Pergamon

PII: S0028–3932(96)00096–6

Neuropsychologia, Vol. 35 No. 4, pp. 399–408, 1997

Printed in Great Britain
0028–3932/97 $17.00+0.00

The Wisconsin Card Sorting Test and the assessment of frontal function: A validation study with event-related potentials

FRANCISCO BARCELÓ,* MARTA SANZ,† VICENTE MOLINA† and FRANCISCO J. RUBIA†

*Department of Psychobiology, Faculty of Psychology, Complutense University, Somosaguas, 28223 Madrid, Spain;
†Brain Mapping Unit, Pluridisciplinar Institute, Complutense University, Pso. Juan XXIII, 1, 28040 Madrid, Spain

(*Received* 9 *February* 1996; *revised* 17 *July* 1996)

Abstract—The Wisconsin Card Sorting Test (WCST) is generally regarded as the prototype of abstract reasoning task and has been routinely used to assess frontal lobe function in a variety of clinical and research contexts. However, there are growing concerns that the WCST fails to discriminate frontal patients from those with lesions in other brain regions or from normals. Event-related potentials (ERP) from frontal, fronto-temporal, temporal, parietal and occipital areas were recorded during the performance of a computerized version of the WCST in order to explore frontal versus non-frontal ERP indexes during WCST activation. The task protocol was contrived to focus on the differences between early and late trials of each WCST series. Cognitive processes underlying these two task conditions have been described as extradimensional and intradimensional shifts in attention, respectively. Differences between early and late WCST trials appeared as soon as 120 msec poststimulus and were associated with a negative field potential centred at the fronto-temporal region of the left hemisphere. Significantly larger amplitudes of the posterior P3b wave for late as compared with early WCST trials also lent support to claims of a strong involvement of working memory mechanisms during WCST performance. Results are discussed in terms of the implications for the utility of ERP measures in clinical neuropsychology. © 1997 Elsevier Science Ltd. All rights reserved.

Key Words: WCST; frontal function; ERPs; attention; working memory; abstract reasoning.

Introduction

The Wisconsin Card Sorting Test (WCST) has been generally regarded as the prototype of abstract reasoning task, and frontal lobe function is said to be specifically implicated in its performance [40]. The WCST was originally used as a test of abstract reasoning and concept formation with unilateral lobectomized patients [22]. This early work revealed worse WCST performance levels in frontal patients than in patients with lesions in other areas, which led to its generalized adoption as an indicator of frontal dysfunction [1, 8, 13, 14, 17, 20, 39, 40, 43].

However, there have been claims that performance on the WCST is sensitive to more generalized brain disorder, or can be disturbed by focal pathology outside frontal areas [40]. Most of these criticisms derive from the incapacity of the WCST to discriminate patients with frontal lesions from those with lesions in other regions [2, 9, 11, 12, 38], or from normals [23, 42].

In one recent report, Anderson *et al*. [2] examined 91 frontal and non-frontal patients through computerized axial tomography and nuclear magnetic resonance 3 months after the onset of their brain damage, but did not find any association between site or size of lesion and WCST performance. These authors pointed out that the WCST does not offer a reliable appraisal of the presence or absence of frontal lobe damage. After an extensive review of the literature, Mountain and Snow [23] also concluded that the utility of the test as a marker of frontal dysfunction for either clinical or research purposes, is not supported by the data.

Given the functional and morphological diversity of the frontal cortex and its interactions with posterior cerebral regions, it is little wonder that many regard the WCST as quite an inappropriate tool to pinpoint the focus of a hypothetical frontal damage. Most neuro-

* Address for correspondence and reprint requests: Francisco Barceló, Department of Psychobiology, Faculty of Psychology, Complutense University, Somosaguas 28223 Madrid, Spain; e-mail: pspsc13@emducms1.sis.ucm.es.

imaging studies have reported activation of several brain areas. Activation of the dorsolateral prefrontal cortex is the most consistent finding in studies using regional cerebral blood flow (rCBF) and single photon emission tomography (SPET) [4, 19, 32, 43]. However, special considerations have brought recent reports of possible implications of parietal, medial temporal, and hippocampal cortices in card sorting [2, 5, 12, 23, 41]. Thus, epileptic patients diagnosed with hippocampal sclerosis showed more serious impairment in WCST performance than epileptic patients with a unilateral temporal or frontal seizure focus as revealed with magnetic resonance imaging [5].

In spite of the relatively good spatial resolution provided by rCBF and SPET studies, these techniques are ill-suited to disentangle the split-second nature of cognitive operations taking place during WCST performance, and hence, are unlikely to unveil possible alterations in the course of information processing. In particular, rCBF and SPET results fail to differentiate between correct and incorrect response periods, or between early and late trials within a WCST series. A swift functional measure of brain activation such as the event-related potential (ERP) may prove of greater usefulness in disentangling the relationships between frontal functions and the miscellany of cognitive operations in play during WCST performance.

In the present ERP study, an analytical approach has been adopted whereby two kinds of cognitive processes are addressed during WCST performance. These are the process of searching and shifting attention to a newly relevant stimulus dimension during the early trials in a series ('novel classification trials'), and the process of maintaining attention to the relevant stimulus dimension towards the end of the series ('repetition trials'). These two processes have also been referred to as 'extradimensional shifts' and 'intradimensional shifts' in attention, respectively [33, 34].

To date, few studies have focused on the components of the ERP in relation to WCST performance. One precedent is that of Mattes *et al*. [20], who examined slow cortical potentials such as the Contingent Negative Variation in a sample of schizophrenic patients and in normals. However, they failed to report any significant differences between classification and repetition trials. At least two methodological shortcomings might account for these negative findings. Firstly, only midline recordings were made. Secondly, key-cards were displayed 1.5 sec after the choice-card, whereas in the conventional protocol key-cards are permanently in sight [20].

These problems have been circumvented in a new computerized version of the WCST, which was adapted in several ways to allow us the concurrent measurement of ERPs. Control over stimulus and response factors was improved by eliminating the ambiguity present in the original version [25]. This had the added advantage of increasing the signal-to-noise ratio in ERP averages.

In summary, the purpose of this study was to examine the frontal versus non-frontal topographical distribution of brain electrical changes and their temporal dynamics during the performance of the WCST in a sample of normal volunteers. To this end, ERPs were recorded from fronto-polar, fronto-temporal, frontal, temporal, parietal and occipital areas of both hemispheres. ERPs elicited by novel classification trials (i.e. 2nd and 3rd trials in a series) were compared with those elicited by repetition trials (i.e. 6th and 7th trials in a series). Two cognitive operations were assumed to be tapped at by either trial periods, namely, (1) the process of searching for a new sorting category at the beginning of each new series, as compared with (2) the consolidation of the correct classification category towards the end of the series. It was expected that a larger ERP activation would take place at frontal as compared with non-frontal brain areas. It was also hypothesized that larger prefrontal activation would be elicited during novel classification trials as compared with repetition trials.

