Available online at www.sciencedirect.com
SCIENCE DIRECT
Brain Research Protocols 11 (2003) 27–37
BRAIN RESEARCH PROTOCOLS
www.elsevier.com/locate/brainresprot

Protocol

The Madrid card sorting test (MCST): a task switching paradigm to study executive attention with event-related potentials

Francisco Barceló*

Department of Psychology, University of the Balearic Islands, Ctra. Valldemossa km 7.5, 07071 Palma de Mallorca, Spain

Accepted 9 January 2003

Abstract

Event-related potentials (ERPs) provide valuable information about the fast brain dynamics subserving cognitive functions such as attention and working memory. Most ERP studies employ cognitive paradigms with a fixed task-set (i.e., press a button to coloured targets), but few have measured ERPs time-locked to shifts in set using a task-switching paradigm. The Madrid card sorting test (MCST) is a dual task protocol in which feedback cues signal unpredictable shifts in set (i.e., from 'sort cards by colour' to 'sort cards by shape'). This protocol allows for an integrated analysis of ERPs to both feedback cues and target card events, providing separate ERP features for the shifting, updating, and rehearsal of attention sets in working memory. Two of these ERP indices are the frontal and posterior aspects of the P300 response. Feedback cues that direct a shift in set also elicit a frontally distributed P3a potential (300–400 ms). Instead, target card events evoke increasingly larger posterior P3b (350–600 ms) activity as the new task set becomes gradually rehearsed. The observed modulations in the frontal and posterior aspects of the P300 response system are interpreted from current models of prefrontal cortex function in the executive control of attention.

Theme: Neural basis of behaviour

Topic: Cognition

Keywords: Cognitive set; Event related potentials; Orienting response; P300; Prefrontal cortex; Task-switching; Wisconsin card sorting test; Working memory

1. Type of research

Scalp-recorded event-related potentials (ERPs) have been extensively and successfully employed as a method to explore the fast brain dynamics underlying attention and working memory processes in humans [20,21,38]. The main advantages of the ERP technique for studying human cognition are (a) its ability to provide a continuous measure of cerebral information processing even in the absence of an overt motor response; (b) its privileged temporal resolution down to the millisecond to tease apart successive stages of cognitive processing; (c) its suitability for exploring the neural substrates of different attention mechanisms across different task conditions; and (d) its reduced costs and noninvasiveness that makes it a rather popular technique in both research and clinical contexts [35,38]. Up to date, however, most ERP protocols have been designed to measure brain activity under fixed task-set conditions (i.e., 'press a button to named targets'). In these paradigms, task instructions declare a set of stimulus properties that define the class of target stimuli that the subject should search for, attend to, or respond to. When a stimulus does not match this set of relevant target properties, it is regarded as a task-irrelevant stimulus, or a distractor [20,21,33]. One classic example of this type of ERP protocol is the so-called 'oddball' target detection paradigm, where the subject searches for one target stimulus and ignores all other distractors. In oddball-type tasks, target events evoke a distinct long latency positive potential (350–600 ms; P3b) maximal over mid-parietal scalp [16,20]. The P3b endogenous potential has been proposed to reflect task-relevant processes such as context updating [13–15], or closure of the event-encoding cycle

*Tel.: +34-97-117-2750; fax.: +34-97-117-3190.
E-mail address: f.barcelo@uib.es (F. Barceló).

1385-299X/03/$ – see front matter
doi:10.1016/S1385-299X(03)00013-8

in working memory [44,47,48]. An earlier positive potential (300–400 ms; P3a) has been proposed to reflect attention switching to task-irrelevant, non-target novel distractors [16,41]. Human lesion, brain imaging, and intracranial studies suggest anatomically and functionally distinct neural sources for the attention set shifting (P3a) and updating (P3b) mechanisms [16,18,23,44].

As mentioned before, however, most of the existing ERP evidence on attention has been gathered under fixed task-set conditions (i.e., 'press a button to named targets'). Indeed, even if the task-set (i.e., the task's rules) changes across successive blocks of trials, ERPs are not normally recorded while the task's rules are being changed. Instead, subjects perform each successive block of trials separately, and even go through a short practice session with the new task-set before the actual ERP recording begins. Under such settings, the frontal (P3a) and posterior (P3b) aspects of the P300 response system are portrayed as two independent indices of attention processing: the former related to bottom-up, exogenous, or involuntary processing of novel non-target distractors; the latter related to top-down, endogenous, or voluntary processing of target events [16,20,21,33]. It should be noted that ERP protocols with a fixed task-set favour a biased interpretation of any attention switches away from the ongoing task-set as involuntarily or exogenously generated by the non-target events. In turn, dual-task or task-switching paradigms could be used to explore ERPs to non-target events that signal a voluntary attention shift to a new task set (i.e., from 'sort by colour' to 'sort by shape'). Remarkably, ERPs have not been normally recorded in dual-task paradigms, nor have been time-locked to the actual shift in the attention set [5,8,11,25]. Only a minority of studies have attempted to describe the brain electrophysiology underlying shifting and updating of attention sets in working memory [5,8,9,26,39]. For the sake of clarity, the term 'task switching' is used to refer to the experimental protocols in which the task changes from trial to trial. In turn, the term 'attention set-shifting' ('set-shifting', for short) is used to denote the putative mental operations involved in task switching (and which may or may not occur at appropriate trials in the task switching protocol) [40].

In the last few years we have developed a task-switching paradigm, the Madrid card sorting test (MCST), inspired by a classic test of prefrontal impairment, the Wisconsin card sorting test (WCST) [19,28,30], to study the fast electrophysiological dynamics related to attention set-shifting [3–11,34]. Initially, we found a gradual modulation of P3b amplitudes across 'shift' and non-shift ('stay') trials time-locked to target card stimuli, but no clear evidence of a frontally distributed ERP activation [8,10]. Subsequent analyses revealed that the actual shift in set takes place at the feedback stage of task performance, when a non-target 'shift' feedback cue instructs the subject to adopt a new rule for the task at hand. In turn, at the card-matching stage the task-set is merely implemented or rehearsed [27,33,36,37]. This led one to a more comprehensive ERP analysis of both contextual processes time-locked to feedback events, and target-related processes time-locked to the card-matching stage of task performance. This novel methodological approach showed that task-switching consists of several cognitive processes, as reflected by a number of ERP components, the most conspicuous of which is the endogenous P300 response [5,9]. Therefore, the MCST task-switching protocol represents a new and promising tool for examining the putative relationship between attention set-shifting and the frontal (P3a) and posterior (P3b) components of the P300 response system. The MCST protocol also allows us to examine modulations in P300 activity during implementation and rehearsal of task-sets at the card-matching stage [8]. The interpretation of observed modulations in the frontal P3a and posterior P3b aspects of the P300 response system in terms of attention set shifting processes may benefit from the solid theoretical grounds yielded by current models about the role of prefrontal cortex in the executive control of attention [22,28,29,33].

