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Effortless control: executive attention and conscious feeling of mental effort are dissociable

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Abstract

Recruitment of executive attention is normally associated to a subjective feeling of mental effort. Here we investigate the nature of this coupling in a patient with a left mesio-frontal cortex lesion including the anterior cingulate cortex (ACC), and in a group of comparison subjects using a Stroop paradigm. We show that in normal subjects, subjective increases in effort associated with executive control correlate with higher skin-conductance responses (SCRs). However, our patient experienced no conscious feeling of mental effort and showed no SCR, in spite of exhibiting normal executive control, and residual right anterior cingulate activity measured with event-related potentials (ERPs). Finally, this patient demonstrated a pattern of impaired behavior and SCRs in the Iowa gambling task—elaborated by Damasio, Bechara and colleagues—replicating the findings reported by these authors for other patients with mesio-frontal lesions. Taken together, these results call for a theoretical refinement by revealing a decoupling between conscious cognitive control and consciously reportable feelings. Moreover, they reveal a fundamental distinction, observed here within the same patient, between the cognitive operations which are depending on normal somatic marker processing, and those which are withstanding to impairments of this system.

Keywords: Executive control; Mental effort; Consciousness; Anterior cingulate cortex; Case study

"But I see well what still misleads you, it is that to stir up your arm, it is not sufficient that you want it, rather it is necessary for you to make some effort. And you think that this effort, of which you have interior feeling, is the true cause of the movement which follows it. But my son, do you clearly see some relationship between what you call effort, and the determination of the animal spirits in the pipes of the nerves which are used for the movements that you want to produce?" Nicolas Malebranche, Méditations Chrétiennes (1683).

1. Introduction

The involvement of the prefrontal cortex in the ability to engage executive control constitutes one of the fundamental results of cognitive neuroscience. Current research focuses on the respective roles of frontal lobe structures such as anterior cingulate cortex (ACC), dorso-lateral prefrontal cortex (DLPFC), or orbito-frontal cortex (OFC) in this general process of control. Most investigated aspects of control include conflict detection and estimation, executive control modulation and response selection processes. In particular, diverging theories stimulate experimental research on the precise role of ACC in control. One influential theory postulates that ACC is involved in conflict monitoring and serves as a regulator signaling to other executive regions such as DLPFC whether ex-

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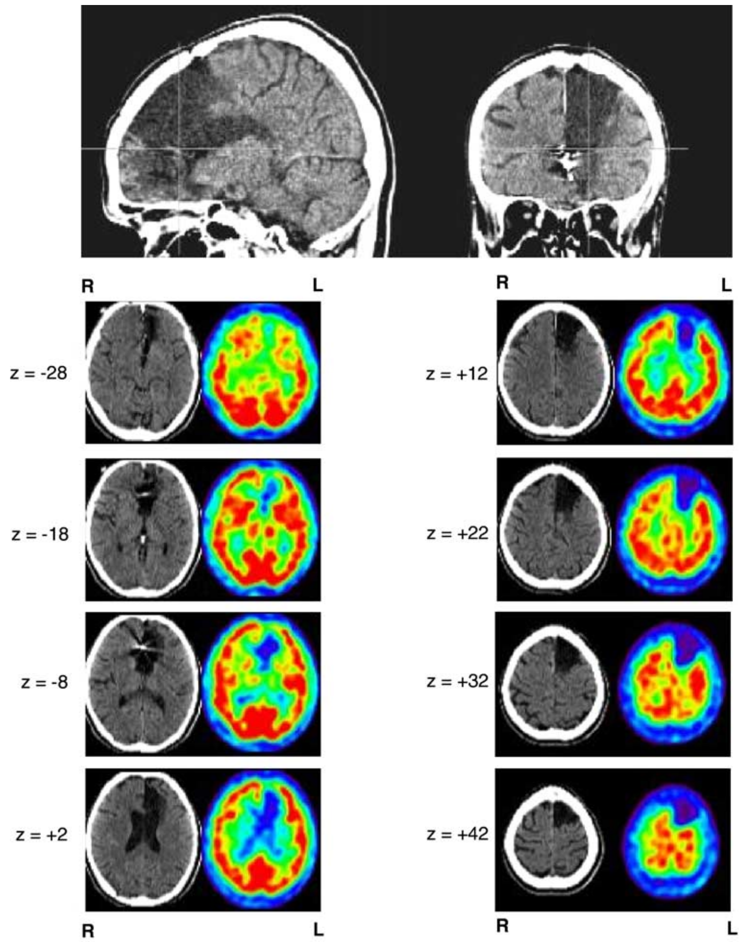

Fig. 1. Anatomy of patient RMB's lesion. Sagittal and coronal sections of a high resolution brain CT-scan (0.39 mm × 0.39 mm × 1 mm), and eight axial sections of CT-scan and rest SPECT normalized in Talairach's space using SPM2 (*z* coordinate is provided for each pair of sections) reveal a stroke lesion delineating part of the left anterior cerebral artery territory. Only the rolandic part of this arterial territory is spared, in accordance with the clinical examination confirming the absence of right motor limb deficit.

ecutive attention has to be reinforced or alleviated (Botvinick, Braver et al., 2001). Another theory attributes to ACC a more active function related to response selection, as illustrated by patients exhibiting dissociations between control abilities depending on the motor response modality (Turken & Swick, 1999).

Within this scientific context, we planned to explore control abilities in patient RMB, a 50-year-old woman presenting with a vast left mesio-frontal ischaemic lesion including the left ACC (Fig. 1). We were initially motivated by the perspective of describing control impairments likely to be found in such a patient, and then to test which theory would best account for them.

We designed a set of behavioral experiments using a simplified Stroop task in which, on each trial the subject had to respond according to the ink color of a color word (e.g. the word "red" written in green ink) (Carter, Macdonald et al., 2000). Stroop trials can be sorted into two categories: congruent trials in which both the ink color and the word itself refer to the same response, and incongruent trials in which the subject has to focus his executive attention to select the relevant information (the ink color) and to inhibit the prepotent response associated with the irrelevant information (the printed color word). Incongruent trials are usually responded slower and with a greater subjective feeling of mental effort.