Methods

Subjects

Twenty-four healthy university students (13 women) took part in the study. Their mean age was 20.5 years (S.D. 1.2 years). They were recruited through advertisements in the campus newspaper and were paid for their collaboration. No subject had a history of alcohol or drug abuse, Axis I and II diagnosis, neurological illness, or head trauma, and were all free from pharmacological treatment. All subjects were right-handed and had normal or corrected to normal vision. They received detailed information about the study protocol and gave informed consent.

Recording system

EEG activity was recorded from the scalp through 20 tin electrodes inserted in a preconfigured cap (ElectroCap International). Recording sites included FP1, FP2, F7, Fz, F8, T7, Cz, T8, P4, Pz, P3, O1, and O2 of the International 10–20 system [29]. Linked mastoids were used as the reference, and Fpz as ground. The electrooculogram (EOG) was recorded bipolarly from electrodes placed above and adjacent to the outer canthi of the right eye. Electrode impedances were kept below 5 kΩ. All EEG and EOG channels were amplified with a SYNAMP (NeuroScan Inc.) DC coupled amplifier system. Recordings were made from DC with a lowpass filter set at 50 Hz (12 dB/octave roll-off). Single trial epochs were digitized at 4 msec/sample and stored in magneto-optical disk for off-line analysis, together with event markers and response latencies. Each epoch was of 1700 msec duration, including a 200 msec prestimulus baseline.

Stimuli

The computerized version of the WCST incorporated with the NeuroStim Inc. package was used as a task model, but its administration protocol was modified in order to improve task control and to eliminate ambiguous responses. With this purpose, 64 colour cards were built-up after the original material of the standard WCST. The stimulus material was

delivered through a computer screen 80 cm away in front of the subject, with each card forming a visual angle of 2.8° wide and 3.5° high. The four key-cards remained always present on the upper third of the screen and afforded eye movements with a maximum visual angle of 12° horizontally. The experimental design, the stimulus sequence and the coding of responses were programmed and controlled through the NeuroStim package.

Procedure

Subjects sat in a comfortable seat in an electrically shielded, quiet and dimly illuminated (2 luxes) cubicle. Each WCST trial started with the display of the four key-cards on the upper third of the computer screen, plus one choice-card occupying the right inferior corner in the lower third of the screen. Subjects were asked to classify the choice-card by pressing one of four buttons on a response panel. The far left button corresponded to the key-card on the far left side of the screen, the far right button corresponded to the key-card on the far right side, and so on. Subjects used their thumbs for button-pressing while holding the response panel with the palms of both hands. Feedback was provided by means of a computer-generated tone (2000 Hz for correct, and 500 Hz for incorrect, 300 msec in duration), with a 1600 msec gap between button-press and feedback onset. The inter-trial interval varied randomly between 3000 and 4000 msec. There was no time limit to issue a response, but subjects were encouraged to respond briskly and to score as many correct responses as possible.

Unlike in the standard WCST version, the three possible classification criteria were mentioned beforehand, as was the fact that these could change during the task. This restricted the influence of variables such as intelligence, and focused the course of inquiry onto the process of searching for a new classification criterion, and on the consolidation of the correct classification criterion. The WCST administration protocol consisted of two blocks with 18 series of 7 trials each. The length of the series remained constant regardless of performance. Such short series were adopted after a pilot study which revealed that university students need only two trials on average to find the new classification criterion. Both the order of the categories and the presentation of choice-cards within each series were determined on a semi-random basis in order to comply with the following constraints: (1) colour, shape and number categories appeared the same number of times; and (2) ambiguity was eliminated from the first four trials in the series. Ambiguous trials were defined as those which can be scored as correct under two or more classification rules simultaneously [25]. Elimination of ambiguity from the early trials in the series eased the correction of the test, and improved the signal-to-noise ratio in the ERPs. The average duration of each block was 15 min, with a 5 min rest period between blocks. Also, there was a 5 min practice period to familiarise subjects with the task and to make sure that instructions had been understood.

Dependent variables

None of the behavioural measures normally derived from the standard WCST were used in the analyses, and only response latencies were obtained and analysed to help making inferences about the putative cognitive processes involved. Nevertheless, an approximation to the standard scoring criteria was made, and a summary table with performance values and the redefinition of variables adapted to our protocol is available in the Appendix. Separate ERP waves were computed for three different WCST task conditions:

(a) WIS23 trials: The second and third trials in each series were averaged together into a WIS23 waveform regardless of subject performance. The WIS23 condition was taken to reflect active search of a new classification rule, after having received negative feedback in the first trial. Even if the new correct classification category was found in the second trial, the third trial was also included in the WIS23 average under the assumption that the new classification rule would not be consolidated yet.
(b) WIS67 trials: Correct trials sixth and seventh in a series were averaged together to yield the WIS67 condition, which was taken as an indicator of automatization of the correct classification rule.
(c) WIS1 trials: All first trials in the series were averaged together, provided that they had been classified incorrectly, to yield the experimental condition WIS1. The WIS1 condition was taken as an indicator of the extent that a category change had been anticipated after the seventh trial. A correct response to the first trial in a series motivated the rejection of all data from that series. This happened in less than 3% of all series, which is in accordance with what would be expected by chance alone.

ERP analyses

Continuous EEG recordings were epoched from 200 msec prior to stimulus onset to 1500 msec after it. Blinks and horizontal eye movements were corrected on a trial-by-trial basis using a standard linear correction procedure [37]. After EOG artifact correction, trials exceeding amplitudes of $\pm 75\,\mu$V at any of the active electrodes were automatically discarded from the averages. Finally, all records were visually edited to double-check the accuracy of the correction and rejection procedures. Any linear trend within the recording epoch was removed prior to averaging, and waveforms were aligned to a 200 msec prestimulus baseline. WIS23 and WIS67 ERP waves were composed of 60 trials on average (range 55–72 trials), whereas WIS1 trials contained half this number.

Averaged ERP waveforms were computed for each event type at each electrode for each subject and across subjects. Mean values of ERP components were obtained in eight different latency windows: P50 (30–80 msec); P100 (80–120 msec); N150 (120–180 msec); P200 (180–270 msec); P3a (270–350 msec); P3b (350–450 msec); slow wave 1 (SW1, 450–800 msec); and SW2 (800–1200 msec). The decision to utilize these time windows was made on empirical grounds after inspection of overall mean waves. ERPs during feedback were not evaluated due to the possible influence of expectancy and/or motivational factors.