2. Time required

The time for data collection typically takes about 1 h for each subject, and depends on two procedural stages. (a) Behavioural procedures: the basic MCST paradigm described here consists of 137 trials arranged into 18 series (Fig. 1a), and can be performed in less than 15 min by the average young healthy subject, who can sort cards rapidly and accurately [8]. For ageing or clinical samples this basic MCST paradigm might take 2–8 min longer to complete [7]. Another 10 min should be allowed for a block of practice trials to warrant that task instructions have been fully understood, and subjects can at least sort cards on command. (b) Electrophysiological procedures: around 30 min are required for electrode placement and impedance testing when using an EEG set-up with 32 channels (ca. 1 min per EEG channel). In order to improve the signal-to-noise ratio in the ERP averages (i.e., from 18 to 36 sweeps per ERP average), one might want to administer a second task block after a 5-min rest period. The time requirements for behavioural and ERP data analysis can be less than 1 h per subject when using appropriate macros and batch files for the analyses.

3. Materials

3.1. Stimuli

The MCST is a simplified computer version of the WCST with special features for ERP research [7,8,34]. The MCST stimulus battery uses the 24 cards of the original 64

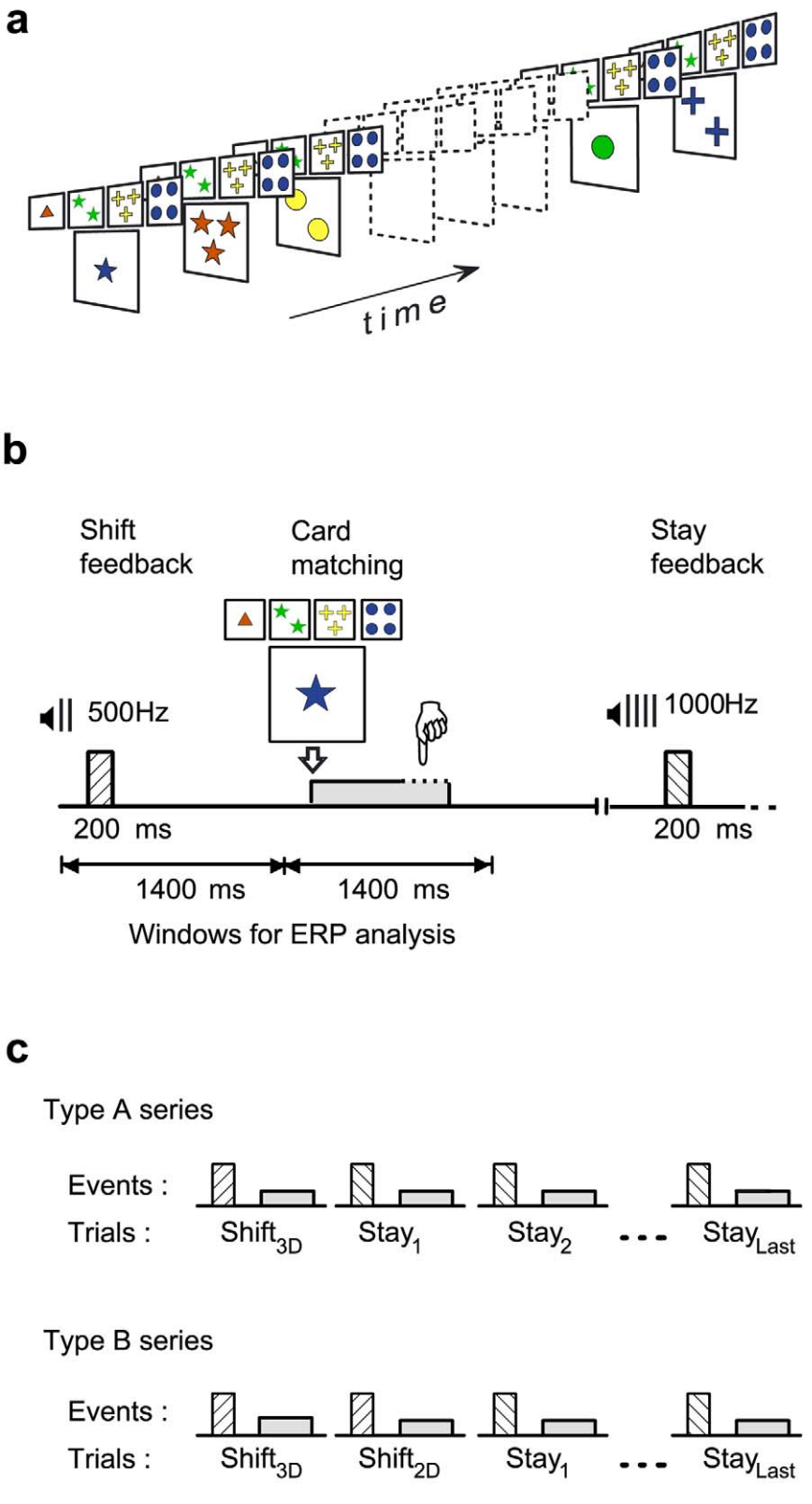

Fig. 1. Task design and ERP trial analysis. (a) Schematic example of one MCST series. Note that each choice-card can be unambiguously matched with each key-card based on just one stimulus dimension. (b) Feedback stage: A 'shift' feedback tone cued subjects to shift the task rule (sound frequency 500 Hz). A 'stay' feedback tone cued subjects to use the same rule again (sound frequency 1000 Hz). Card-matching stage: The choice-card remained on display until a response was given. (c) Trial analysis based on the subject's responses. In the first trial of a series ($shift_{3D}$ trial), subjects inhibited the old rule and adopted one of the remaining two for responding. In type B series, subjects had to shift set twice to find the correct rule ($shift_{2D}$ trials). In the first stay trial ($stay_1$) the subject repeated his previous choice of rule. The last stay trial of a series ($stay_{Last}$) was preceded by another three to five stay trials.

WCST cards that can be matched unambiguously with the four key cards based on just one stimulus dimension (i.e., either colour, shape, or number of items in the card; see Fig. 1). Unambiguous cards are required for both a sensitive scoring of sorting errors and set-shifting ability [7]. These 24 choice-cards were repeatedly used in 137 trials semi-randomly arranged into 18 series (Fig. 1a). The correct sorting rule was initially unknown to the subject, and changed randomly from one series to the next (see Task instructions and procedure). The stimuli were prepared with the Draw module of the STIM package (NeuroScan Inc.), but could also be designed in BMD, TIF or JPG format with any other graphic package with at least 256 colours and a resolution of 40 pixels/cm. Each task trial began with the display of a compound stimulus with the four key-cards on top of one choice-card, all centred in the middle of a computer monitor (NEC MultiSync, 1024×768 pixels resolution; Fig. 1b). The cards subtended a visual angle of 4° horizontally and 3.5° vertically at a distance of 1.5 m from the computer screen. Smaller stimuli do not really minimise eye movement artefacts in the EEG recordings, and may interfere with reduced visual acuity of some elderly or neurological patients. The coloured geometrical shapes were outlined in black upon a white background to improve visual contrast. Card stimuli were displayed upon a dark screen background. The luminance of the cards area (85 cd/m^2) and the background luminance (10 cd/m^2) were held constant throughout the experiment. The stimulus sequence was controlled with the Gentask module of the STIM package (NeuroScan Inc.), but has also been implemented using other stimulus delivery software such as MEL v1.0 (Psychology Software Tools Inc.) and Presentation v0.50 (Neurobehavioral Systems Inc.) [6–9,34]. Stimulus delivery and task performance were monitored and stored in an IBM compatible personal computer (Pentium 200 MMX processor, 128 MB RAM, 8 GB hard disk).