Our results section begins with a detailed description of patient RMB's performance in this Stroop task (Experiments 1–3). Unexpectedly, control abilities of patient RMB evaluated in various versions of this Stroop tasks were amazingly preserved, and no dissociation was observed between manual and vocal response modalities. Moreover, we could show the presence of an efficient dynamic regulation of control abilities as indexed by Gratton and proportion effects.

However, we accidentally discovered that she had lost entirely the ability to experience and report a feeling of mental effort normally present during this task. In order to better assess and describe this unexpected deficit, we designed a further set of experiments exploring subjective verbal and non-verbal report of mental effort during the Stroop task in patient RMB and in normals (Experiments 4–7).

Once we could establish the existence of a dissociation between preserved cognitive aspects of control on the one hand,

and impaired consciously reportable feeling of mental effort on the other hand, we hypothesized that the spared right ACC might subtend preserved control. We tested this hypothesis by replicating one of the Stroop experiments while recording scalp event-related potentials (ERPs), and confirmed the implication of this unlesioned neural structure, by revealing a correlation between its activity and patient RMB's executive attention performance (Experiment 8).

Finally, given that mental effort is normally associated to a cortege of bodily or somatic markers, we checked if patient RMB's lack of mental effort was associated to an impairment of skin conductance response (SCR)—a well-known somatic marker—during the Stroop task, and during the perception of external emotional stimuli (Experiments 9–11).

2. Methods

2.1. Patient RMB

Miss RMB was a right-handed 50-year-old lady who suffered in 1993 from a subarachnoid haemorrhage complicated by a vasospasm in the left anterior cerebral artery territory. She was referred to one of us (L.N.) for mild memory complaint. In July 2002, physical neurological examination revealed only discrete motor frontal lobe symptoms such as bilateral Babinski sign and hyperactive tendon reflexes. Educational level was 4 years of universitary studies.

The ischaemic lesion encompassed the left ACC, the genu of the corpus callosum, part of the orbito-frontal cortex, and spared the motor cortex (see Fig. 1 for imaging data recorded more than 10 years from stroke onset). Rest ^{99m}Tc-ECD SPECT discarded additional abnormalities due to diaschisis.

While estimation of global cognitive status was in the normal range (e.g. Folstein's MMSE = 29/30), detailed neuropsychological assessment showed a mild dysexecutive syndrome affecting attentional resources, particularly in divided attention, in complex tasks, in free recall performance (delayed free recall = 9/16 and delayed total recall = 15/16 in the Grober and Buschke test), and conceptual and planning abilities. She was fully aware of these mild impairments, and did not manifest any symptom of anosognosia when committing errors during testing.

2.2. Comparison subjects

Ten right-handed comparison healthy subjects (9 females; 37–62-year-old; mean age = 54) gave their informed consent. Educational level ranged from 2 to 10 years after high school (mean = 6.3 years).

2.3. Procedure

Experiments were approved by the French ethical committee for biomedical research, and patient RMB and the 10 comparison subjects gave their informed consent. All Stroop experiments used the set of four stimuli defined by color words "rouge" (French word for "red") and "vert" (French word for "green") presented either in green or red ink. Congruent stimuli correspond to the color words presented in the corresponding ink, while incongruent are the color words presented in the different ink. Subjects had to respond to ink color as accurately and fast as possible. Analyses of variance were performed on correct RTs ranging between 250 and 1500 ms. Single subject (patient RMB) analyses on RTs, ERPs and SCRs were performed through ANOVAs (or through the equivalent Student's *t*-test when a simple comparison between two conditions was tested like in the SCR section) using trials as the random factor. This methodology is widely used in experimental psychology and in ERP or fMRI statistical analyses (see for instance Anderson & Phelps (2001); Cole, Heywood, Kentridge, Fairholm, & Cowey (2003), or from our lab: Cohen et al. (2000) for an illustration of behavioural, ERPs and fMRI single subjects analyses). Group analyses performed on the comparison subjects used median RT values.

2.4. Experiment 1: manual Stroop

Three hundred and twenty trials were randomly presented on a computer screen (distance to screen = 50 cm) at a 4 s rate, using Expe6 software (Pallier, Dupoux et al., 1997). Subjects responded pressing either left or right buttons of a response pad (electrical geodesics) connected to the parallel port of the computer. Subjects were instructed to press the left button for green ink words, and the right button for red ink words.

2.5. Experiment 2: vocal Stroop

The only modification with Experiment 1 was the use of a voice-key connected to the serial port of the PC to record vocal RTs. Subjects were instructed to name the ink color. The experimenter monitored vocal responses to identify errors. A practice block of 16 trials was offered.

2.6. Experiment 3: blocked Stroop

Nine blocks of 40 trials similar to those used in Experiment 1 were presented. Proportion of incongruent trials randomly varied across blocks from 10 to 90%. A pause was offered at the end of each block.

2.7. Experiment 4: verbal comparison of mental effort

Ninety-six pairs of Stroop trials were randomly presented to the subjects, immediately after the SCR experiment (Experiment 10), using the very same procedure and instructions. After each pair of trials, subjects had to explicitly verbalize which one of these two trials was subjectively felt as the more difficult. No practice was proposed.

2.8. Experiment 5: verbal description of Stroop trials

The very same trials as in Experiment 4 were proposed to patient RMB She had to perform the Stroop task on pairs of trials, and then to explicitly categorize trial one as congruent or incongruent.

2.9. Experiment 6: verbal comparison of RTs

This experiment was a replication of Experiment 4, the only difference being the nature of the secondary task. After each pair of trials, patient RMB was instructed to verbally indicate which of two preceding response times was the larger.

2.10. Experiment 7: non-verbal comparison of mental effort

This experiment was a replication of Experiment 4, the only difference being the response modality which was non verbal. After each pair of trials, two faces appeared on the screen (a smiling face on the left, a sad face on the right) and patient RMB was instructed to press the button with the smiling face if the second trial was judged less difficult, or the button with the sad face if the second trial was judged more difficult than the preceding trial of the pair.