Statistical analyses

Three within-subject factors entered all ANOVAs for ERP data, namely, Electrode (6 levels; fronto-polar, fronto-temporal, frontal, temporal, parietal and occipital), Hemisphere (2 levels; right and left), and Task. Mid-line electrodes were not included in these analyses. Task conditions were dependent upon the substantive hypothesis under consideration in each of two repeated-measures ANOVA designs. In the first design, the Task factor compared WIS1 and WIS67 conditions in order to test the assumption that subjects did not anticipate a shift in the sorting category. If the assumption is correct, the first trial in a series (WIS1) would be responded to in the same way as the two last trials of the previous series (WIS67). In the second ANOVA design, WIS23 and WIS67 conditions were compared in order to evaluate the two main hypotheses addressed in this study. Each of these ANOVA designs were repeated for ERP mean values at every one of the 8 time windows considered.

ANOVAs adopted a partial factorial model with the terms Task, Task by Hemisphere, and Task by Hemisphere by Electrode. Response latencies to choice-card onsets were analysed following the same experimental logic, except that only the Task factor entered the analysis.

ANOVA results are reported with Greenhouse Geisser adjusted degrees of freedom where appropriate. The Bonferroni procedure was used to determine the significance level using a familywise error rate of 0.05. Statistical analyses were performed using the SPSS-x package from the Complutense university mainframe.

Results

Experimental assumptions

The analysis of behavioural data showed no significant differences between reaction times to WIS1 and WIS67 conditions, (mean $\pm$ S.E. $= 1.04 \pm 0.04$ sec, and 0.99 ± 0.04 sec, respectively), which suggests that these two task conditions were equivalent and that changes in classification criteria after the seventh trial were not anticipated. Had the change in category been anticipated, WIS1 latencies would have been more similar to WIS23 rather than to WIS67 latencies. Also as expected, ERP amplitudes during WIS1 and WIS67 trials did not show any significant difference in any of the time windows examined, as revealed by the series of null results from the first ANOVA design. Thus, together with reaction time data, ERP data confirmed that changes in classification criteria were not anticipated.

Experimental hypotheses

Performance data. Response latencies were significantly slower in WIS23 trials than in WIS67 trials, [$t(23) = 5.55$; $P < 0.001$], (mean $\pm$ S.E. $= 1.38 \pm 0.08$ sec, and 0.99 ± 0.04 sec, respectively); which is consistent with the hypothesis of different cognitive and/or motor decision processes taking place in WIS23 as opposed to WIS67 trials. This can also indicate that responses to WIS67 trials had been automatized to a reasonable extent.

ERPs. Differences in ERP amplitudes between WIS23 and WIS67 trials were evaluated in the second ANOVA design. Significant differences were found at fronto-temporal (120–800 msec), frontal (180–800 msec), fronto-polar (350–450 msec), temporal (180–800 msec) and parietal (350–800 msec) areas. Grand average ERP waveforms across the sample of 24 subjects are displayed in Fig. 1.

The P50 and P100 components did not show any significant task effect. This can be interpreted as an indication of convergence of the stages of sensory processing of WIS23 and WIS67 trials at visual striate and extrastriate cortices.

The earliest reliable difference between WIS23 and WIS67 trials appeared in the 120–180 msec time window, with one significant Task $\times$ Hemisphere $\times$ Electrode interaction at F7, [$F(1,23) = 4.98$, $P < 0.05$]. The effect was due to a unilaterally more negative beginning of the P200 wave for WIS23 as compared to WIS67 trials. The effect was not observed at the F8 lead.

The conspicuous P200 component (180–270 msec) was present mainly at fronto-polar and fronto-temporal sites, although this time window did not yield any trial differences at fronto-polar sites [$F(1,23) = 0.9$, ns]. Significant differences between WIS23 and WIS67 were confined to frontal [$F(1,23) = 5.10$, $P < 0.05$], fronto-temporal [$F(1,23) = 10.27$, $P < 0.01$], and temporal [$F(1,23) = 7.06$, $P < 0.05$] regions of the left hemisphere. In all cases, P200 amplitudes were significantly reduced for the WIS23 condition.

The early P3a component was measured 270–350 msec after stimulus onset. As with the P200 wave, significant Task effects were confined to frontal [$F(1,23) = 7.79$, $P < 0.01$], fronto-temporal [$F(1,23) = 14.96$, $P < 0.001$] and temporal [$F(1,23) = 14.74$, $P < 0.001$] regions of the left hemisphere. These significant third-order interactions were due to lower WIS23 than WIS67 amplitudes at left sites. It should be noted, though, that the inter-hemispheric asymmetry also affected WIS67 trials only at the fronto-temporal region [$F(1,23) = 6.52$, $P < 0.05$]. Figure 2 shows the topographical distribution of these effects, which were also replicated in the following two time windows.

The P3b wave elicited 350–450 msec after choice-card onset was mainly apparent at posterior leads. The direction of significant effects at frontal [$F(1,23) = 16.0$, $P < 0.001$], fronto-temporal [$F(1,23) = 39.60$, $P < 0.001$], and temporal [$F(1,23) = 27.85$, $P < 0.001$] sites replicated those reported for the previous time window. This included an inter-hemispheric asymmetry affecting both WIS23 and WIS67 trials at frontal and fronto-temporal (but not temporal) sites. However, there were two new significant three-way interactions at fronto-polar [$F(1,23) = 4.78$, $P < 0.05$], and parietal sites [$F(1,23) = 6.70$, $P < 0.05$). These effects were caused by significantly larger ERP amplitudes for WIS67 than for WIS23 trials at parietal electrodes; whereas the reverse was true at fronto-polar regions, where WIS67 amplitudes were close to baseline values. Thus, the amplitude of the parietal P3b wave appears to be inversely related to fronto-polar activation, which might reflect different sides of a common dipole generator. In any case, the hemispheric symmetry of both the fronto-polar and parietal effects suggests that they may be caused by a brain mechanism different from the one responsible for the ERP effects found at the dorso-frontal and fronto-temporal areas. Finally, it is worth noting that WIS23 and WIS67 trials did not differ at occipital leads.