3.2. EEG equipment

Electroencephalogram (EEGs) were recorded, amplified, and analysed using a set of SYNAMP amplifiers and SCAN v3.0 software (NeuroScan Inc.). The EEG signal was captured using an commercial cap with 32 tin electrodes, plus four tin electrodes for electrooculogram (EOG) recordings (ElectroCap International Inc). Signal acquisition and analysis was accomplished in an IBM compatible personal computer with similar specifications to the one used for stimulus delivery.

4. Detailed procedure

4.1. Human subjects

The present protocol has been implemented in both young and elderly normal subjects [7–11], as well as in neurological patients with traumatic brain injury and cerebrovascular lesions [4,6,7]. The present dataset corresponds to a sample of young highly efficient task performers. Twenty-seven right-handed subjects (15 females; mean age 23±4 years, range 18–34 years), took part in the study. They had normal or corrected-to-normal visual acuity and no history of neurological or psychiatric disorder. Experiments were carried out in accordance with the Declaration of Helsinki. Subjects filled in an informed consent form and were paid for their participation.

4.2. Electrode placement

EEGs were recorded from 29 active electrodes positioned at Fp1, Fp2, AF3, AF4, F7, F8, F3, Fz, F4, FC5, FC6, FC1, FC2, T7, T8, C3, Cz, C4, P7, P8, P3, Pz, P4, PO7, PO8, PO1, PO2, O1 and O2, in accordance to the revised 10/20 International System [1], all referenced to the left mastoid (M1). The EEG signal was also obtained from the right mastoid (M2), in order to compute a linked-mastoid reference off-line. EOGs were recorded from below versus above the orbital rim of the left eye (vertical EOG), and from the lateral orbital rim of the left versus right eyes (horizontal EOG). For further details concerning electrode placement procedures see Ref. [35].

4.3. Task instructions and procedure

Each trial began with the onset of a compound stimulus with the four MCST key-cards on top of one choice-card, all centred on a computer screen (Fig. 1a). Subjects were instructed to match the choice-card with one of the four key-cards following one of three possible rules: number, colour, or shape of items in the choice-card. Likewise, subjects were informed that the correct sorting rule would change without notice after a variable number of correct matches, and then they would have to find the new correct rule by trial-and-error. The correct sorting rule was to be determined on the basis of an auditory feedback cue delivered within a variable interval of 1500–2000 ms after the response (200 ms duration, 10 ms rise/fall times; 65 dB SPL; 1000 Hz for ‘stay’ cues, 500 Hz for ‘shift’ cues). Thus, each correct card match was followed by a ‘stay’ feedback cue prompting the subject to use the same sorting rule again. After a varying number of correct card matches, the rule changed unpredictably and the subject had to adopt a new rule upon hearing a ‘shift’ feedback cue (e.g., from shape to number, or to colour). Subjects used their thumbs for responding while holding a panel with four key-buttons aligned. The far left button designated the key-card on the far left of the display, the far right button designated the key-card on the far right, and so on. The card stimulus remained on display until a response was given. There was a fixed time interval of 1400 ms between feedback onset and the onset of the next card. The length

of each series varied randomly between six and eight trials to avoid anticipation of a new series. Subjects performed two blocks of 137 trials each, with a 5-min rest period between blocks. The average duration of each task block was 12 min. The task was practised for about 5 min, or 5–7 series, to make sure that subjects had understood the instructions, and could sort cards efficiently (see operational criteria for efficiently completed WCST series below [7]). The sequence of trials used for practice was different from that in the main task. In sum, for our fully instructed, practised, and efficient normal subjects, a 'shift' cue was a signal to think differently and find a new answer for the same card sorting problem, whereas a 'stay' cue was a signal to give the same answer just used before.

4.4. ERP recordings

The EEG signal was amplified (band pass, 0.01–100 Hz; 12 dB/octave roll/off), digitised at 250 Hz/channel, recorded continuously for the whole duration of the task block, and stored on hard disk for off-line editing and averaging. Electrode impedances were kept below 5 kΩ. EOGs were also recorded for eye blink correction [42].

4.5. Behavioural analyses

The correct coding of behavioural events in the MCST is of paramount importance for a reliable interpretation of the ERP averages. For the present study, ERP averages were obtained from efficiently completed MCST series only. An efficiently completed MCST series was scored if all the three following conditions were met: (a) the new sorting rule was not anticipated at the beginning of a new series (i.e., the first trial in a series was a shift trial; Fig. 1c); (b) the subject shifted set efficiently and found the new rule in the second (in type A series) or third trial (in type B series, Fig. 1c); and (c) the rule was not missed thereafter [7]. Therefore, the stimulus delivery system should allow for an adaptive coding of both feedback and card events as a function of the subject's behaviour, in order to correctly sort out 'shift' from 'stay' trials in completed MCST series (see Fig. 1c). This adaptive coding of task events was achieved with the Gentask v3.0 module of the STIM package (NeuroScan Inc.), but could also be implemented with other stimulus delivery software such as MEL v1.0 (Psychology Software Tools Inc.) or Presentation v0.50 (Neurobehavioral Systems Inc.) [6,34]. A more detailed analysis of MCST errors due to inefficient set shifting can be found in Refs. [3,7].

For the purposes of behavioural and ERP analyses, trials were re-defined as consisting of both a feedback stage (i.e., starting at the onset of a feedback event), and a card-matching stage (i.e., starting at the onset of the following target card) (see Figs. 1b, c) [32,43]. Furthermore, shift trials were also classified into two different types following prior functional magnetic resonance imaging (fMRI) studies [24]. Thus, we defined three-dimensional shift trials ($shift_{3D}$) as those where subjects had to handle three rules in working memory (i.e., inhibit the previous rule and consider the other two for responding; Fig. 1c). In two-dimensional shift trials ($shift_{2D}$), only two rules were handled, after having discarded one in the previous trial. In stay trials, a 'stay' feedback cue prompted the subject to use the same task rule again. After the first shift feedback cue of a new series ($shift_{3D}$), an ideal subject has 50% chance of choosing an incorrect task rule, and so needs to shift set again ($shift_{2D}$) to achieve the correct rule. This is a very efficient trial-and-error process in normal subjects, who can use past contextual information to optimise set shifting [7]. Therefore, in efficiently completed MCST series there can be either no errors (as in type A series), or just one such efficient error (as in type B series; Fig. 1c).

