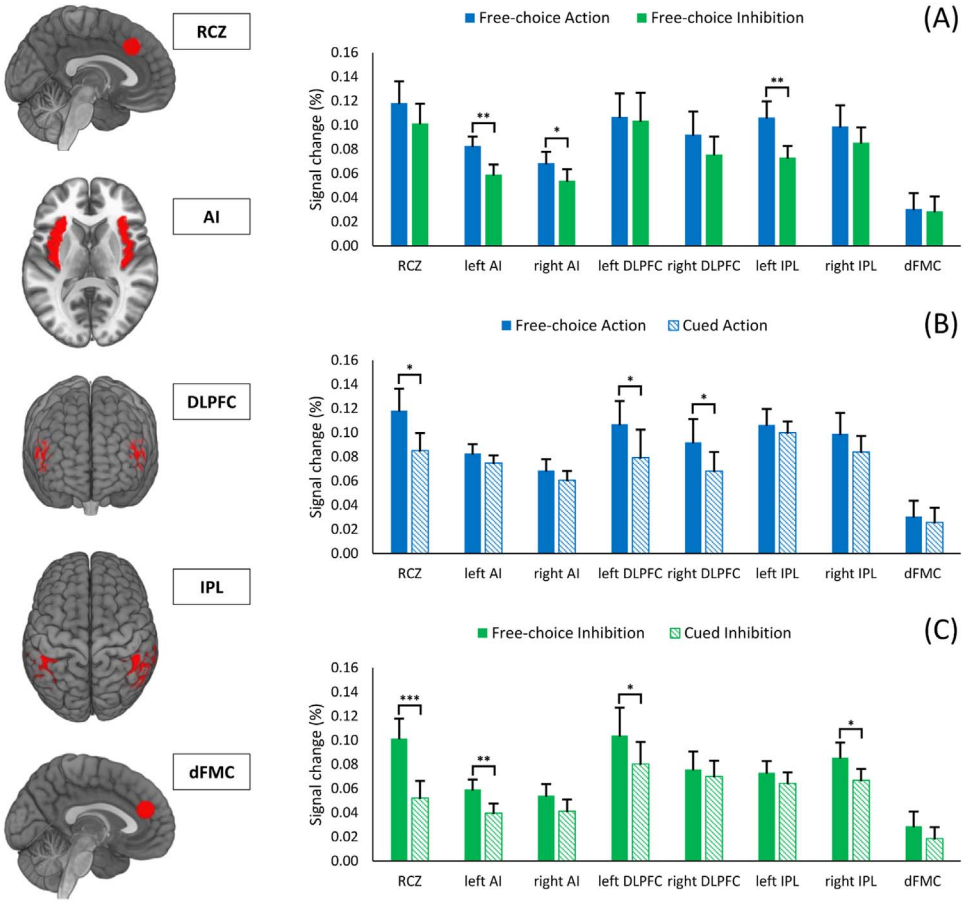

Fig. 4. Comparison between free-choice and cued conditions within the considered ROIs: A) Free-choice action > Free-choice inhibition; B) Free-choice action > Cued action; C) Free-choice inhibition > Cued inhibition. RCZ: Rostral Cingulate Zone; AI: Anterior Insula; DLPFC: Dorso-Lateral PreFrontal Cortex; IPL: Inferior Parietal Lobule; dFMC: Dorsal FrontoMedian Cortex. ROIs are mapped to an MNI render provided with the MRIcroGL software. Charts represent mean percent signal change. Error bars show standard error of mean. ***$p < .001$; **$p < .01$; *$p < .05$.

compared to congruent, $t(23) = .28$, $p = .390$, or neutral, $t(23) = .82$, $p = .792$, primes or for congruent primes when compared to incongruent, $t(23) = .28$, $p = .609$, or neutral, $t(23) = 1.04$, $p = .851$, primes.

4. Discussion

Previous research suggested that activity of some neural structures in the fronto-medial wall may account for the voluntary choices of response alternatives (RCZ; Kühn and Brass, 2009), implementation of the response (preSMA) and intentional inhibition of responses (dFMC; Brass and Haggard, 2008; Lynn et al., 2014). Beyond the RCZ, making voluntary action choices involve a broader network including AI (Brass and Haggard, 2010; Droutman et al., 2015), the IPL and the DLPFC (Forstmann et al., 2006; Mueller et al., 2007).