The pattern of results for the SW1 component examined 450–800 msec after choice-card onset replicated that obtained for the previous time window, with significant differences between WIS23 and WIS67 task conditions at frontal [$F(1,23) = 7.73$, $P < 0.01$], fronto-temporal [$F(1,23) = 11.34$, $P < 0.01$], and temporal [$F(1,23) = 14.98$,

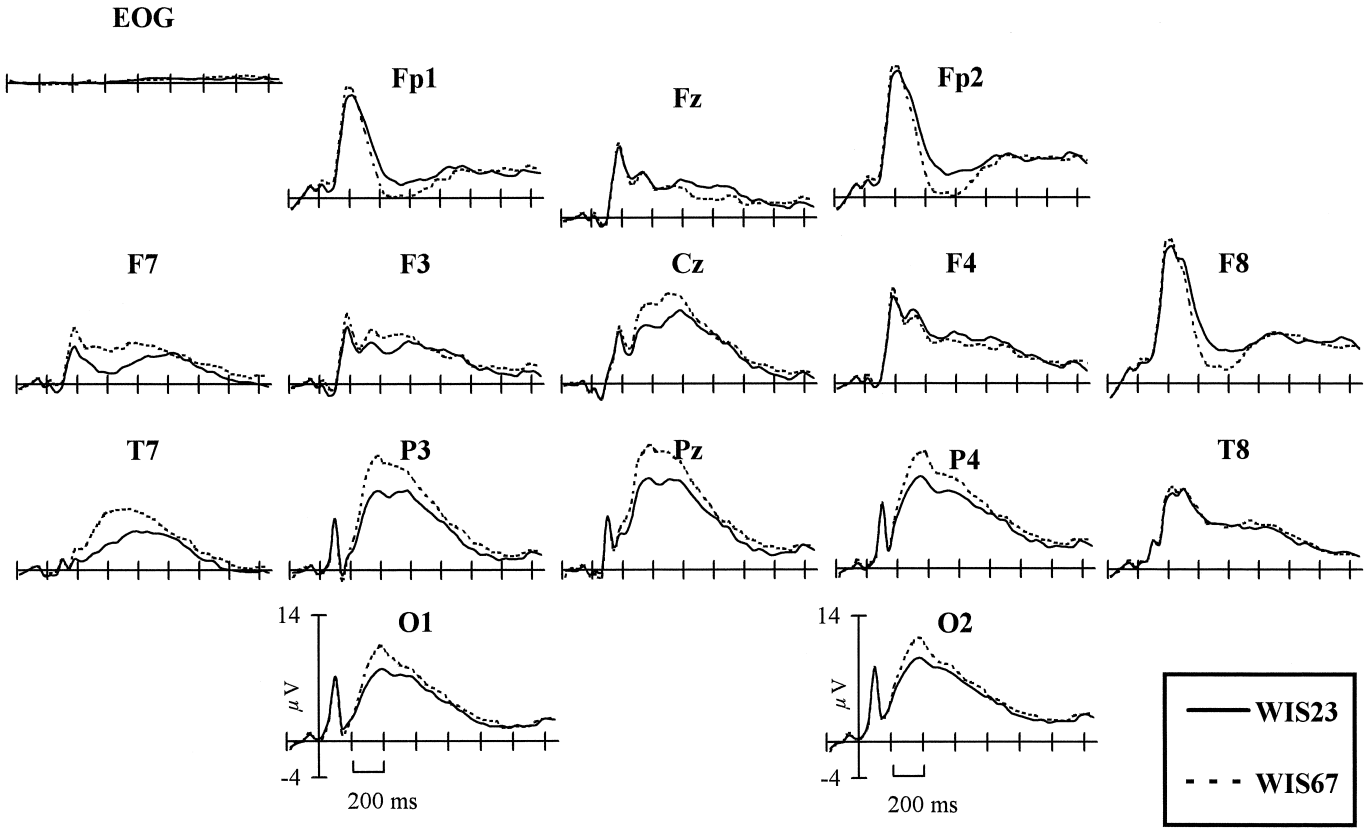

Fig. 1. Grand average ERP waveforms elicited by novel classification trials (WIS23) and repetition trials (WIS67) at all electrode positions. Tick marks on the scale bar represent 200 msec, starting 200 msec prior to choice-card onset.

$P<0.001$], and parietal [$F(1,23)=5.67$, $P<0.05$] areas. No other significant Task, Task × Hemisphere, or Task × Hemisphere × Electrode effects were found beyond 800 msec after choice-card onset.

Discussion

This study aimed to validate the WCST in a sample of normal subjects by measuring ERPs from various frontal and non-frontal scalp locations of both hemispheres. Two cognitive processes assumed to be associated with frontal function were isolated and compared. The first of these was the shifting of attentional set from an old to a newly relevant stimulus dimension (i.e. 'extradimensional shifts' in attention). The other process pertained to the ability of maintaining set to the relevant stimulus dimension across a series of changing stimuli, that is, 'intradimensional shifts' in attention [33]. These two attentional processes were indexed by WIS23 and WIS67 trials, respectively. The task was designed so that set could be found and shifted rapidly, with only one or two perseverative errors at the beginning of each new series (see the Appendix). Extra information prior to WCST

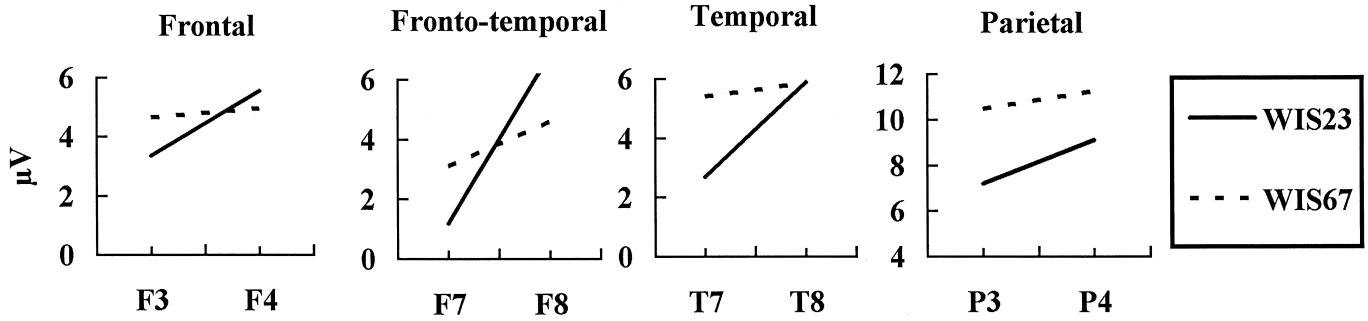

Fig. 2. Mean ERP amplitudes during the 270–350 msec time window showing the Task by Hemisphere interaction, which was significant at frontal, fronto-temporal and temporal areas, but not the parietal area. The effect was due to hemispheric differences in ERP amplitudes for novel classification trials (WIS23) as compared with repetition trials (WIS67).

administration guaranteed a rapid acquisition and automatization of the new set. Under these controlled conditions, card sorting was related to significant ERP changes at fronto-polar and frontal areas, but also at temporal and parietal areas. ERP amplitudes to WIS23 and WIS67 trials differed from each other as early as 120 msec, and up to 800 msec after, the onset of the choice-card. These differences appeared early at the left fronto-temporal region, and later at parietal areas of both hemispheres.