4.6. Off-line ERP analyses

The continuous EEG recordings were split-up into averaging windows (epochs) of 1400 ms around both feedback and card events, including a 200-ms baseline in both cases (Fig. 1b). After applying an eye blink correction algorithm [42], trials with EEGs exceeding ±75 μV in amplitude, muscle, or any other artifacts were discarded. As mentioned before, both feedback-locked and card-locked ERPs were computed across shift and stay trials from completed MCST series only. In the present sample of young healthy subjects, overall task performance ranged between 32 and 36 successfully completed series.

Mean ERP amplitudes were measured relative to a 200-ms pre-stimulus baseline. For feedback-locked averages, mean amplitude values were computed for the P3a component (375–400 ms post-stimulus onset) and P3b (550–600 ms post-stimulus onset). For card-locked averages, only mean P3b amplitudes were measured (550–600 ms post-stimulus onset). These P300 changes may be measured from just two midline electrodes where P300 amplitudes reach a maximum. Thus, the P3a potential was measured at Fz, and the P3b potential at Pz. A more complete analysis of inter-hemispheric ERP effects related to task switching will be reported elsewhere.

4.7. Statistical design

Mean P3a amplitudes and reaction times were subjected to a main analysis of variance (ANOVA) design with Trial ($shift_{3D}$, $shift_{2D}$, $stay_1$, $stay_2$, $stay_3$, $stay_{Last}$) as the repeated measures factor. Mean P3b amplitudes were subjected to a main ANOVA design with Stage (feedback vs. card-matching) and Trial ($shift_{3D}$, $shift_{2D}$, $stay_1$, $stay_2$, $stay_3$, $stay_{Last}$) as repeated measures factors. All post-hoc tests of simple effects were performed using the Bonferroni correction with a significance level of $P<0.05$. (This design could be simplified further by averaging $shift_{3D}$ and

$shift_{2D}$ trials together, and discarding $stay_2$ and $stay_3$ trials).

5. Results

Fig. 2 presents the grand-average ERP waveforms evoked by feedback and card events from $shift_{3D}$ trials as compared to $stay_2$ (Fig. 2a) or $stay_{Last}$ (Fig. 2b) trials in the MCST series. Fig. 3 displays the mean P300 amplitudes (Fig. 3, upper panel) and behavioural task performance (Fig. 3, lower panel) across shift and stay MCST trials. It can be observed that feedback cues signalling a shift to a new task rule evoked a distinct frontally distributed P3a potential that was absent after the first stay cue ($P<0.0001$, for the main Trial effect; Figs. 2 and 3). A sharp reduction in P3a amplitude was observed in response to the first ($P<0.003$), and second stay cues ($P<0.0001$; Fig. 3), but there was no decrement in P3a amplitude from $shift_{3D}$ to $shift_{2D}$ trials ($P>0.2$; Fig. 3). In turn, $shift_{2D}$ cues evoked larger P3a potentials than $stay_1$ cues ($P<0.003$; Fig. 3). $Stay_2$ and later trials evoked similar brain responses in both type A and B series (Refs. [8,9]). Finally, P3a amplitudes to $shift_{3D}$ cues did not diminish over successive task blocks, consistent with behavioural evidence that set shifting costs do not decline with practice [36].

Feedback cues also elicited a distinct pattern of P3b activity across shift and stay trials ($P<0.0001$, for the main Trial effect; Figs. 2, 3). There was a reduction in P3b amplitude from $shift_{3D}$ to $shift_{2D}$ cues ($P<0.003$), and between $stay_1$ and $stay_2$ cues ($P<0.001$), but no P3b change was observed between $shift_{2D}$ and $stay_1$ cues (Fig. 3). Thus, unlike the P3a, the P3b response to feedback cues was sensitive both to the number of rules held in memory, and to the subject's ability to predict the next task rule. Although the P3a and P3b components have never been compared in a similar task-switching paradigm, the present results reveal a significant interaction between the type of P300 component (P3a vs. P3b) and the type of early task-set Trials ($shift_{3D}$, $shift_{2D}$, $stay_1$), suggesting their differential role in switching (P3a) and updating (P3b) of task-sets in working memory ($P<0.03$, for the cuadratic trend; see Fig. 3, upper panel).

At the card-matching stage, we observed the expected P3b response to visual targets, with a gradual P3b incre-