In the present study we compared intentional action and inhibition trials, with externally-driven trials. Despite the vast literature on response inhibition, few studies attempted to explore the role of intentionality as a mediator for this process. Alike free actions, voluntarily inhibiting an action requires the explicit decision not to implement a pre-potent action (Lynn et al., 2014). We hypothesized that such a decision would trigger activity on the same network reported for free-choice actions. In this respect, when contrasting free-choice versus cued trials at the whole brain level, we detected activity on a network including the RCZ, the bilateral IPL, the right SFG, the bilateral DLPFC and the left AI. These activations closely match previous findings comparing free and cued choices (Forstmann et al., 2006; Lynn et al., 2016; Schel et al., 2014; Wisniewski et al., 2016).

4.1. Making voluntary choices

To further explore the findings obtained at the whole brain level and to better examine the neural pattern underlying intentional situations, we conducted a ROI analysis on the key areas identified in previous literature (Forstmann et al., 2006; Schel et al., 2014). We found that the level of intentionality had the ability to modulate their activity: specifically, when contrasting free-choice action trials with cued action trials we observed significant activity in the RCZ and bilateral DLPFC, which was not detectable for the opposite comparison. The same ROIs, together with AI and right IPL, where significantly more activated by free-choice inhibition trials than by cued inhibition trials. Furthermore, when comparing free-choice actions with free-choice inhibition neither the RCZ nor the DLPFC showed any effect. Rather, only the bilateral AI and left IPL showed significant differential activity. A similar pattern emerged at the whole brain level. Altogether, these findings suggest that 'intentional' trials recruited RCZ and DLPFC, independently from the choice's outcome (action or inhibition).

The RCZ has been shown to support various cognitive processes such as response conflict (Orr and Banich, 2014) voluntary control of actions (Forstmann et al., 2006) and even decision-making (Lau et al., 2004). In all these studies RCZ activation arises when participants deal with uncertainty while voluntary deciding a plausible response option. With respect to RCZ, our data fits with the view that intentionally deciding to inhibit the response is the functional synonymous of evaluating a response option. As outlined by Lynn et al. (2014), we acknowledge that the obtained results might be driven, at least partially, by some specific features of the experimental paradigm adopted: at the appearance of free-choice trials, participants might have first inhibited the action tendency in all trials that were not Go trials, in order to avoid an increase in the rate of false-alarms for cued No-go trials or

responding impulsively in free-choice trials (i.e., producing an unbalanced number of free action responses). If so, the decisional processes under investigation could have not been exclusively related to choosing whether to inhibit the response in free-choice trials, but also regarding whether to re-initiate the action or not. Intuitively this might have elicited the activation of the RCZ, but not of the dFMC. This is not consistent with the idea put forward by Parkinson and Haggard (2014) that intentional inhibition mechanisms could be revealed by the kind of experimental design adopted here. Rather, our findings are in line with what has been reported by Kühn and Brass (2009). They employed a modified version of the SST (De Jong et al., 1995; Verbruggen and Logan, 2009) including a free-choice condition, to demonstrate that the activity of the 'voluntary choice network' was comparable for voluntary action and non-action decisions. Since in their paradigm participants take the decision in advance, such as an unbiased choice between responding or not, these authors refer to an *early whether* and *late whether* component in intentional inhibition (based on the *what*, *when*, *whether* model of Brass and Haggard, 2008). Here we demonstrated that also in the context of a Go/No-go paradigm, the contribution of the RCZ is fundamental in making *early* – free – decisions *whether* to act or not to act.

In both free-choice conditions, additionally to the RCZ other brain areas were involved namely the DLPFC, the IPL and the AI. The activation of the DLPFC is thought to reflect attention and working memory related processes due to random generation of button presses allowing to keep track of previous choices (Hadland et al., 2001; Jahanshahi et al., 2000). Since the task required participants to decide as freely as possible at the appearance of the free-choice target, and to respond/inhibit the action 'in a random but balanced manner' this might have determined its involvement. Nevertheless, DLPFC activity might equally reflect a general preparatory process like increased demands on conflict monitoring (Brass and Haggard, 2007; Lau et al., 2006). Teuchies et al. (2016) found activity in the DLPFC in free-choice trials, but the ROI did not show the conflict activation pattern found in other areas (i.e., the RCZ and AI). This evidence supports the view that the DLPFC might be involved in attention to the selection of the response rather than in the actual response selection (Lau et al., 2004). It must be said, however, that divergent results might be partly due to the differences in tasks, stimuli and designs across studies.