The earliest trial differences were found just 120 msec after choice-card onset only at the F7 lead, where WIS23 trials showed reliably lower ERP amplitudes than WIS67 trials. These differences lasted up to 800 msec after choice-card onset. Although this left-side effect overlapped the beginning of the conspicuous P200 wave at fronto-polar leads, it is our contention that these two frontal ERP features reflect very disparate brain processes. We suggest that early differences between WIS23 and WIS67 trials reflect the activation of the left dorsolateral prefrontal cortex (DLPFC) during the execution of the WCST, with a larger amount of DLPFC activation affecting WIS23 trials. It was possible to distinguish three other ERP features during the performance of the WCST. These ERP features were: (a) the visual P100 wave; (b) a prominent P200 wave at fronto-polar areas; and (c) a large P3b wave centred in the mid-parietal region. Next a plausible interpretation of the functional significance of each of these ERP features is offered, together with some speculations about their putative brain origins.

Early sensory processing in the primary visual cortex

Lack of significant trial effects for the P50 and P100 components suggests that both task conditions received a similar degree of perceptual processing at the striate and extrastriate visual cortices. This is also a guarantee that differences in pre-stimulus feedback outcomes between WIS23 and WIS67 trials did not induce changes in the perceptual processing of subsequent trials. Thus, WIS23 trials were typically preceded by delivery of negative feedback, whereas WIS67 trials were preceded by delivery of positive feedback. Modulations of sensory-evoked brain potentials have been reported in response to changing levels of expectancy in cuing paradigms [18]. However, the lack of ERP differences at the early perceptual stages makes it unlikely that expectancy, motivational, or other unspecific attentional processes associated with feedback might be held responsible for the ERP effects found at post-perceptual stages of processing.

Visual scanning and frontal eye fields

The conspicuous P200 wave which was apparent at fronto-temporal and fronto-polar leads might reflect the activation of the frontal eye fields during the visual scanning of the stimulus display. Brooks-Eidelberg and Adler [3] described a monophasic positive waveform very similar to our P200 wave both in its duration and in its gross topographical distribution. They noted that this positive wave had its peak during, or just after, voluntary saccades. Two structures have been proposed as candidates for cortical generators of this frontal saccadic potential, namely, the frontal eye fields (FEFs, or area 8, in and near the arcuate sulcus), and the supplementary eye fields (SEFs), located dorsomedially at the rostral part of the supplementary motor area. The authors tentatively proposed the SEFs as the possible generators on the basis of the midline maximum and the lack of laterality effects [3]. However, our P200 reaches a maximum dorsally and rostrally rather than medially, which make FEFs more likely candidates of the origin of this frontal P200 wave. The frontal eye fields lie just anterior to the face–hand junction of the premotor cortex, in the posterior part of the middle frontal gyrus. They play a role in the initiation of voluntary eye movements and visual search. In particular, they are said to take part in processes of selection, comparison, analysis, and integration of various stimuli of the visual scene. Their lesion results in a visual search disorder with a deficit in the active component of perception [40].

The hemispheric asymmetry affecting the P200 wave at the fronto-temporal region could be interpreted in terms of an overlying negative electrical field centred at the left DLPFC which, in consequence, reduced the amplitude of an otherwise symmetrical left fronto-temporal P200 wave. Neither the occipital P100 wave nor the fronto-polar P200 wave differentiated between WIS23 and WIS67 trials, which suggests that both visual striate cortex and frontal eye field activation were similar in both task conditions.

Working memory and the parietal P3b wave

Another conspicuous feature of the present dataset is the large posterior P3b wave, with its distinctive hemispheric symmetry. This large P3b wave started around 300 msec after choice-card onset and lasted for another 500 msec. This P3b wave lends support to claims that the WCST summon activation of brain areas other than frontal [5, 41], and is consistent with evidence about the strong demands placed upon working memory during WCST performance [14, 41]. Both WIS23 and WIS67 trials elicited large P3b waves, although amplitudes were reliably larger for repetition trials. Lack of Task differences for occipital P3b waves indicate that these may reflect volume conduction from parietal areas.

It is well known that larger P3b amplitudes are associated with better recognition performance, which has been taken as an indication that the P3b index engagement of neocortical working memory processes leading to long-term encoding [6, 7, 26, 35]. In this respect, the finding of

larger P3b waves during WIS67 trials is consistent with the context-updating model proposed by Donchin and Coles [6]. These authors claim that the updating process involves the marking of a relevant aspect of the stimulus that make it distinctive with respect to other stimulus dimensions. This updating of the memory representation of a stimulus feature is assumed to facilitate the subsequent recall of the event, by providing valuable retrieval cues; so that the greater the updating that follows an individual event, the higher the probability of later recalling that event. This is precisely what would be expected to happen during WIS67 trials, as compared with early WIS23 trials, as the classification rule has undergone a larger amount of updating (i.e. has been made more 'distinctive' and is better consolidated into memory) towards the end of the trial series. Thus, our P3b component meets the prediction that P3b amplitude is proportional to the degree of updating of the memory representation of the relevant stimulus dimension within each classification series [7].

There was a recovery to baseline values of the frontopolar P200 component at a time when the parietal P3b wave reached its maximum. This could be interpreted in terms of a temporal sequencing of the cognitive operations indexed by each of these components. Namely, the updating of the stimulus category would take place after the visual scanning of the stimulus display has been completed.