2.11. Experiment 8: ERP Stroop

Two hundred and forty trials identical to those used in Experiment 1 were randomly presented in three blocks of 80 trials. Patient RMB was trained during an initial practice block of 16 trials. Stimuli were delivered at a 4 s rate on a standard PC-compatible SVGA (Super Video Graphics Array) screen (Enhanced Graphic Adapter mode, 70 Hz refresh rate). The electroencephalogram was digitized at 125 Hz from 128 scalp electrodes referenced to the vertex (Tucker, 1993), for a 1000 ms period starting 200 ms before the onset of the word, using a 0.5–40 Hz band pass recording filter. We rejected trials with incorrect responses, voltages exceeding $\pm 100\,\mu$V, transients exceeding $\pm 50\,\mu$V, electro-oculogram activity exceeding $\pm 70\,\mu$V, or response times outside a 250–1000 ms interval. The remaining trials were averaged in synchrony with stimulus onset, digitally transformed to an average reference, low-pass filtered at 20 Hz, and corrected for baseline over a 200 ms window before stimulus onset. N1 and N2 events were visually identified on the grand-averaged ERP of electrode Fz located in front of the ACC. We compared congruent and incongruent trials by averaging the signal through the six successive samples covering the visually identified N2 (288–528 ms after word onset), across four contiguous electrodes (5, 6, 11 and 12 from EGI system) with a criterion of $p < 0.05$ in a unilateral *t*-test. Two-dimensional maps of scalp voltage and *t*-values were constructed by spherical spline interpolation. Source estimation of N2 event was tested using BESA software.

2.12. Experiment 9: SCR Stroop

The SCRs were recorded with a skin conductance amplifier through a constant (direct current (dc)) 13 V bridge circuit, and digitized at 100 Hz. Three hundred and twenty trials identical to those used in Experiment 1 were randomly presented in four blocks of 80 trials. A practice block of 16 trials was given at the beginning of this session. Temporal structure of triamls was slowed in order to record event-related SCR. A transistor–transistor logic (TTL) signal was send to the dc amplifier 2 s before word 1 presentation, then 4 s later word 2 was presented and then next TTL was sent 2.5 s later. Variations of skin electrical conductance were recorded on the left hand in patient RMB and in the 10 comparison subjects. Standard surface electromyogram (EMG) electrodes (Ag-AgCl, 8 mm diameter) were placed on the ventral and dorsal surface of the hand, and on the ventral forearm (15 cm from the wrist) as a ground electrode. Skin potential signals were filtered and amplified using a bioelectric amplifier (Notocord system). Skin potential signals were digitized at a sampling rate of 100 Hz and entered into a personal computer. Skin potential records distorted by EMG or movement artifacts were excluded from further analysis by visual inspection. Signal averaging and *t*-tests were performed in Matlab 6.5 (Natick, MA).

2.13. Experiment 10: SCR IAPS

At the end of the main SCR experiment (Experiment 9), 12 pictures selected from the International Affective Picture System (IAPS) battery (Lang, Bradley et al., 1995) were presented on a PC screen in a passive viewing condition while recording SCR. Each picture was presented during 5 s and was immediately followed by a blank screen during 10 s. Distance to screen was 70 cm.

2.14. Experiment 11: SCR gambling task

The computerized version of the Iowa gambling task was performed (see (Bechara, Damasio et al., 2000) for design and instructions) while SCRs were recorded as described in Experiment 10. Artefact rejection and signal averaging of the 5 s period preceding card selection (anticipation analysis: good decks versus bad decks), and of the 5 s period following card selection (reward analysis: net positive outcome versus net negative outcome) were performed in Matlab 6.5 (Natick, MA) (Table 1).

3. Results

3.1. Behavior

3.1.1. Stroop effects

We first tested patient RMB in a manual version of this basic Stroop task (Experiment 1). Analysis of correct trials showed the classical Stroop effect ($F(1, 299) = 37.13$;

Table 1
Synthetic view of experimental results

Experiment no.	Experiment name	Patient RMB	Comparison group
1	Manual Stroop	Stroop and Gratton effects	Stroop and Gratton effects
2	Vocal Stroop	Stroop and Gratton effects	Not performed
3	Blocked Stroop	Stroop and proportion effects	Not performed
4	Verbal comparison of mental effort	Chance-level	Better than chance-level
5	Verbal description of Stroop trials	Better than chance-level	Not performed
6	Verbal comparison of RTs	Better than chance-level	Not performed
7	Non verbal comparison of mental effort	Chance-level	Not performed
8	ERP Stroop	Right ACC dipole correlates with Stroop effect	Not performed
9	SCR Stroop	No SCR	SCR modulated by Stroop effect
10	SCR IAPS	Emotional SCR	Emotional SCR
11	SCR gambling task	Impaired behavior, reward SCR without anticipation SCR	Not performed

$p < 10\text{E}{-4}$; effect size = 120 ms: 707 ms on congruent trials versus 827 ms on incongruent trials). The Stroop effect was also present on error rates: patient RMB committed nine errors on a total number of 320 trials, only on incongruent trials.

Given that executive attention may show dissociable patterns according to the response modality (Turken & Swick, 1999), we replicated this task using a voice-key to record vocal naming responses (Experiment 2). We observed the very same pattern of results: analysis of correct trials showed the classical Stroop effect ($F(1, 295) = 43.52$; $p < 10\text{E}{-4}$; effect size = 120 ms: 790 ms on congruent trials versus 910 ms on incongruent trials). The Stroop effect was also present on error rates: patient RMB committed three errors on a total number of 320 trials, only on incongruent trials.

We could further investigate patient RMB performance in the Stroop task by directly comparing it to the performance of comparison subjects tested in Experiment 9, in which subjects had to respond manually as in Experiment 1, while we recorded their behavioral responses and their SCRs. Again, patient RMB showed a Stroop effect on RT analysis (314 trials, $p < 10\text{E}{-4}$, effect size = 129 ms: 699 ms on congruent trials versus 828 ms on incongruent trials), and on error rates (six errors on incongruent trials, none on congruent trials). Compared to the group of 10 normal subjects, her performance was slowed (global RT beyond 2 standard deviations of the group), but the size of her Stroop effect calculated as an RT ratio ([Icg–Cg]/Cg) felt within one standard deviation of the distribution of normals (0.18 versus a mean of 0.09, ranging from 0.01 to 0.28 individual values).