The insular cortex, and more precisely the left AI, has been commonly reported in tasks requiring intentional demands (Brass and Haggard, 2007; Droutman et al., 2015; Mueller et al., 2007) and response inhibition studies (Aron, 2006; Swick et al., 2011). Despite its well-established role in interoceptive awareness (Craig, 2009) the description of the specific function elicited by various cognitive tasks is often explicitly neglected. In our study the bilateral activation of AI was involved in action trials, both free-choice and cued, when compared with inhibition trials, and in free-choice inhibition when compared with cued inhibition conditions. A recent perspective suggests that the AI may play a role in monitoring and evaluating action-outcomes by signalling whether an action was successful or not. The feedback information may reinforce action representations to make them more or less available in future occasions (Brass and Haggard, 2010). In this light, it is possible that the AI evaluates the outcomes of the responses when performed, and identifies the consequences of not acting in intentional inhibition. Likewise for the AI, the same pattern of activation was observed for the IPL: the right IPL showed differential activity in free-choice inhibition trials compared with cued inhibition conditions and the left IPL in both free-choice and cued action trials compared with inhibition trials. The activation of the left IPL in both free-choice and cued action trials is consistent with the evidence for a role of this region within the fronto-parietal action control network (Forstmann et al., 2006) and for the visuomotor processing required for planning actions.

4.2. Masked priming of free-choices

Non-consciously perceived information has been demonstrated to impact free response selection from both the behavioural (Bodner and Mulji, 2010; Ocampo, 2015; Parkinson and Haggard, 2014) and neural (Teuchies et al., 2016) perspective, suggesting that free-choices among response alternatives are subjected to non-conscious cognitive processes (Ocampo, 2015). The fact that the 'voluntary choice network' (Forstmann et al., 2006; Mueller et al., 2007) is shown to be sensitive to non-conscious information in the environment, raised the question of whether such decisions are truly voluntary processes or might be the result of neural activity underlying a partial unconscious process (Libet, 1985; Soon et al., 2008). Driven by this curiosity, as a secondary goal of our study we tested whether it was possible to bias the free decision to withhold the response as demonstrated for free actions. To this end, our experimental manipulation included masked prime arrows to test whether responses to targets were *facilitated* when targets were preceded by response-congruent primes, and *obstructed* when preceded by response-incongruent primes (Parkinson and Haggard, 2014). At the behavioural level, our results showed that No-go primes slowed down RTs in both cued actions and free-choice action conditions and that Go primes induced more errors in cued inhibition condition. In contrast with our hypotheses however, masked primes were unable to modulate the free decision process, neither toward a significant increase of choices to act in action-congruent conditions, nor toward an increase of choices to inhibit in inhibition-congruent conditions. To further test our subliminal manipulation we conducted a ROI analysis, including the congruency between the priming and the response of participants as effects of interest. The selected brain areas were not modulated by the congruency between prime and participant' responses (i.e., to press or not to press). This suggests that our masked primes (though of the exact nature of previously used subliminal primes) did not modulate the decision to act or not to act, and this inefficacy was played out in a lack of significant neural activity within choice-related brain activity. In line with Parkinson and Haggard (2014), we found no effect of primes on free-choices at positive compatibility response latencies (Bavelier et al., 2000). Since our paradigm embedded similar short latencies we cannot rule out the possibility that within this short window of time primes could have worked by affecting the motor state of the response and not only the choice per se. However the effect of priming at the level of choice cannot be ruled out either. Results on cued No-go trials demonstrated that even in absence of an effect on the neural activity of M1, incongruent primes were able to bias participants' performance increasing false-alarms. This evidence supports the idea of an effect of priming at a decisional level.

These findings are in contrast with what has been reported by Teuchies et al. (2016) who demonstrated that the brain's 'voluntary choice network' might be modulated by subliminal information. Though, it must be said, that the paradigm by Teuchies et al. (2016) requested a choice between action alternatives, and not the choice of whether or not to act. Speculatively, subliminal effects might produce weaker effects in a Go/No-go task set rather than in a situation where a direct stimulus-response mapping is set and the direction of the response is primed.