To ascribe a putative brain origin to this P3b wave can only be done on speculative grounds. In an extensive review of intracraneal and lesion studies, Rugg [36] has evaluated the relative contribution of brain generators in prefrontal cortex, the temporo-parietal junction, and the medial temporal lobes, including hippocampal formation, to the scalp-recorded P3a and P3b components (see also [15]). In light of this evidence, the temporal–parietal junction, involving the posterior superior temporal gyrus and adjacent inferior parietal cortex of both hemispheres, appears to make the largest contribution to the scalp-recorded P3b [15, 26, 30, 36]. But even in simple oddball tasks, the resulting P3-like activity seems to reflect the interaction of multiple generators encompassing prefrontal–posterior, prefrontal–hippocampal, or posterior–hippocampal distributed networks [15, 21]. In our comparatively complex WCST protocol, signs of both P3a and P3b wave activity are present. A P3a wave is clearly visible in the 300–350 msec latency window at Fz, F3 and F4 sites (Fig. 1). No task effects were associated with this P3a component at frontal leads, except for those found at F3, most likely due to volume conduction of the DLPFC effect centred at F7 (discussed below). This early P3a might be indexing attentional orienting to every new sorting card in the series [15], and would thus be triggered by early and late trials alike. The significant task effects affecting the P3b with its mid-parietal maximun indicate that this component has a rather different functional significance. At least two different cognitive processes could be postulated in relation to this P3b wave. One has already been mentioned, which is the encoding or consolidation of a template of the classification rule into memory. The other one is the comparison of every new stimulus-card with the developing template. In both cases, it would appear that performance of the WCST demands a good deal of interaction between the contents of working memory and some register in long-term memory [10, 26]. The theoretical role of the hippocampus in the formation of new memories, and its consideration as a comparator fits in well with this postulated interaction between working memory and long-term memory [10, 26, 30], and is also consistent with reports that hippocampal lesions compromise WCST performance [5, 41]. Further research would be necessary to elucidate whether the template is progressively stored in association cortex at the temporo-parietal junction, or whether it might temporarily be held at hippocampal structures, while it is being compared with incoming information from working memory. Dipole EEG modeling using a larger number of electrodes might help to clarify these issues [21].

Attentional set-shifting and the left DLPFC

Another finding of our study was the association of both WCST task conditions with what might be a negative field potential centred in the fronto-temporal region of the left hemisphere. Significant Task effects suggested that this field potential was stronger during WIS23 trials. We suggest that this long-lasting negative potential might reflect the activation of the left DLPFC. This interpretation would be in accord with many functional neuroimaging studies which have consistently reported increases in activation at the DLPFC of the left hemisphere during performance of the WCST [13, 24, 32]. Weinberger and collaborators have reported a bilateral prefrontal rCBF activation [43], or even activation of the right anterior DLPFC [19]. However, Marenco *et al.* also described a marginal SPET activation at the left posterior DLPFC area. Moreover, they reported a set of reliable correlations between perfusion values at the left prefrontal region and WCST performance [19].

It may seem difficult to draw an analogy between our ERP data and SPET or rCBF results given the coarse spatial resolution of the former. However, many neuroimaging studies also suffer certain technical limitations which obscure interpretation of results. Control over stimulus and response factors is compromised by the need to average metabolic changes often over 1 min periods. This makes it impossible to differentiate between correct and incorrect trials, let alone motor and cognitive processes in a sub-second scale. It is not surprising then, that neuroimaging studies of the WCST yield an apparently non-specific brain activation, with implication of areas as far apart as the left primary sensory-motor cortex, premotor and supplementary motor area, left parietal cortex, right operculum, bilateral cuneus or the cerebellum [24].

In spite of these difficulties, it is tempting to draw some comparisons. It seems plausible that Marenco *et al.*'s SPET bilateral activation corresponds with the distinctive fronto-polar P200 wave which was most conspicuous bilaterally and anteriorly. In turn, their left posterior DLPFC activation may correspond with what we interpret to be a negative field potential centred at the F7 site. Early WCST research found no significant differences between left and right frontal lobe patients [22]. Others have reported that deficits in card sorting are more frequent and more lasting after left frontal than right frontal lobe damage [8, 40]. A larger implication of the left DLPFC is supported by reports that WCST performance is not deteriorated after surgical removal of the right frontal structures, including dorsolateral prefrontal and orbital areas [41]. From a theoretical point of view, the implication of semantic networks in abstract reasoning and visual classification is more consistent with a left hemisphere locus of operation of WCST effects [31].

To date few ERP studies have assessed the validity of the WCST as a frontal lobe task, and results have not been clear-cut. Thus, Mattes *et al.* [20] did not find specific impairment in frontal slow cerebral potentials of schizophrenic patients during the WCST. Moreover, they failed to find significant differences between classification and repetition trials (that is, WIS23 and WIS67 trials) at any of the ERP time windows explored. Their significant Group and Task effects were confined to feedback periods, which makes difficult the interpretation of results due to the likely influence of expectancy and motivational factors. The authors attributed their inconclusive results to two possible weaknesses; namely, that the appropriate parts of the trials were not measured, and that only midline recordings were obtained. Besides, in their task protocol key-cards were presented 1500 msec after the choice-card, whereas in the standard WCST protocol key-cards remain permanently in sight. Our results suggest that Mattes *et al.*'s self-criticisms should not be overlooked in future ERP research on the WCST [20].

From the three ERP components identified as related to card sorting, at least one of them has a non-frontal origin (the P3b wave). This finding is in itself relevant to the current debate about the sensitivity and specificity of the WCST to prefrontal function [23, 41]. Among the frontal ERP components, perhaps the fronto-temporal hemispheric asymmetry is the one which deserves more careful consideration for being a novel feature. Even though it is tempting to relate it to the activation of the left DLPFC, alternative hypotheses about its brain origin remain the matter for future research. There are two arguments which support a genuine brain origin of the fronto-temporal asymmetry against a contamination from the retino-corneal potential during horizontal eye movements. Firstly, the fronto-polar P200 wave is a genuine brain potential related to horizontal saccades which shows a neat *hemispheric symmetry* regardless of the direction of saccades [3]. Secondly, key-cards rendered the same visual angle (12°) in both WIS23 and WIS67 trials, but these two task conditions differed significantly at left fronto-temporal and temporal electrodes. If the P200 wave reflects genuine brain activation associated with horizontal scanning of the visual display, and WIS23 and WIS67 trials elicited similar fronto-polar P200 waves, it follows that the hemispheric asymmetry cannot be simply attributed to differential oculomotor activation. Such an interpretation has gained support from a preliminary study in our laboratory where key-cards rendered a much narrower (4.5°) visual angle. The issue of a likely confounding with visual scanning mechanisms should be tackled in future research about the functional role of the left DLPFC during the execution of the WCST. Our suggestion of a left DLPFC involvement in the WCST is also consistent with a recent report by Lacroix *et al.*, who found a focus of EEG coherence at the left prefrontal F7 area relative to other parietal, frontal and temporal regions [16].