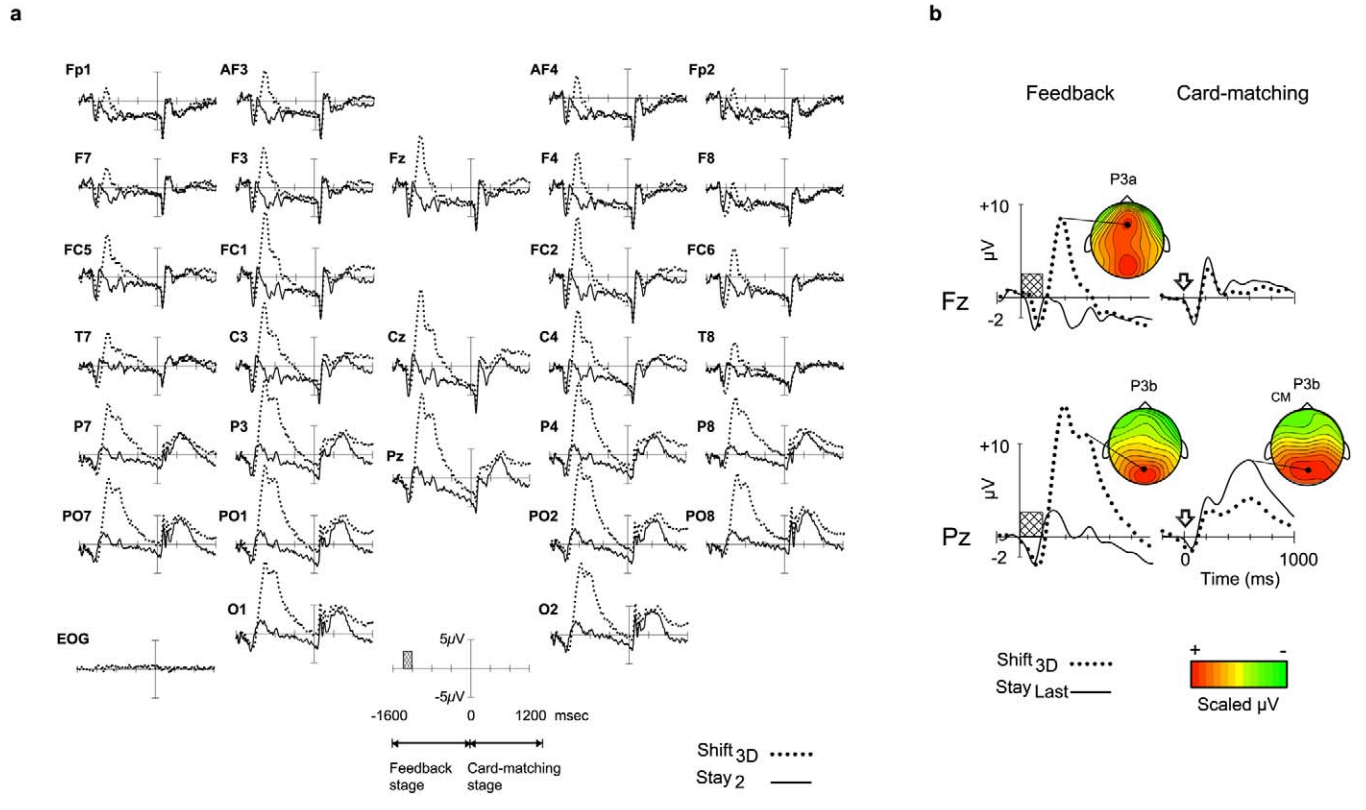

Fig. 2. ERPs to feedback and card events. (a) Grand-average ERP waveforms time-locked to feedback events from $shift_{3D}$ and $stay_2$ trials in the MCST series. Feedback-locked ERPs were measured from 29 electrodes and aligned to a 200-ms prestimulus baseline. (b) Grand-average ERPs time-locked to the onset of feedback cues (shaded rectangles) and card events (wide arrows) are displayed for $shift_{3D}$ and $stay_{Last}$ trials. Only the frontal (Fz) and parietal (Pz) midline electrodes are shown. Voltages are in microvolts (μV). Scalp potential maps are displayed for mean P3a and P3b activity evoked by $shift_{3D}$ feedback cues, and for mean P3b activity evoked by the last card-matching event in the series ($_{CM}$P3b). The colour scale is in normalised units [35].

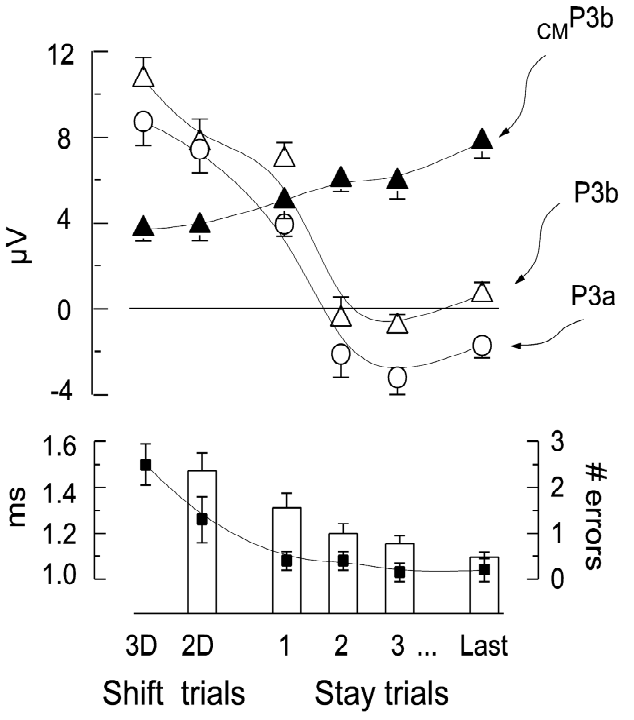

Fig. 3. ERPs and behavioural responses across shift and stay trials. Upper panel: Group-averaged mean (±S.E.M.) amplitudes in microvolts of the P3a and P3b responses plotted across shift and stay trials in the MCST series. Mean P3a and P3b amplitudes were measured from the mid-frontal (Fz) and mid-parietal (Pz) scalp regions, respectively. P3a and P3b responses were time-locked to feedback events. $_{CM}$P3b responses were time-locked to card-matching events. Lower panel: Mean (±S.E.M.) reaction times from completed MCST series (solid squares), and mean number of random of errors from failed series (bars), are plotted across shift and stay MCST trials.

ment from shift to stay trials as revealed in the main Trial effect ($P<0.0001$; Figs. 2b and 3), but no evidence of a P3a potential [8–10]. However, the pattern of P3b responding at the card-matching stage differs substantially from that observed at the feedback stage, as revealed by a significant interaction between Stage and Trial ($P<0.0001$; see Fig. 3). These results suggest that the posterior P3b response system accomplishes rather different functions during the feedback and card-matching stages of WCST performance [32,37].

The analysis of behavioural responses confirmed the well established costs in speed and accuracy related to task-set shifting [33,36,37]. Response times were slower during shift as compared to stay trials (up to ca. 500 ms; $P<0.0001$; Fig. 3, lower panel), indicating a gradual speed-up in responding from $shift_{3D}$ to $shift_{2D}$ trials ($P<0.02$), and from $shift_{2D}$ to $stay_1$ trials ($P<0.03$). The analysis of errors from failed series indicated that subjects were more likely to miss the task rule in $shift_{2D}$ ($P<0.001$) and $stay_1$ trials ($P<0.01$), as compared to the last trial in the series ($P<0.001$, for the main Trial effect; Fig. 3).

6. Discussion

The MCST protocol provides a method to study the ERP dynamics underlying the executive control of attention and, in particular, the cognitive operations of shifting, updating, and rehearsal of task-sets in working memory. This novel ERP paradigm has so far provided evidence supporting a role for the frontally distributed P3a response in the executive control of attention set shifting [5,9]. Past ERP studies of attention set shifting either focused on target events only [8,11], or failed to link the observed P3a-like activation to task switching [25]. In our modified version of the WCST, feedback events that directed a shift in the subject's mental set to new task rules, also elicited P3a responses whose amplitude, latency and scalp topography closely resemble those elicited by non-target novel events in 'oddball' tasks [16,44]. However, our 'shift' feedback tone cannot be defined as a 'non-target novel' stimulus, as it had been learned to denote a shift in the task's rules, and the same tone was used along the practice and test sessions. Instead, the 'shift' tone prompted the subject to 'think differently', and to flexibly adopt a new solution (or task set) for the same card sorting problem. These results indicate that the P3a response system may reflect the activation of a more general brain 'switching' mechanism responsible for processing both stimulus and task novelty.

While 'shift' trials were infrequent relative to 'stay' trials (i.e., overall probabilities were 0.25 and 0.75, respectively), 'oddball' processes like uncertainty alone cannot explain the observed modulations of P3a brain potentials. First, oddball tasks with a fixed task-set and equally infrequent non-target tones elicit substantially smaller P3a potentials that decline rapidly with repetition [13,16]. Second, task uncertainty cannot account for the functional dissociation of P3a responses to feedback and card events [8]. Third, 'shift' trials from similar tasks evoke peak fMRI activation at prefrontal cortex regardless of their relative frequency of occurrence [24,32]. Fourth, in a follow-up study similar P3a responses were elicited by unpredictable 'shift' cues delivered with an overall probability of either 0.45 or even 0.65 compared to 'stay' feedback cues [5]. That said, brain responses to the first stay feedback cue revealed that task uncertainty did play a role in the early trials of each new WCST series. Indeed, our feedback cues do not make it explicit which task rule was to be used next. This ambiguity might disrupt WCST performance in prefrontal patients who, according to current proposals, might not rely on internal representations to project future actions based on past stimulus–response contingencies [28–30]. Even normal subjects who can anticipate the next set need to practice it at least once before reaching pre-shift levels of behavioural efficiency [36]. Indeed, the brain responses observed to the first stay cue may reflect residual reorienting and updating to the newly established task set (Fig. 3) [33,37,40].