4.3. The role of dFMC

Similar to studies that failed to reveal an involvement of the dFMC in intentional inhibition tasks (Hartwell et al., 2011; Kühn and Brass, 2009) or to those observing dFMC activity in cued-choice trials (Lynn et al., 2016; Severens et al., 2012), we did not collect evidence in favour of an activation of the dFMC in intentional inhibition trials. The interpretation of its function in the context of 'disengagement from strong impulses' (Lynn et al., 2014) may partially explain the lack of dFMC activity in our task. Lynn et al. (2014) described three critical determinants to engage the dFMC in intentional inhibition paradigm: first,

the response must be given under the circumstance of choice. Second, there must be enough time permitting to take an in-the-moment decision in order to avoid pre-decisions or post-decisions. Third, the decision must be taken under a strong urge to act (Lynn et al., 2014). Although a balanced frequency of cued Go and No-go trials might have produced a weaker response tendency if compared with previous paradigms that used a higher proportion of Go trials, the present paradigm was designed to produce an adequate impulse toward action: participants were explicitly instructed to always prepare the response but eventually decide to withhold it by taking an in-the-moment decision. This was further stressed by giving a very short response window (1 s) in order to avoid post-decisions. Moreover, the higher error rate in cued No-go compared to Go trials allows us to affirm that our design successfully induced a robust urge toward the action. However, although participants were instructed to avoid such behaviour, the possibility that they took the decision before the start of the trial, thus producing pre-decisions, was not controlled. As mentioned above, in free-choice trials participants could have first decided to inhibit the action tendency and only subsequently decided whether to perform the action or not. As a consequence dFMC activity was not elicited. Taking into account these considerations, we cannot rule out that a lack of significant differential activity in the dFMC in the first ROI analysis might be due specific features of the experimental design. Based on our hypotheses and supported by the results of false alarms in cued inhibition trials, the second ROI analysis capitalized on the effect of incongruent primes to boost action pre-potency in free-choice inhibition trials. Although we hypothesized that this manipulation would have produced a pronounced activation of the neural mechanisms involved in intentional inhibition (dFMC) this was not the case. These mixed findings point to the fact that at present no clear conclusions can be drawn on the validity of masked priming as a tool for the determination of the psychological mechanisms and neural substrates of intentional inhibition.

5. Conclusions

The present fMRI study aimed at investigating the neural correlates of intentional choice between action and inhibition within the same paradigm. In agreement with previous studies the BOLD activity of brain areas concerned with voluntary decision processes was modulated by the degree of intentionality of the response (Lynn et al., 2016; Schel et al., 2014; Teuchies et al., 2016). The left AI was specifically tuned to monitor the consequence of the responding in both free-choice and cued conditions, and to withhold the response in intentional inhibition conditions. The RCZ and the DLPFC were equally active both when participant freely decide to implement the response and when participants freely inhibit an already prepared response. These findings confirm the key role of both structures in making voluntary choices, suggesting that – at least for the present experiment – free-choices to inhibit and free-choices to act might be considered two side of the same coin, or rather two possible outcomes of the same decision process.

Acknowledgements

This work was supported by the Strategic Project (N. 2010XPMFW4) of the University of Padova entrusted to Umberto Castiello. TDA and UC designed the experiment, TDA, CB, RM and DM collected the data, TDA and CB analysed the data, TDA and UC wrote the manuscript.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.neuropsychologia.2017.11.035.