One major obstacle in localization of higher brain functions is the definition of the cognitive operations themselves [40]. A good deal of progress has been made using well-standardized and operationally valid task paradigms, such as the attentional set-shifting paradigm. This may be taken as a simplified analog of the WCST, and can also be used in experimental research with monkeys [33, 34]. Roberts *et al.* hypothesize that attentional set shifting is mediated by a balanced interaction of prefrontal and striatal dopaminergic activity, with enhanced shifting following depressed prefrontal dopaminergic function, and impaired shifting resulting from elevated prefrontal dopaminergic function and depressed striatal dopaminergic function. This hypothesis has the merit of being consistent with the presumed inhibitory role of dopaminergic pathways in prefrontal cortex. If this is so, deficits in attention set shifting ability and perseverative responses may both be linked to problems in inhibitory control. This would explain the poor performance of prefrontal patients on the WCST in terms of their inability to suppress previous incorrect responses, and explains why Parkinson's disease and other frontal lobe patients are mostly impaired in their ability to perform extradimensional shifts in attention [27]. Under this interpretative framework, the negative ERP wave affecting mostly WIS23 trials might be taken to signal the operation of dopaminergic inhibitory pathways along the left DLPFC. This line of reasoning has also led to the generalized use of the WCST to assess hypothetical prefrontal dysfunction in schizophrenia [4, 17, 43], and in other psychiatric conditions [1]. However, with the implication of brain areas other than frontal, the utility of the WCST on its own as a valid diagnostic tool of frontal dysfunction is at stake. Even if frontal function is correctly diagnosed, more than one cognitive function might be compromised (i.e. visual scanning versus inhibitory control).

ERPs have already made substantial contributions to the study of cognition and psychopathology, and have the potential to make more substantial contributions in

the future. One line of research would be to study functional brain systems involved in the execution of different neuropsychological tests traditionally regarded as measures of frontal function, such as the WCST or the Halstead Category Test. All being regarded as tests of frontal function, they have been shown to share a small variance of their performance scores [28]. ERPs are particularly well-suited to capture the dynamics of cognitive processes, and could contribute further to searching for similarities and differences between neuropsychological tests both at the behavioural and electrophysiological levels. In so doing, it would be necessary to adopt a system level approach, with a larger number of electrodes to obtain a wider sampling of brain activation which would help make more precise anatomical inferences. In this study we have shown the potential utility of ERPs' measures in establishing links between neurophysiological constructs and cognitive processes, and hence, towards the improvement of the construct validity of neuropsychological tests.

Acknowledgements—An earlier version of this paper was presented to the First Conference on Functional Mapping of the Human Brain, Paris, June 1995. This work was partly supported by a postdoctoral grant from the Ministerio de Educación y Ciencia awarded to Francisco Barceló, and by funds from the Fundación Ramón Areces to the Brain Mapping Unit. Thanks are due to Dr. M. D. Rugg and two anonymous reviewers for their detailed comments on an earlier version of this article. We acknowledge the computer assistance of Mr Fernando Rodrìguez-Bermejo in the preparation of the Figures.

References

1. Abbruzzese, M., Bellodi, L., Ferri, S. and Scarone, S. Frontal lobe dysfunction in schizophrenia and obsessive–compulsive disorder: A neuropsychological study. *Brain and Cognition* **27,** 202–212, 1995.
2. Anderson, S. W., Damasio, H., Jones, R. D. and Tranel, D. Wisconsin Card Sorting Test performance as a measure of frontal lobe damage. *Journal of Clinical and Experimental Neuropsychology* **13,** 909–922, 1991.
3. Brooks-Eidelberg, B. A. and Adler, G. A frontal cortical potential associated with saccades in humans. *Experimental Brain Research* **89,** 441–446, 1992.
4. Catafau, A. M., Parellada, E., Lomeña, F. J., Bernardo, M., Pavia, J., Ros, D., Setoain, J. and González-Monclus, E. Prefrontal and temporal blood flow in schizophrenia: Resting and activation technetium-99m-HMPAO SPECT patterns in young neuroleptic-naive patients with acute disease. *Journal of Nuclear Medicine* **35,** 935–941, 1994.
5. Corcoran, R. and Upton, D. A role for the hippocampus in card sorting? *Cortex* **29,** 293–304, 1993.
6. Donchin, E. and Coles, M. G. H. Is the P300 component a manifestation of context updating? *Behavioral Brain Science* **11,** 357–427, 1988.
7. Donchin, E. and Fabiani, M. The use of event-related brain potentials in the study of memory: Is P300 a measure of event distinctiveness? In *Handbook of Cognitive Psychophysiology*, J.R. Jennings and M. Coles (Editors), pp. 471–510. Wiley, New York, 1991.
8. Drewe, E. A. The effect of type and area of brain lesion on Wisconsin card sorting test performance. *Cortex* **10,** 159–170, 1974.
9. Eslinger, P. J. and Damasio, A. R. Severe disturbance of higher cognition after bilateral frontal lobe ablation: Patient EVR. *Neurology* **35,** 1731–1741, 1985.
10. Fuster, J.M. *Memory in the Cerebral Cortex*. An empirical approach to neural networks in the human and nonhuman primate. The MIT Press, Cambridge, Mass., 1995.
11. Heck, E. T. and Bryer, J. B. Superior sorting and categorising ability in a case of bilateral frontal lobe atrophy: An exception to the rule. *Journal of Clinical and Experimental Neuropsychology* **10,** 467–476, 1986.
12. Hermann, B. P., Wyler, A. R. and Richey, E. T. Wisconsin Card Sorting Test performance in patients with complex partial seizures of temporal lobe origin. *Journal of Clinical and Experimental Neuropsychology* **10,** 467–476, 1988.
13. Kawasaki, Y., Maeda, Y., Suzuki, M., Urata, K., Higashima, M., Kiba, K., Yamaguchi, N., Matsuda, H. and Hisada, K. SPECT analysis of regional cerebral blood flow changes in patients with schizophrenia during the Wisconsin card sorting test. *Schizophrenia Research* **10,** 109–116, 1993.
14. Kimberg, D. Y. and Farah, M. J. A unified account of cognitive impairments following frontal lobe damage: The role of working memory in complex, organized behavior. *Journal of Experimental Psychology*: *General* **122,** 411–428, 1993.
15. Knight, R.T., Grabowecky, M.F. and Scabini, D., Role of human prefrontal cortex in attention control. In *Epilepsy and the functional Anatomy of the Frontal Lobe*, H.H. Jasper, S. Riggio, and P.S. Goldman-Rakic (Editors), pp. 21–36. Raven Press, New York, 1995.
16. Lacroix, D., Vo, T.M.D., Lamer, R. and Chaput, Y. Imaging of quantified EEG coherence changes during the WCST in healthy subjects. *Human Brain Mapping*, Suppl. 2 (Abstract), 1995.
17. Lenzenweger, M. F. and Korfine, L. Perceptual aberrations, schizotypy, and the Wisconsin Card Sorting Test. *Schizophrenia Bulletin* **20,** 345–357, 1994.
18. Mangun, G. R. and Hillyard, S. A. Modulations of sensory-evoked brain potentials indicate changes in perceptual processing during visual–spatial priming. *Journal of Experimental Psychology*: *Human Perception and Performance* **17,** 1057–1074, 1991.
19. Marenco, S., Coppola, R., Daniel, D. G., Zigun, J. R. and Weinberger, D. R. Regional cerebral blood flow during the Wisconsin card sorting test in normal subjects studied by xenon-133 dynamic SPECT: Comparison of absolute values, percent distribution values, and covariance analysis. *Psychiatric Research Neuroimaging* **50,** 177–192, 1993.
20. Mattes, R., Cohen, R., Berg, P., Canavan, A. G. M. and Hopmann, G. Slow cortical potentials (SCPS) in schizophrenic patients during performance of the