Taken together, these results reveal a preserved executive attention recruitment as indexed by the Stroop task.

3.1.2. *Dynamic modulation of control: Gratton and proportion effects*

Many authors have used the Stroop task, or similar interference paradigms such as the flanker paradigm, in order to investigate the dynamic modulation of these interference effects. This modulation is reflected in particular in the Gratton effect, which consists in an interaction between the congruities of the previous and current trial-types. Following an incompatible trial, performance becomes faster on incompatible trials but slower on compatible ones, reflecting the transition to a more controlled process (Gratton, Coles et al., 1992). Another classical way of modulating executive attention consists in using different blocks of trials in which the proportion of incongruent trials is varied. From a theoretical perspective, these dynamic effects may receive different interpretations based either on genuine conflict-monitoring (Botvinick, Braver et al., 2001; Kerns, Cohen et al., 2004), or alternatively on executive control by-passing in some trials via episodic memory for the previous trial (Mayr, Awh et al., 2003). Whether these dynamic effects reflect the dynamic of executive attention recruitment or not, they provide a simple way to estimate trial-to-trial flexibility in executive control regulation.

3.2. *Gratton and proportion effects*

Experiments 1 (manual response) and 2 (vocal response) were also designed to test the Gratton effect in our patient. In both experiments, this effect was reliably found.

In Experiment 1, while no main effect of the preceding trial Stroop congruity (congruent versus incongruent) was observed ($F(1, 299) = 0.63$, $p = 0.43$), the crucial interaction between the current trial Stroop congruity and the preceding trial Stroop congruity was highly significant (see Fig. 2; $F(1, 299) = 11.58$, $p = 0.0008$). Restricted contrasts showed a strong Stroop effect for trials occurring immediately after a congruent trial (size effect = 176 ms, $F(1, 148) = 45.78$, $p < 10\text{E}{-4}$), while a marginal Stroop effect was observed on trials following an incongruent trial (size effect = 53 ms, $F(1, 151) = 3.57$, $p = 0.06$).

Paralleling those results, no main effect of preceding trial Stroop status (congruent versus incongruent) was observed in Experiment 2 ($F(1, 295) = 0.54$, $p = 0.46$), while the crucial interaction between current trial Stroop status and preceding trial Stroop status was found significant ($F(1, 295) = 7.99$, $p = 0.005$). Restricted contrasts showed a strong Stroop effect for trials occurring immediately after a congruent trial (size effect = 172 ms, $F(1, 148) = 61.08$, $p < 10\text{E}{-4}$), while this effect was smaller on trials following an incongruent trial (size effect = 69 ms, $F(1, 147) = 5.57$, $p = 0.02$).

We also engaged patient RMB in a block version of this Stroop task in which the proportion of incongruent trials was

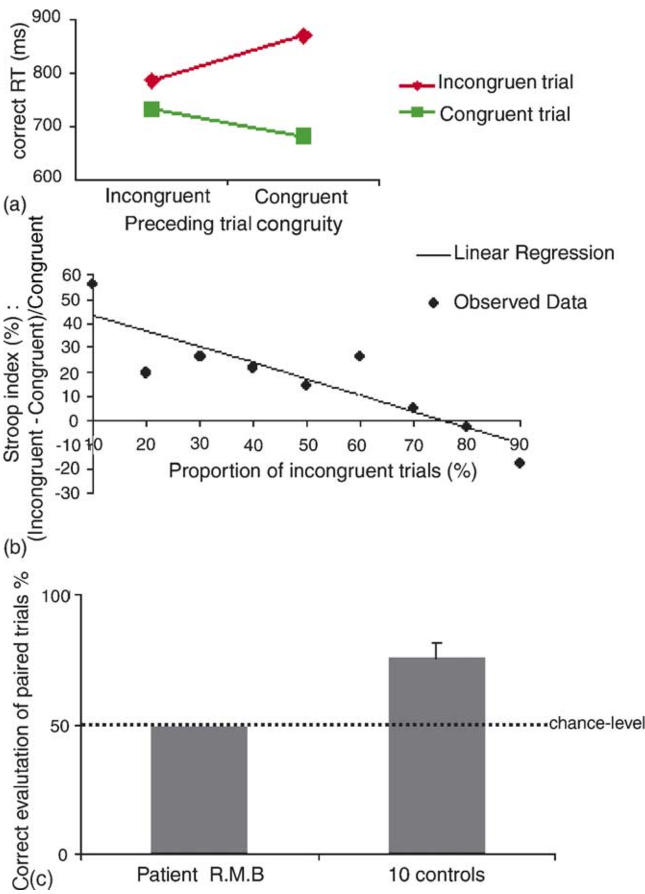

Fig. 2. Behavioral measures of preserved executive control without associated feeling of conscious effort. (a) Mean response times of patient RMB as a function of conflict in trial *n* and in trial *n*–1 in a simplified Stroop task with 50% incongruent trials (Experiment 1), demonstrating fast trial-to-trial modulation of executive attention (Gratton effect). (b) Stroop index of patient RMB in a block version of the same Stroop task using 10 random blocks of trials, demonstrating adequate modulation of executive attention with the proportion of incongruent trials (varying from 10 up to 90% of trials, see Experiment 3). (c) Self-evaluation of mental effort was assessed though a forced-choice task on pairs of trials identical to the ones used in Experiment 1. Immediately after having performed the Stroop task on a given pair, patient RMB and 10 comparison subjects indicated which of the two trials felt more difficult to them. Subjective evaluation was classified as correct when RT of the subjectively "harder" trial was larger than RT of the subjectively "easier" trial.