Activation in this P3a response system ceased completely at the second stay cue, after the new set had been rehearsed once. Rostral anterior cingulate (BA 24/32), mid-dorsolateral (BA 9/46), and mid-ventrolateral prefrontal cortices (BA 12/47) become simultaneously active in response to shift feedback cues in similar tasks [32,43]. Likewise, human lesion, fMRI and intracranial recording data from oddball tasks provide support for lateral—rather than medial—prefrontal sources for the P3a response [23,44].

The present results may help us resolve apparent inconsistencies in past brain imaging and clinical WCST research. First, an outdated model of prefrontal function, and the inherently poor temporal resolution of most metabolic brain imaging studies, had led us to expect maximal prefrontal ERP activation during the card-matching stage rather than the feedback stage of WCST performance [8,12,24]. In contrast, the observed P3a activation suggests that the shift in set may well be time-locked to the feedback cue, and therefore, it occurs well before the next target card is on display. This new account is consistent with more recent fMRI [32,43] and behavioural evidence [33,37,40], suggesting that the internal representation of task rules must be activated (i.e., updated) in anticipation of the behaviour they govern (i.e., card sorting) [28,29]. Second, our ERP results provide support for the view that prefrontal cortex acts in concert with posterior association cortices for the executive control of cognitive set shifting [28,45]. Indeed, Fig. 2 reveals instant widely distributed neural activation across both frontal and posterior brain generators in response to 'shift' feedback cues. This argues against the strict localizationist view conveyed by some studies that display isolated prefrontal foci of brain activation during WCST performance (i.e., see Fig. 5 in Ref. [24]). These images reflect a biased interpretation of the real fMRI data, and might show 'statistically constructed foci ('tips of iceberg') within much wider areas or networks that are functionally active but remain largely invisible' to metabolic neuroimaging [17]. Third, an ERP index of set-shifting may help us to explain apparent inconsistencies in the anatomy reported by different metabolic studies. The stereotaxic coordinates of prefrontal regions with significant fMRI/positron emission tomography (PET) activation during WCST performance show a good deal of variability across studies [12,24,32]. One possible interpretation is that different anatomical fMRI activation elicited by the same task reflects disparate cognitive processes. Another possibility is that these different fMRI patterns may be just showing 'tip-of-iceberg' activation from different parts of the same neural network that gives rise to the P3a response. The present ERP results support the latter alternative. Finally, the finding of feedback-locked frontally-distributed P3a activity helps to complete the picture offered by previous ERP studies [8–10], suggesting that efficient WCST performance demands the activation of a widespread network of brain areas, with a key role played by prefrontal cortex. Further research will be necessary to map specific types of WCST deficits to specific anomalies in the frontal (P3a) and posterior (P3b) aspects of the P300 components reported here [3,4,7,30,45].

As in previous studies, a steady build-up in P3b activation to card onset was apparent as the new task set became established and gradually rehearsed [8,10]. This was paralleled by a steady improvement in response speed and efficiency, indicating a growing degree of automaticity in task performance [28,37]. Unlike P3b responses to feedback cues, P3b activity time-locked to the card was modulated neither by the number of task-sets in working memory, nor by their predictability [8,9]. This suggests a differential role of the posterior association cortices responsible for P3b elicitation during the updating (feedback) and rehearsal (card-matching) of task rules in working memory [32,43]. It could be argued that long-term memory networks at posterior association cortex need to be differentially engaged both for the rapid retrieval of new task rules during set-shifting and updating (feedback stage), as well as for the gradual rehearsal and consolidation of practised task-sets (card-matching stage), leading to proficient task performance [31]. Such a proposal could help us to re-interpret and integrate apparently contradictory accounts of the functional role of the P3b response in terms of either 'context updating' [13–15], or 'perceptual closure' processes [18,47,48]. Future ERP research with task-switching paradigms is needed to explore further the double dissociation of P3b responses reported here. Future studies should also address the implications of the present results for current models of P300 function [13–15,48], which may thus benefit from their integration within the solid theoretical framework provided by current models of prefrontal cortex function and the executive control of attention [2,17,28,29,33,37,40,45].

6.1. Trouble-shooting

In a follow-up study we have observed that self-paced set-switching tasks, or those which allow for predictable switches in task-set, evoke a much reduced frontal P3a-like component [5]. This might be due to the fact that certain degree of subjective uncertainty is necessary for an event to trigger P3a-like activity [13,14]. Alternatively, a predictable or self-paced shift in set may occur at any point along the inter-trial interval of a task-switching protocol. This can create a substantial 'latency jitter' that may also substantially reduce the amplitude of any switch-related P3a component during the ERP averaging procedure [35]. Further research is needed to elucidate whether the frontal P3a response system also becomes active during predictable switches in task-set. This will probably involve making appropriate adjustments for the latency jitter of self-paced shifts in set in relation to the external triggering events.

In its present form, the MCST protocol can be easily

completed almost without errors by normal subjects. In contrast, it might pose quite a hard challenge for certain type of neurological or psychiatric patients with impaired working memory or attention control, resulting in a rather large number of distractions and perseverative errors [6,7]. The original WCST instructions name these errors as 'wrong' task performance [19], which can be aversive or even humiliating for the patient, and may introduce motivational or emotional interference. One way around this problem can be to instruct subjects that feedback cues should be regarded as signals to 'shift the rule' or 'stay with the same rule', respectively, rather than signals of 'wrong' or 'right' sorting performance. We have used this strategy successfully both with normal subjects and patients, who do not see their behaviour constantly evaluated when the computer program requires them to 'shift' their sorting rule several times in a row.

Work with clinical samples may also require decreasing the cognitive demands made by the present MCST protocol. For instance, to make the task easier we could instruct subjects to sort cards following just two task rules (i.e., either by colour or shape). This would also eliminate the additional process of hypothesis testing necessary only when there are more than two task-sets involved. Such adjustments in task difficulty may help avoid a 'floor effect' problem in the behavioural performance of certain patient groups, even though the present MCST settings have proved to be sensitive to both normal age-related cognitive impairment and prefrontal damage [6,7]. On the other hand, one might easily increase the difficulty of the present MCST protocol to avoid a 'ceiling effect' in the behavioural performance of fully instructed, and well-practised normal subjects, who can shift set efficiently and typically score very few set-shifting errors. For instance, in order to make the task harder, we could instruct subjects to sort cards following one of four task rules: colour, shape, number, or 'none' (that is, sort the card in the pile that shares none of the card's features). To limit the time for responding, or to intersperse task-irrelevant visual or auditory distractors would also increase the cognitive demands made by the present MCST protocol. These adjustments in task difficulty could be achieved with only minor changes in the task's instructions and schedule, but keeping the same stimulus material.