Wisconsin card-sorting test (WCST). *Neuropsychologia* **29,** 195–205, 1991.
21. Mecklinger, A. and Ullsperger, P. The P300 to novel and target events: A spatio-temporal dipole model analysis. *NeuroReport* **7,** 241–245, 1995.
22. Milner, B. Effects of different brain lesions on card sorting. *Archives in Neurology* **9,** 90–100, 1963.
23. Mountain, M. A. and Snow, W. G. Wisconsin Card Sorting Test as a measure of frontal pathology: A review. *Clinical Neuropsychology* **7,** 108–118, 1993.
24. Nagahama, Y., Fukuyama, H., Yamauchi, Y., Matsuzaki, S., Ouchi, Y., Kimura, J., Yonekura, Y. and Shibasaki, H. Functional localization and lateralization of the activated cortex during the Wisconsin Card Sorting Test. *Human Brain Mapping*, Suppl. 2 (Abstract), 1995.
25. Nelson, H. E. A modified card sorting test sensitive to frontal lobe defects. *Cortex* **12,** 313–324, 1976.
26. Nielsen-Bohlman, L. and Knight, R. T. Electrophysiological dissociation of rapid memory mechanisms in humans. *NeuroReport* **5,** 1517–1521, 1994.
27. Owen, A. M., Roberts, A. C., Polkey, C. E., Sahakian, B. J. and Robbins, T. W. Extra-dimensional versus intra-dimensional set shifting performance following frontal lobe excision, temporal lobe excision or amygdalo-hippocampectomy in man. *Neuropsychologia* **29,** 993–1006, 1991.
28. Perrine, K. Differencial aspects of conceptual processing in the category test and the Wisconsin Card Sorting Test. *Journal of Clinical and Experimental Neuropsychology* **15,** 461–473, 1993.
29. Pivik, R. T., Broughton, R. J., Coppola, R., Davidson, R. J., Fox, N. and Nuwer, M. R. Guidelines for the recording and quantitative analysis of electroencephalographic activity in research contexts. *Psychophysiology* **30,** 547–558, 1993.
30. Polich, J. and Squire, L. R. P300 from amnesic patients with bilateral hippocampal lesions. *Electroencephalography and Clinical Neurophysiology* **86,** 408–417, 1993.
31. Posner, M. I. and Petersen, S. E. The attention system of the human brain. *Annual Reviews Neuroscience* **13,** 25–42, 1990.
32. Rezai, K., Andreasen, N. C., Alliger, R., Cohen, G. *et al*. The neuropsychology of the prefrontal cortex. *Archives in Neurology* **50,** 636–642, 1993.
33. Roberts, A. C., Robbins, T. W. and Everitt, B. J. The effects of intradimensional and extradimensional shifts on visual discrimination learning in humans and non-human primates. *Quarterly Journal of Experimental Psychology* **40,** 321–341, 1988.
34. Roberts, A. C., De Salvia, M. A., Wilkinson, L. S., Collins, P., Muir, J. L., Everitt, B. J. and Robbins, T. W. 6-hydroxydopamine lesions of the prefrontal cortex enhance performance on an analog of the Wisconsin card sort test: Possible interactions with subcortical dopamine. *Journal of Neuroscience* **14,** 2531–2544, 1994.
35. Ruchkin, D. S., Johnson, R., Grafman, F., Canoune, H. and Ritter, W. Distinctions and similarities among working memory processes: An event-related potential study. *Cognitive Brain Research* **1,** 53–66, 1992.
36. Rugg, M.D. Cognitive event-related potentials: Intracranial and lesion studies. In *Handbook of Neuropsychology*, *Vol*. 10, F. Boller and J. Grafman (Editors), pp. 165–185. Elsevier, Amsterdam, 1995.
37. Semlitsch, H. V., Anderer, P., Schuster, P. and Preslich, O. A solution for reliable and valid reduction of ocular artifacts applied to the P300 ERP. *Psychophysiology* **23,** 695–703, 1986.
38. Shallice, T. and Burgess, P. W. Deficits in strategy application following frontal lobe damage in man. *Brain* **114,** 727–741, 1991.
39. Stuss, D. T. and Benson, D. F. Neuropsychological studies of the frontal lobes. *Psychological Bulletin* **95,** 3–28, 1984.
40. Stuss, D.T. and Benson, D.F. *The Frontal Lobes*. Raven Press, New York, 1986.
41. Upton, D. and Corcoran, R. The role of the right temporal lobe in card sorting: A case study. *Cortex* **31,** 405–409, 1995.
42. Van der Broek, M. D., Bradshaw, C. M. and Szabadi, E. Utility of the modified Wisconsin Card Sorting Test in neuropsychological assessment. *British Journal of Clinical Psychology* **32,** 333–343, 1993.
43. Weinberger, D. R., Berman, K. F. and Zee, R. F. Physiologic dysfunction of dorsolateral prefrontal cortex in schizophrenia. *Archives in General Psychiatry* **43,** 114–124, 1986.

Appendix

Definition of variables

Medians, means and standard deviations for various WCST scoring criteria across the sample of 24 normal volunteers

	Median	Mean	S.D.
Total No. trials	252	252	0
Total No. series	36	36	0
Categories completed	35	34	3.8
Total No. errors	56	58.9	11.2
Perseverative errors	20.0	18.3	10.4
Random errors	3.5	4.6	3.75
WIS67 random errors	1.0	1.9	2.38
Anticipations	1.0	0.8	0.9

Perseverative errors:	All consecutive errors starting from the second trial in the series.
Random errors:	Those occurring after at least one correct response.
WIS67 random errors:	Random errors occurring in the last two trials of the series.
Anticipations:	Whenever the first stimulus in the series was classified correctly. Guessing of the new classification rule motivated the rejection of ERP data for that series.
Categories completed:	The criteria for achieving a category were: (a) there was no anticipation; (b) there were less than four perseverative errors; and (c) there were no WIS67 random errors.