randomly varied from 10 to 90% (Experiment 3) (Carter, Macdonald et al., 2000). In normal subjects, the amount of interference has been shown to decrease when the percentage of incongruent trials increases. The main effect of Stroop across the nine randomized blocks was highly significant ($F(8, 336) = 23.26$, $p < 10E{-}4$), while the main effect of incongruent trials probability was marginal ($F(8, 336) = 1.67$, $p = 0.11$). Crucially, the interaction between these two factors was highly significant ($F(8, 336) = 3.39$, $p = 0.0009$). As can be seen on Fig. 2, this interaction reflected a negative linear relation between the Stroop effect indexed by a ratio ($100 \times$ [incongruent – congruent]/congruent) and incongruent trial probability factor, as in normals. We confirmed the statistical significance of this linear relation ($F(1, 7) = 22.50$, $p = 0.002$, regression equation: %Stroop = 49–0.66.%Icg). Further restricted contrasts revealed that while the Stroop effect was significant within each block of trials from 10 to 60% of incongruent trials ($p < 0.05$), this effect vanished in blocks with high-probability of incongruent trials (70, 80 and 90%). Finally, she committed only four errors throughout the experiment. These errors only occurred in the 10, 20, 30 and 50% blocks.

Taken together, these four experiments reveal preserved control abilities in this patient, indexed by Stroop effects and by significant dynamic modulations of this Stroop effect, as described in normals. Only a mild global slowing of RTs was observed.

3.2.1. Evaluation of conscious feeling of mental effort

In contrast, however, patient RMB was totally unable to estimate and report normally associated co-variations of mental effort (Experiment 4). Each of the ten comparison subjects tested was able to report which of two successive trials was the more difficult: the subjects' introspective judgments corresponded to the difference in response time in 67–85% of trials (chance-level = 50%; see Fig. 2). However, patient RMB performed at chance-level in this forced-choice verbal task (50% correct). This deficit could not be simply explained by an episodic memory impairment given that when asked to recall the congruity of the stimulus presented on the preceding trial, she performed much better than chance-level (Experiment 5; 82% correct responses, $p < 0.0001$ in χ^2 test). Interestingly, she understood the task. For instance, upon encountering an incongruent trial after a congruent one with a RT difference superior to 400 ms, she told us: "Yes, this one was a tricky trial, with ink opposite to the word, thus it should be more difficult to me, however I do not feel any sensation of difficulty here". Additionally, patient RMB readily identified her three errors in the Stroop task. In order to better assess her cognitive monitoring of her own performances in this task, we asked her (Experiment 6) in a similar block of pairs of trials, which one had requested her the largest amount of time to respond. Again, she performed much more better than chance-level in this forced-choice task (75%, $p < 0.001$). Thus, cognitive monitoring of performance seemed intact, but the associated feeling of conscious effort was lost.

Given that the left anterior section of corpus callosum was lesioned (see Fig. 1), one may suppose that this deficit in mental effort verbalization corresponds to a partial interhemispheric disconnection sometimes observed in anterior "split-brain" patients (Gazzaniga, LeDoux et al., 1977). However, neurological examination did not reveal any disconnection signs, and in a replication of our task using non-verbal left-hand responses to both the Stroop task and the subsequent report of mental effort, patient RMB still performed at chance-level in estimating trial-by-trial changes in difficulty (Experiment 7, 50% correct).

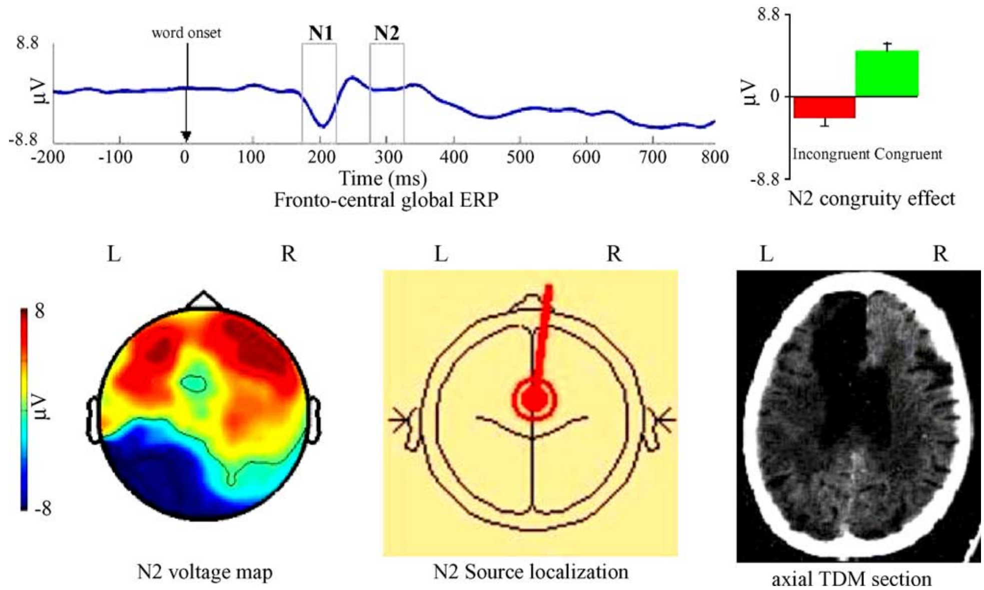

Fig. 3. ERP experiment. (a) Stimulus-locked grand-averaged ERP of patient RMB in the Stroop task, at the fronto-central electrode Fz. (b) N2 amplitude averaged across a temporal window (288–326 ms after word onset), and across four contiguous fronto-central electrodes revealed a significant congruity effect ($p = 0.04$). (c) Interpolated voltage map of N2 event at 326 ms after word onset. (d) A single dipole located at the putative right ACC coordinates in BESA coordinate system ($+0.03 \pm 0.2 \pm 0.05$) previously estimated by Van Veen and Carter (2002) accounted for 75% of N2 component variance isolated by subtracting congruent trials from incongruent trials. (e) Axial TDM section of patient RMB's brain.