References

Akaike, H., 1987. Factor analysis and AIC. Psychometrika 52, 317–332. http://dx.doi.org/10.1007/BF02294359.
Aron, A.R., 2011. From reactive to proactive and selective control: developing a Richer model for stopping inappropriate responses. Biol. Psychiatry 69, e55–e68. http://dx.doi.org/10.1016/j.biopsych.2010.07.024.
Aron, A.R., 2006. Cortical and subcortical contributions to stop signal response inhibition: role of the subthalamic nucleus. J. Neurosci. 26, 2424–2433. http://dx.doi.org/10.1523/JNEUROSCI.4682-05.2006.
Bavelier, D., Deruelle, C., Proksch, J., 2000. Positive and negative compatibility effects. Percept. Psychophys. 62, 100–112.
Bari, A., Robbins, T.W., 2013. Inhibition and impulsivity: behavioral and neural basis of response control. Prog. Neurobiol. 108, 44–79. http://dx.doi.org/10.1016/j.pneurobio.2013.06.005.
Bodner, G.E., Mulji, R., 2010. Prime proportion affects masked priming of fixed and free-choice responses. Exp. Psychol. 57, 360–366. http://dx.doi.org/10.1027/1618-3169/a000043.
Brass, M., Haggard, P., 2010. The hidden side of intentional action: the role of the anterior insular cortex. Brain Struct. Funct. 214, 603–610. http://dx.doi.org/10.1007/s00429-010-0269-6.
Brass, M., Haggard, P., 2008. The what, when, whether model of intentional action. Neuroscientist 14, 319–325. http://dx.doi.org/10.1177/1073858408317417.
Brass, M., Haggard, P., 2007. To do or not to do: the neural signature of self-control. J. Neurosci. 27, 9141–9145. http://dx.doi.org/10.1523/JNEUROSCI.0924-07.2007.
Brett, M., Anton, J.-L., Valabregue, R., Poline, J.-B., 2002. Region of interest analysis using the MarsBar toolbox for SPM 99. Neuroimage 16, S497.
Burnham, K.P., Anderson, D.R., 2010. Model Selection and Multimodel Inference: A Practical Information-theoretic Approach, 2 ed. Springer, New York, NY.
Craig, A.D., 2009. How do you feel – now? The anterior insula and human awareness. Nat. Rev. Neurosci. 10, 59–70. http://dx.doi.org/10.1038/nrn2555.
De Jong, R., Coles, M.G., Logan, G.D., 1995. Strategies and mechanisms in nonselective and selective inhibitory motor control. J. Exp. Psychol. Hum. Percept. Perform. 21, 498–511.
Demanet, J., De Baene, W., Arrington, C.M., Brass, M., 2013. Biasing free choices: the role of the rostral cingulate zone in intentional control. NeuroImage 72, 207–213. http://dx.doi.org/10.1016/j.neuroimage.2013.01.052.
Droutman, V., Bechara, A., Read, S.J., 2015. Roles of the different sub-regions of the insular cortex in various phases of the decision-making process. Front. Behav. Neurosci. 9. http://dx.doi.org/10.3389/fnbeh.2015.00309.
Filevich, E., Kühn, S., Haggard, P., 2012. Intentional inhibition in human action: the power of "no.". Neurosci. Biobehav. Rev. 36, 1107–1118. http://dx.doi.org/10.1016/j.neubiorev.2012.01.006.