6.2. Alternative and support protocols

Task switching protocols and dual-task paradigms have long been used to explore the mechanisms underlying the executive control of attention, mostly using behavioural measurements [2,22,30,33,36,37,40], or metabolic neuroimaging techniques [12,24,32,43]. Remarkably, few previous ERP studies have attempted to measure the fast brain dynamics underlying attention set shifting processes [3–5,8–11,39,49]. Indeed, behavioural studies can offer us useful hints about the formal structure and interactions of cognitive operations in task switching, but are less informative about the underlying brain mechanisms. On the other hand, metabolic neuroimaging studies lack the sufficient temporal resolution to resolve the elusive relationships among extremely fast cognitive operations and their specific neural substrates. This coarse temporal resolution in the functional analysis of cognitive-to-brain relationships may have led to the wrong impression that the card-matching stage of WCST performance demands larger prefrontal resources than the feedback stage [12,24]. The novel evidence provided by the present MCST ERP protocol represents an important step forward in our understanding of the temporal dynamics of activation across a frontal–posterior brain network responsible for the executive control of human attention. In the MCST protocol, ERPs time-locked to non-target feedback events cannot be interpreted as reflecting just exogenous or involuntary processes. Alternatively, results from this dual-task protocol are best taken to suggest a role of the frontally distributed P3a response system in the executive control of attention set shifting. This type of task-switching protocol can pave the way for an integration of the large database from the P300 research program with current models of prefrontal cortex function and the executive control of attention. Within this wider framework, future ERP research should address the relationships between the frontal (P3a) and posterior (P3b) components of the P300 response system with a number of variables known to affect task switching processes, such as: (a) stimulus familiarity and rule complexity [37], (b) implicit versus explicit cueing [36,37], (c) time allowed to reconfigure set [27,36], (d) task expectancy, uncertainty and repetition [27,36,40,43,46], (e) perceptual versus motor set-shifting [39,46], (f) endogenous, internally-driven versus exogenous, externally-driven factors [37,46], or (g) number of sets held in memory [9,24,33]. This promises to be a fruitful research program that will eventually help to clarify the relationships of the frontal (P3a) and posterior (P3b) aspects of the P300 response system, with prefrontal cortex function and the executive control of attention.

7. Quick procedure

(i) Human subjects. Recruit subjects and give them preliminary information about ERP recording and the task protocol. Instruct subjects to relax and avoid excessive muscle or eye movements during the recording session.

(ii) Electrode placement. Place electrodes for EEG and EOG recordings. Double-check ground and reference electrodes. Keep electrode impedances below 5 kΩ.

(iii) Task instructions and procedure. Explain the MCST protocol in detail, and have 10 min practice to ensure

subjects have understood the task and can sort cards efficiently.

(iv) ERP recordings. The EEG is amplified band pass filtered (0.01–100 Hz; 12 dB/octave roll/off), digitised at 250 Hz/channel, and stored on the computer's hard disk. After the first task block is finished, you may want to run the task again after a 5-min rest period.

(v) Behavioural analyses. Make sure that feedback and card events are correctly classified into 'shift' and 'stay' trials as a function of the subject's sorting performance. Select efficiently completed MCST series from those with any random or perseverative errors. Use an appropriate coding system to sort 'shift' and 'stay' trials into $shift_{3D}$, $shift_{2D}$, $stay_1$, $stay_2$, $stay_3$, $stay_{Last}$ trials (see Fig. 1c).

(vi) Off-line ERP analyses. Merge behavioural data with EEG data. Split-up the continuous EEG file into averaging epochs of 1400 ms time-locked to both feedback and card events, including a 200-ms baseline in both cases (see Fig. 1b). Edit the EEG file, correct eye-blink EOG artifacts when possible, and discard epoch trials with residual artifacts [35]. Compute the ERP averages for each type of stimulus. Measure the amplitude of P3a (375–400 ms post-stimulus onset) and P3b (550–600 ms post-stimulus onset) components at the Fz and Pz electrodes. For feedback-locked ERPs, both P3a and P3b components are measured. For card-locked ERPs, only the P3b is measured.

(vii) Statistical analyses. Compare P300 amplitudes in a repeated-measures design with Stage (feedback vs. card-matching) and Trials ($shift_{3D}$, $shift_{2D}$, $stay_1$, $stay_2$, $stay_3$, $stay_{Last}$). This design can be simplified by averaging $shift_{3D}$ and $shift_{2D}$ trials together, and discarding $stay_2$ and $stay_3$ trials.

(viii) Topographical analyses and dipole estimation.

8. Essential literature references

Original papers: [7,8,11,30,32].
Book chapters: [2,22].
Review papers: [4,29,33].

Acknowledgements

Supported by grants from Fundación Complutense del Amo, Fundación Mapfre Medicina, and Comunidad de Madrid (08.5/0012/98).

References

[1] AEEGS, American Electroencephalographic Society guidelines for clinical electroencephalography, J. Clin. Neurophysiol. 11 (1994) 111–113.

[2] A. Allport, E.A. Styles, S. Hsieh, Shifting intentional set: exploring the dynamic control of tasks, in: C. Umiltà, M. Moscovitch (Eds.), Attention and Performance XV: Conscious and Nonconscious Information Processing, MIT Press, Cambridge, MA, 1994, pp. 421–452.

[3] F. Barceló, Electrophysiological evidence of two different types of error in the Wisconsin card sorting test, Neuroreport 10 (1999) 1299–1303.

[4] F. Barceló, Does the Wisconsin card sorting test measure prefrontal function?, Spanish J. Psychol. 4 (2001) 79–100.

[5] F. Barceló, Nuevas soluciones para un viejo problema: una respuesta de orientación a la novedad de la tarea, III Congreso Español de Psicofisiología, Santiago de Compostela, 2002.

[6] F. Barceló, R.T. Knight, Role of dorsolateral prefrontal cortex in attentional set shifting: parsing the cognitive significance of WCST errors with event-related potentials, Psychophysiology 36 (1999) S30.

[7] F. Barceló, R.T. Knight, Both random and perseverative errors underlie WCST deficits in prefrontal patients, Neuropsychologia 40 (2002) 349–356.

[8] F. Barceló, J.M. Muñoz-Céspedes, M.A. Pozo, F.J. Rubia, Attentional set shifting modulates de target P3b response in the Wisconsin card sorting test, Neuropsychologia 38 (2000) 1342–1355.

[9] F. Barceló, J.A. Periáñez, R.T. Knight, Think differently: a brain orienting response to task novelty, Neuroreport 13 (2002) 1887–1892.

[10] F. Barceló, F.J. Rubia, Non-frontal P3b-like activity evoked by the Wisconsin card sorting test, Neuroreport 9 (1998) 747–751.

[11] F. Barceló, M. Sanz, V. Molina, F.J. Rubia, The Wisconsin card sorting test and the assessment of frontal function: a validation study with event-related potentials, Neuropsychologia 35 (1997) 399–408.

[12] K.F. Berman, J.L. Ostrem, C. Randolph, J. Gold, T.E. Goldberg, R. Coppola, R.E. Carson, P. Herscovitch, D.R. Weinberger, Physiological activation of a cortical network during performance of the Wisconsin card sorting test: a positron emission tomography study, Neuropsychologia 33 (1995) 1027–1046.

[13] E. Donchin, Surprise! Surprise?, Psychophysiology 18 (1981) 493–513.

[14] E. Donchin, M.G.H. Coles, Is the P300 component a manifestation of context updating?, Behav. Brain Sci. 11 (1988) 343–356.