3.3. ERP correlates of the Stroop effect

On the basis of this behavioral dissociation between preserved control and altered conscious report of mental effort, we then asked if patient RMB's residual ACC subtended her effective mental control. fMRI investigation was precluded by a neuro-surgical implantation of a metallic clip to occlude the arterial aneurysm responsible of the hemorrhage. We therefore replicated one of our Stroop experiments while recording event-related potentials. Based on a recent ERP investigation of a Stroop like interference effect (Van Veen & Carter (2002)), we focused the analysis on the N2 effect recorded on electrodes close to ACC. Behavioral results replicated again the main effect of Stroop (mean incongruent RT 835 ms, mean congruent RT 700 ms, size effect = 135 ms, $p < 10\text{E}{-4}$), and the Gratton effect (interaction $p < 0.001$).

Inspection of the grand averaged ERPs revealed a flat activity up to 176 ms after stimulus onset where a first negativity occurred (N1), followed at 288 ms after stimulus onset by a second negativity (N2). As in the study by Van Veen and Carter (2002), the N2 showed a congruity effect in the predicted direction ($F(1, 189) = 2.60$, $p = 0.05$ unilateral t-test, N2 more negative on incongruent than on congruent trials). Moreover, N2 was significantly more negative on incongruent trials following congruent trials than on incongruent trials following incongruent trials ($p = 0.04$), paralleling the response times. The topography of this N2 effect was examined by substracting ERPs from incongruent–incongruent trials and from congruent–incongruent trial. A single dipole located in the right ACC (coordinates symmetrical on the x-axis to those found by Van Veen and Carter (2002): $+0.03 + 0.20 + 0.5$ accounted for 75% of the variance, see Fig. 3).

In spite of the rough spatial resolution inherent to dipole fitting, these results are suggestive of a correlation between patient RMBs preserved executive attention ability and residual right ACCs activity.

3.4. SCR correlates of the Stroop effect

We then explored the somatic markers usually associated with feelings of mental effort, within the context of the Stroop task. Whenever a normal subject experiences mental effort, his body is the field of various detectable reactions affecting heart rate, blood pressure, breathing rate, pupillary diameter or SCR (Andreassi, 2000). Clinical neuropsychology and brain-imaging studies converge to attribute a crucial role to mesio-frontal structures, including the ACC, in the generation of these somatic signals (Tranel & Damasio 1994; Critchley, Mathias et al., 2003). On these grounds, we hypothesized that the absence of any conscious feeling of mental effort in patient RMB could be related to an inappropriate generation of those somatic signals, the patient's lesion affecting mesio-frontal cortical systems essential for the coupling of bodily reactions to a cognitive evaluation of the current task. We therefore predicted anomalies in somatic markers such as the skin conductance response recorded during Stroop task performance. This prediction was confirmed in a last replication of the Stroop task, in which trial duration was increased in order to record the slow temporal dynamics of SCRs (Experiment 9).

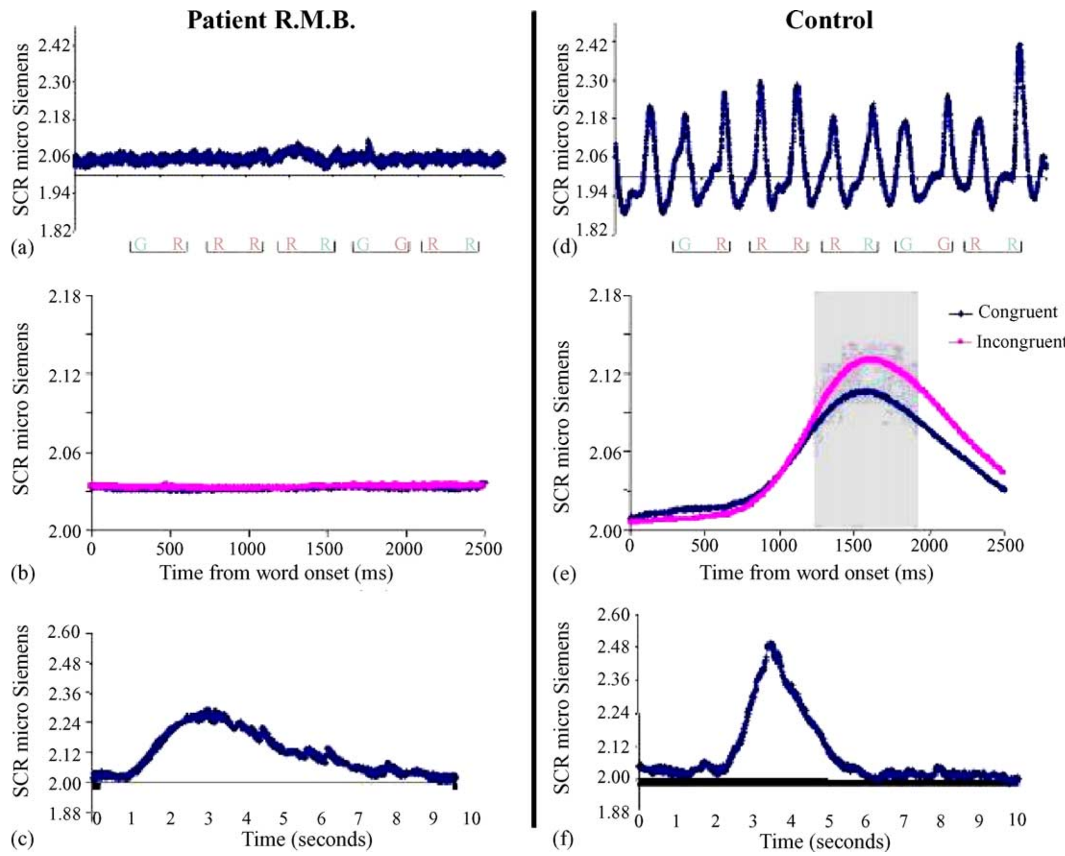

Fig. 4. Skin conductance response data. Panels a and d show the raw SCR signal (expressed in microSiemens) recorded during 10 consecutive trials of the Stroop experiment (G = word "green", R = word "red", letter color corresponds to word ink), for patient RMB (a), and for one of the 10 controls (d). Panels b and e show the stimulus-locked averaged SCR signal of congruent (blue curves) and incongruent (pink curves) trials for patient RMB (b), and for the 10 normal subjects averaged together (e). The shaded area in (e) corresponds to a minimum of 50 consecutive samples showing a significant difference between congruent and incongruent trials ($p < 0.05$ in a two-tailed *t*-test). Panels c and f show the normal SCR recorded after presentation of an erotic picture in patient RMB (c) and in 1 of the 10 comparison subjects (f).