Forstmann, B.U., Brass, M., Koch, I., von Cramon, D.Y., 2006. Voluntary selection of task sets revealed by functional magnetic resonance imaging. J. Cogn. Neurosci. 18, 388–398. http://dx.doi.org/10.1162/089892906775990589.
Friston, K.J., Holmes, A.P., Worsley, K.J., Poline, J.-P., Frith, C.D., Frackowiak, R.S.J., 1994a. Statistical parametric maps in functional imaging: a general linear approach. Hum. Brain Mapp. 2, 189–210. http://dx.doi.org/10.1002/hbm.460020402.
Friston, K.J., Worsley, K.J., Frackowiak, R.S., Mazziotta, J.C., Evans, A.C., 1994b. Assessing the significance of focal activations using their spatial extent. Hum. Brain Mapp. 1, 210–220. http://dx.doi.org/10.1002/hbm.460010306.
Gold, J.I., Shadlen, M.N., 2007. The neural basis of decision making. Annu. Rev. Neurosci. 30, 535–574. http://dx.doi.org/10.1146/annurev.neuro.29.051605.113038.
Hadland, K.A., Rushworth, M.F.S., Passingham, R.E., Jahanshahi, M., Rothwell, J.C., 2001. Interference with performance of a response selection task that has no working memory component: an rTMS comparison of the dorsolateral prefrontal and medial frontal cortex. J. Cogn. Neurosci. 13, 1097–1108. http://dx.doi.org/10.1162/089892901753294392.
Hanes, D.P., Schall, J.D., 1996. Neural control of voluntary movement initiation. Science 274, 427–430.
Hartwell, K.J., Johnson, K.A., Li, X., Myrick, H., LeMatty, T., George, M.S., Brady, K.T., 2011. Neural correlates of craving and resisting craving for tobacco in nicotine dependent smokers: crave and resist. Addict. Biol. 16, 654–666. http://dx.doi.org/10.1111/j.1369-1600.2011.00340.x.
Jahanshahi, M., Dirnberger, G., Fuller, R., Frith, C.D., 2000. The role of the dorsolateral prefrontal cortex in random number generation: a study with positron emission tomography. NeuroImage 12, 713–725. http://dx.doi.org/10.1006/nimg.2000.0647.
Konishi, S., Nakajima, K., Uchida, I., Kikyo, H., Kameyama, M., Miyashita, Y., 1999. Common inhibitory mechanism in human inferior prefrontal cortex revealed by event-related functional MRI. Brain 122, 981–991. http://dx.doi.org/10.1093/brain/122.5.981.
Kühn, S., Brass, M., 2009. When doing nothing is an option: the neural correlates of deciding whether to act or not. NeuroImage 46, 1187–1193. http://dx.doi.org/10.1016/j.neuroimage.2009.03.020.
Kühn, S., Haggard, P., Brass, M., 2009. Intentional inhibition: how the "veto-area" exerts control. Hum. Brain Mapp. 30, 2834–2843. http://dx.doi.org/10.1002/hbm.20711.
Lau, H., Rogers, R., Ramnani, N., Passingham, R., 2004. Willed action and attention to the selection of action. NeuroImage 21, 1407–1415. http://dx.doi.org/10.1016/j.neuroimage.2003.10.034.
Lau, H., Rogers, R.D., Passingham, R.E., 2006. Dissociating response selection and conflict in the medial frontal surface. NeuroImage 29, 446–451. http://dx.doi.org/10.1016/j.neuroimage.2005.07.050.
Leuthold, H., Kopp, B., 1998. Mechanisms of priming by masked stimuli: inferences from event-related brain potentials. Psychol. Sci. 9, 263–269. http://dx.doi.org/10.1111/