[15] E. Donchin, M.H.G. Coles, Context updating and the P300, Behav. Brain Sci. 21 (1998) 152–153.

[16] D. Friedman, Y.M. Cycowicz, H. Gaeta, The novelty P3: an event-related brain potential (ERP) sign of the brain's evaluation of novelty, Neurosci. Biobehav. Rev. 25 (2001) 355–373.

[17] J.M. Fuster, The Prefrontal Cortex. Anatomy, Physiology, And Neuropsychology of the Frontal Lobes, Lippincott-Raven, Philadelphia, PA, 1997.

[18] E. Halgren, K. Marinkovic, P. Chauvel, Generators of the late cognitive potentials in auditory and visual oddball tasks, Electroencephalogr. Clin. Neurophysiol. 106 (1998) 156–164.

[19] R.K. Heaton, G.J. Chelune, J.L. Talley, G.G. Kay, G. Curtis, Wisconsin Card Sorting Test (WCST). Manual Revised and Expanded, Psychological Assessment Resources, Odessa, FL, 1993.

[20] C.S. Herrmann, R.T. Knight, Mechanisms of human attention: event-related potentials and oscillations, Neurosci. Biobehav. Rev. 25 (2001) 465–476.

[21] S.A. Hillyard, G.R. Mangun, M.G. Woldorff, S.J. Luck, Neural systems mediating selective attention, in: M.S. Gazzaniga (Ed.), The Cognitive Neurosciences, MIT Press, Cambridge, MA, 1995, pp. 665–681.

[22] D.E. Kieras, D.E. Meyer, J.A. Ballas, E.J. Lauber, Modern computational perspectives on executive mental processes and cognitive control: where to from here, in: S. Monsell, J. Driver (Eds.), Control of Cognitive Operations. Attention and Performance XVIII, MIT Press, Cambridge, MA, 2000, pp. 681–712.

[23] R.T. Knight, D. Scabini, Anatomic bases of event-related potentials and their relationship to novelty detection in humans, J. Clin. Neurophysiol. 15 (1998) 3–13.

[24] S. Konishi, K. Nakajima, I. Uchida, M. Kameyama, K. Nakahara, K. Sekihara, Y. Miyashita, Transient activation of inferior prefrontal cortex during cognitive set shifting, Nat. Neurosci. 1 (1998) 80–84.
[25] R. Mattes, R. Cohen, P. Berg, A.G.M. Canavan, G. Hopmann, Slow potentials (SCPS) in schizophrenic patients during performance of the Wisconsin card-sorting test (WCST), Neuropsychologia 29 (1991) 195–205.
[26] A. Matthews, H. Flohr, S. Everling, Cortical activation associated with midtrial change of instruction in a saccade task, Exp. Brain Res. 143 (2002) 488–498.
[27] N. Meiran, Z. Chorev, A. Sapir, Component processes in task switching, Cogn. Psychol. 41 (2000) 211–253.
[28] E.K. Miller, The prefrontal cortex and cognitive control, Nat. Rev. Neurosci. 1 (2000) 59–65.
[29] E.K. Miller, J.D. Cohen, An integrative theory of prefrontal cortex function, Annu. Rev. Neurosci. 24 (2001) 167–202.
[30] B. Milner, Effects of different brain lesions on card sorting, Arch. Neurol. 9 (1963) 100–110.
[31] Y. Miyashita, T. Hayashi, Neural representation of visual objects: encoding and top-down activation, Curr. Opin. Neurobiol. 10 (2000) 187–194.
[32] O. Monchi, M. Petrides, V. Petre, K. Worsley, A. Dagher, Wisconsin card sorting revisited: distinct neural circuits participating in different stages of the task identified by event-related functional magnetic resonance imaging, J. Neurosci. 21 (2001) 7733–7741.
[33] H. Pashler, J.C. Johnston, E. Ruthruff, Attention and performance, Annu. Rev. Psychol. 52 (2001) 629–651.
[34] J.A. Periáñez, F. Barceló, Adaptación Madrid del test de clasificacion de cartas de Wisconsin: un estudio comparativo de consistencia interna, Rev. Neurol. 33 (2001) 611–618.
[35] T.W. Picton, S. Bentin, P. Berg, E. Donchin, S.A. Hillyard, R.J. Johnson, G.A. Miller, W. Ritter, D.S. Ruchkin, M.D. Rugg, M.J. Taylor, Guidelines for using human event-related potentials to study cognition: recording standards and publication criteria, Psychophysiology 37 (2000) 127–152.
[36] R.D. Rogers, S. Monsell, Costs of a predictable switch between simple cognitive tasks, J. Exp. Psychol. Gen. 124 (1995) 207–231.
[37] J.S. Rubinstein, D.E. Meyer, J.E. Evans, Executive control of cognitive processes in task switching, J. Exp. Psychol. Hum. Percept. Perform. 27 (2001) 763–797.
[38] M.D. Rugg, M.G.H. Coles (Eds.), Electrophysiology of Mind. Event-related Brain Potentials and Cognition, Oxford University Press, Oxford, 1995.
[39] M.F.S. Rushworth, R.E. Passingham, A.C. Nobre, Components of switching intentional set, J. Cogn. Neurosci. 14 (2002) 1139–1150.
[40] E. Ruthruff, R.W. Remington, J.C. Johnston, Switching between simple cognitive tasks: the interaction of top-down and bottom-up factors, J. Exp. Psychol. Hum. Percept. Perform. 27 (2001) 1404–1419.
[41] E. Schröger, C. Wolff, Attentional orienting and reorienting is indicated by human event-related brain potentials, Neuroreport 9 (1998) 3355–3358.
[42] H.V. Semlitsch, P. Anderer, P. Schuster, O. Preslich, A solution for reliable and valid reduction of ocular artifacts applied to the P300 ERP, Psychophysiology 23 (1986) 695–703.
[43] M.H. Sohn, S. Ursu, J.R. Anderson, V.A. Stenger, C.S. Carter, The role of prefrontal cortex and posterior parietal cortex in task switching, Proc. Natl. Acad. Sci. USA 97 (2000) 13448–13453.
[44] M. Soltani, R.T. Knight, Neural origins of the P300, Neurosci. Biobehav. Rev., in press.
[45] D.T. Stuss, R.T. Knight (Eds.), Principles of Frontal Lobe Function, Oxford University Press, New York, 2002.
[46] F.J. Tornay, E.G. Milan, A more complete task-set reconfiguration in random than in predictable task switch, Q. J. Exp. Psychol. A 54 (2001) 785–803.
[47] R. Verleger, Event-related potentials and cognition: a critique of the context updating hypothesis and an alternative interpretation of P3, Behav. Brain Sci. 11 (1988) 343–356.
[48] R. Verleger, Toward an integration of P3 research with cognitive neuroscience, Behav. Brain Sci. 21 (1998) 150–152.
[49] L. Wang, R. Kakigi, M. Hoshiyama, Neural activities during Wisconsin card sorting test-MEG observation, Brain Res. Cogn. Brain Res. 12 (2001) 19–31.