Patient RMB again showed behavioral evidence of Stroop interference and the Gratton effect, but no variation of SCR could be visually observed on a trial–trial basis. Averaged SCRs were flat and did not show any significant difference between congruent and incongruent trials (see Fig. 4). In sharp contrast, the study of 10 comparison subjects revealed an event-related SCR visible on a trial–trial basis in every normal subject (see Fig. 4). Moreover, SCR amplitude correlated with the engagement of executive attention. Specifically, averaged SCRs were significantly more intense after an incongruent trial than after a congruent trial. This tight coupling between cognitive difficulty and somatic response was simply absent in patient RMB Importantly, patient RMB remained able to generate large SCRs and to report feelings of emotion at a level comparable to normal subjects when presented with emotional pictures taken from the IAPS battery (Experiment 10). This demonstrated a normal ability to express externally generated emotions and associated feelings in patient RMB, suggesting that the deficit is restricted to situations in which such feelings are generated internally from an "auto-evaluation" of cognitive difficulty (Dehaene & Changeux, 1991).

3.4.1. *Patient RMB behavior and SCRs in the Iowa gambling task*

Finally, we tested this patient on the Iowa gambling task elaborated by Damasio and Bechara (Bechara, Damasio et al., 2000), to look for an intra-subject dissociation between some cognitive processes—such as the Stroop task—found to be relatively independent from somatic markers, and some other cognitive processes such as decision-making previously found to depend on the integrity of the somatic markers. We followed the methodology and instructions developed by Bechara and colleagues, and set the inter-trial interval at 6 s (Experiment 11). Briefly, patient RMB was presented with four 4 decks of cards (ABCD). On each trial, she was asked to select one card from any deck she wanted. She was were told that each time she selected a card, the computer would tell her that she won some money. Sometimes, the computer would tell her that she won some money, but also that she lost some money. She was not told ahead of time how much money she would win or lose as she selected from each deck. She was instructed that she was completely free to switch from one deck to another at any time, and as often as they wished. Her goal in the game was to win as much money as possible. Two of the decks were disadvantageous (decks A and B) in the long run, because although they brought higher gain in the short run, the delayed loss was even larger, so that they yielded a higher loss in the long run. The other two decks were advantageous (decks C and D) in the long run, because although they brought lower gain in the short run, the delayed loss was lower, so that they yielded higher gain in the long run. In this task, normal subjects progressively identify advantageous decks and preferentially select cards from them. Patient RMB behave as typical 'ventro-medial' patients, being unable to progressively distinguish good decks from bad decks. Indeed from the first block of 20 trials to the fifth one, she equally picked cards from advantageous and disadvantageous decks (see Fig. 5a). Interestingly, on two occasions after picking a card from a bad desk (trials # 44 and 70, loosing US$ 1500 and 1750, respectively) she spontaneously said "I know I should not pick up cards from this deck". At then end of the experiment, we asked her whether she noticed any difference between the four desks. She surprisingly answered "Yes, A and B are bad desks. I should not have select cards from them". Asking her why she nevertheless picked up cards from these desks all along the experiment, she smiled and said "Because, you never know". During this experiment, SCRs were recorded and processed using the same method as for the Stroop experiment. As described in both normal subjects and 'ventro-medial' patients, she displayed significant positive and negative reward during the 5 s interval following card selection (both see Fig. 5b). In particular, *t*-tests comparing the activation window (SCR signal averaged from 2500 to 3500 ms after response selection) and the baseline window (SCR signal averaged from 0 to 1000 ms after response selection) revealed highly significant reward SCRs both for positive and negative rewards (both p's $< 10^{-4}$). However and most importantly, no SCR anticipation could be observed during the 5 s interval before disadvantageous desks card selection (see Fig. 5c). When comparing the 5 s anticipatory period of the SCR signal between good and bad decks card selection, we could not observe any significant difference ($p = 0.37$ in a *t*-test). This last result reproduces earlier findings in patients with similar ventro-mesial frontal cortex lesions (Bechara, Damasio et al., 2000; Bechara, Tranel et al., 2000).

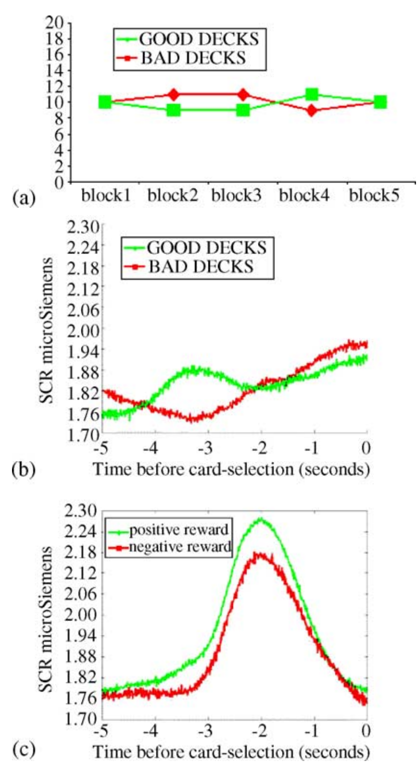

Fig. 5. Behavior and SCR data of patient RMB in the Iowa gambling task. (a) Behavior: number of cards picked by patient RMB from advantageous (green curve) and disadvantageous (red curve) decks in each of the five successive sets of 20 trials. From the first to the fifth blocks she picked equally from both types of decks. (b) Anticipation SCR: SCR signal (expressed in microSiemens) recorded during the 5 s preceding card selection did not show any significant difference between cards to be picked from advantageous (green curve) and disadvantageous decks (red curve), as tested by paired *t*-tests. (c) Reward SCR: SCR signal recorded during the 5 s following card selection revealed a major reward signal, both on positive (green curve) and negative (red curve) rewards. These responses were found highly significant when compared to respective baseline levels (see text).