1467-9280.00053.
Libet, B., 1985. Mediation of slow-inhibitory postsynaptic potentials. Nature 313, 161–162.
Lingnau, A., Vorberg, D., 2005. The time course of response inhibition in masked priming. Percept. Psychophys. 67, 545–557.
Logan, G.D., 1994. On the ability to inhibit thought and action: A users' guide to the stop signal paradigm. In: Inhibitory Processes in Attention, Memory, and Language. Academic Press, San Diego, pp. 189–239.
Lynn, M.T., Demanet, J., Krebs, R.M., Van Dessel, P., Brass, M., 2016. Voluntary inhibition of pain avoidance behavior: an fMRI study. Brain Struct. Funct. 221, 1309–1320. http://dx.doi.org/10.1007/s00429-014-0972-9.
Lynn, M.T., Muhle-Karbe, P.S., Brass, M., 2014. Controlling the self: the role of the dorsal frontomedian cortex in intentional inhibition. Neuropsychologia 65, 247–254. http://dx.doi.org/10.1016/j.neuropsychologia.2014.09.009.
Mazaika, P.K., Whitfield-Gabrieli, S., Reiss, A.L., 2007. Artifact repair for fMRI data from high motion clinical subjects. In: Proceedings of the Presented at the Annual Meeting of the Organization for Human Brain Mapping.
Mueller, V.A., Brass, M., Waszak, F., Prinz, W., 2007. The role of the preSMA and the rostral cingulate zone in internally selected actions. NeuroImage 37, 1354–1361. http://dx.doi.org/10.1016/j.neuroimage.2007.06.018.
Ocampo, B., 2015. Unconscious manipulation of free-choice by novel primes. Conscious. Cogn. 34, 4–9. http://dx.doi.org/10.1016/j.concog.2015.03.007.
Oldfield, R.C., 1971. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 9, 97–113.
Orr, J.M., Banich, M.T., 2014. The neural mechanisms underlying internally and externally guided task selection. NeuroImage 84, 191–205. http://dx.doi.org/10.1016/j.neuroimage.2013.08.047.
Parkinson, J., Haggard, P., 2014. Subliminal priming of intentional inhibition. Cognition 130, 255–265. http://dx.doi.org/10.1016/j.cognition.2013.11.005.
Pinheiro, J.C., Bates, D.M., 2000. Mixed-effects models in S and S-PLUS. In: Statistics and Computing. Springer-Verlag, New York, NY, pp. 57–96.
Roth, R.M., Saykin, A.J., Flashman, L.A., Pixley, H.S., West, J.D., Mamourian, A.C., 2007. Event-related functional magnetic resonance imaging of response inhibition in obsessive-compulsive disorder. Biol. Psychiatry 62, 901–909. http://dx.doi.org/10.1016/j.biopsych.2006.12.007.
Schel, M.A., Kühn, S., Brass, M., Haggard, P., Ridderinkhof, K.R., Crone, E.A., 2014. Neural correlates of intentional and stimulus-driven inhibition: a comparison. Front. Hum. Neurosci. 8. http://dx.doi.org/10.3389/fnhum.2014.00027.
Schlaghecken, F., Eimer, M., 2004. Masked prime stimuli can bias "free" choices between response alternatives. Psychon. Bull. Rev. 11, 463–468. http://dx.doi.org/10.3758/BF03196596.
Schurger, A., Sitt, J.D., Dehaene, S., 2012. An accumulator model for spontaneous neural activity prior to self-initiated movement. Proc. Natl. Acad. Sci. USA 109, E2904–E2913. http://dx.doi.org/10.1073/pnas.1210467109.
Severens, E., Kühn, S., Hartsuiker, R.J., Brass, M., 2012. Functional mechanisms involved in the internal inhibition of taboo words. Soc. Cogn. Affect. Neurosci. 7, 431–435. http://dx.doi.org/10.1093/scan/nsr030.
Simon, J.R., 1969. Reactions toward the source of stimulation. J. Exp. Psychol. 81, 174–176. http://dx.doi.org/10.1037/h0027448.
Smith, P.L., 2000. Stochastic dynamic models of response time and accuracy: a foundational primer. J. Math. Psychol. 44, 408–463. http://dx.doi.org/10.1006/jmps.1999.1260.
Soon, C.S., Brass, M., Heinze, H.-J., Haynes, J.-D., 2008. Unconscious determinants of free decisions in the human brain. Nat. Neurosci. 11, 543–545. http://dx.doi.org/10.1038/nn.2112.
Swick, D., Ashley, V., Turken, U., 2011. Are the neural correlates of stopping and not going identical? Quantitative meta-analysis of two response inhibition tasks. NeuroImage 56, 1655–1665. http://dx.doi.org/10.1016/j.neuroimage.2011.02.070.
Teuchies, M., Demanet, J., Sidarus, N., Haggard, P., Stevens, M.A., Brass, M., 2016. Influences of unconscious priming on voluntary actions: role of the rostral cingulate zone. NeuroImage 135, 243–252. http://dx.doi.org/10.1016/j.neuroimage.2016.04.036.
Tzourio-Mazoyer, N., Landeau, B., Papathanassiou, D., Crivello, F., Etard, O., Delcroix, N., Mazoyer, B., Joliot, M., 2002. Automated anatomical labeling of activations in SPM using a macroscopic anatomical parcellation of the MNI MRI single-subject brain. NeuroImage 15, 273–289. http://dx.doi.org/10.1006/nimg.2001.0978.
van den Wildenberg, W.P.M., Wylie, S.A., Forstmann, B.U., Burle, B., Hasbroucq, T., Ridderinkhof, K.R., 2010. To head or to heed? Beyond the surface of selective action inhibition: a review. Front. Hum. Neurosci. 4. http://dx.doi.org/10.3389/fnhum.2010.00222.
Verbruggen, F., Logan, G.D., 2009. Models of response inhibition in the stop-signal and stop-change paradigms. Neurosci. Biobehav. Rev. 33, 647–661. http://dx.doi.org/10.1016/j.neubiorev.2008.08.014.
Wagenmakers, E.-J., Farrell, S., 2004. AIC model selection using Akaike weights. Psychon. Bull. Rev. 11, 192–196. http://dx.doi.org/10.3758/BF03206482.
Wisniewski, D., Goschke, T., Haynes, J.-D., 2016. Similar coding of freely chosen and externally cued intentions in a fronto-parietal network. NeuroImage 134, 450–458. http://dx.doi.org/10.1016/j.neuroimage.2016.04.044.
Woo, C.-W., Krishnan, A., Wager, T.D., 2014. Cluster-extent based thresholding in fMRI analyses: pitfalls and recommendations. NeuroImage 91, 412–419. http://dx.doi.org/10.1016/j.neuroimage.2013.12.058.