4. Discussion

Our behavioral and neurophysiological investigation of patient RMB revealed a novel dissociation between preserved conscious executive control, reflected in normal behavioral performance—including verbal and non-verbal reports of task monitoring—and residual ACC activity, and absence of any associated subjective feeling of mental effort. This lack of consciousness of mental effort coincided with a lack of bodily-mediated physiological responses indexing mental effort in healthy subjects. We verified that neither the patient's minor memory impairment, nor her partial anterior callosal split could offer an alternative interpretation to our results. In particular we checked that in spite of impaired feeling of mental effort, she could well estimate her own RTs and even describe objective trial difficulty. This qualifies the hypothesis that in such a task subjective reports could be solely driven by the allocation of executive attention per se, or by the post hoc realization that some trials take longer than others, or by subjects' awareness of why some trials should be easier than others. Moreover, patient RMB is not affected by a general inability to generate bodily markers, and to consciously experience emotional feelings, as demonstrated in our control experiment using affective pictures. The singularity of the dissociation seems to lie in an inability to translate actual periods of mental effort—as occurs during executive attention recruitment—into physiological emotional signals and eventually into a conscious feeling of having made a mental effort.

We tentatively suggest that the lesion prevented the residual activity of the right ACC, which still varied with the requirements for executive attention, from signaling internal changes in executive recruitment to the left ventro-mesial prefrontal regions known to be involved in the generation of emotional somatic markers. Our disconnection hypothesis suggests that a purely cognitive evaluation of the current internal level of interference or conflict may be sufficient to increase or decrease the level of control in a given task. Under this view, the feeling of conscious effort would be a by-product of executive attention, but would not play a causal role in its deployment. This is in sharp contrast with more intuitive conceptions attributing a causal role to mental effort in executive attention regulation. Indeed, given that voluntary executive attention is normally associated with a subjective feeling of mental effort proportional to the intensity of the attentional engagement (Dehaene, Kerszberg et al., 1998), one may tentatively consider that the role of mental effort is to signal when executive attention needs to be deployed because our cognitive resources are close to being depleted. Under this view, executive control would increase after one becomes conscious of the need for mental effort. By discarding such hypotheses, this case offers insights to self-consciousness parcellation. Our results suggest that the conscious appraisal of one's own mental work, a key element of self-consciousness, may result from a surprisingly indirect series of computations that can be selectively impaired, rather than from a direct introspective access to the inner workings of the central executive. This patient was clearly conscious of many if not all aspects of cognitive control, including task monitoring, error detection, objective description of trial complexity, while having lost conscious appraisal of feeling of mental effort. Just like perceptual awareness is dissociable into many subcomponents of color, shape or movement, self-consciousness may also consist in a mosaic of dissociable subsystems. In particular, consciousness of one's own mental efforts may dissociate from other self-representation systems such as the body schema and the autobiographic memory system, which appeared to be intact in our patient.

From an anatomical perspective, the fact that patient RMB' lesion affected mostly the left anterior ACC fits with the functional distinction of ACC in anterior affective and posterior cognitive divisions (Bush, Luu et al., 2000). Additionally, our data would support a functional distinction between the left and right ACC. Patient RMB' right cognitive and affective ACC divisions were intact, and active in the ERP experiment, but they were apparently insufficient to implement a normal cognitive-emotional coupling. This hypothesis is supported by a recent study by Markela-Lerenc, Ille et al. (2004) investigating the Stroop effect in normal subject using high resolution ERPs. They reported a strong effect of stimulus congruity, the generator of which was located in the right ACC according to dipole source modeling. This contrasts with a recent group study suggesting an opposite lateralization for social, decision-making and emotional functioning (Tranel, Bechara et al., 2002). This apparent discrepancy, however, merely underlines the importance of investigating hemispheric specialization of cognitive-emotional coupling in a wider number of patients and through a variety of tasks.

Finally, this case study calls for a discussion of the "somatic marker hypothesis" formulated by Bechara, Damasio et al. (2000) in the related field of cognitive neuroscience of feelings and emotions. Mental effort is not usually considered as an emotional feeling, yet it belongs to the wider class of feelings defined as the conscious appraisal of one's own state (Damasio, 1999). Four aspects of our results fit with this hypothesis. First, in accordance with this theory, we observed a tight relation between SCR variations and conscious mental effort in normal subjects. Second, in the absence of such SCR variations in patient RMB during the Stroop task, no conscious mental effort could be reported by the patient, verbally or not. Third, when presented with emotional pictures, patient RMB did show SCR variations and did report conscious emotional feelings. Finally, she performed as 'medio-ventral' patients described by Damasio and colleagues in the Iowa gambling task: she was unable to progressively select advantageous decks of cards, and she lacked any SCR anticipation signaling the intention to select a disadvantageous deck, while reward signals were still present. These observations support the central role of this bodily-mediated system in the conscious appraisal of emotions and mental effort.

However, our study also qualifies the idea that cognitive decision making systematically depends on a correct appraisal of one's own feelings, by revealing an experimental situation in which cognition and mental effort are dissociated. This dissociation clearly demonstrates that the co-occurrence of these two processes in normal subjects does not mean that the former always depends upon the latter, as proposed by Damasio and colleagues for some decision-making processes. In that respect, our results contrast with previous results demonstrating that decision making, for instance in gambling situations (Bechara, Damasio et al., 1994; Bechara, Tranel et al., 1996), depends on the integrity of the bodily-mediated system. The confrontation of those results raises several fundamental questions. Will the dissociation between executive control and mental effort generalize to other top-down controlled processes? More generally, which cognitive processes depend on this somatic marker signaling system, and which do not? These questions illustrate the complexity of cognitive-emotional interactions which have been previously found to manifest very different properties such as reciprocal inhibition (Drevets & Raichle, 1998) and emotional gating (Pochon, Levy et al., 2002). It should be stressed that if patient RMB did not suffer from executive control difficulties in the simple laboratory tasks that we investigated here, she definitely exhibits executive dysfunction when engaged in more complex situations, such as problem solving or dual task performance.

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