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Attentional set shifting modulates the target P3b Response in the Wisconsin card sorting test

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Abstract

For years the Wisconsin card sorting test (WCST) has been used as a test of frontal lobe function. Recent event-related potential (ERP) research has shown large differences in the amplitude of P3b responses evoked by early and late trials within each WCST series ([8]: Barceló F., Sanz M., Molina V., Rubia FJ. The Wisconsin Card Sorting Test and the assessment of frontal function: A validation study with event-related potentials. Neuropsychologia 1997;35:399–408). In this study, 16 normal subjects performed a WCST adaptation to investigate the role of attentional set shifting in these WCST P3b effects. Two control tasks were designed to examine whether early–late WCST P3b changes reflect category selection (attention) or category storage (memory) operations. Results suggest both a sharp P3b attenuation during shift WCST trials, followed by a gradual P3b build-up during post-shift trials. This P3b modulation could not be attributed to selection or storage of simple sensory stimulus dimensions, nor was it observed when the new rule was externally prompted by the first card in the WCST series. Instead, WCST P3b changes seem related to the endogenously generated shift in the perceptual rule used to sort the cards (i.e., the shift in set). The gradual build-up in P3b amplitude paralleled a progressive improvement in sorting efficiency over several post-shift WCST trials. A model based on formal theories of visual attention and attentional set shifting is proposed to account for these effects. The model offers firm grounds for prediction and bridges the gap between related clinical and experimental evidence.

Keywords: Attention; Evoked potentials; Prefrontal cortex; Wisconsin card sorting test; Working memory

1. Introduction

The Wisconsin card sorting test (WCST) originally earned its reputation as a test of frontal lobe function and has long been adopted as an indicator of frontal dysfunction in neuropsychology, behavioural neurology and neuropsychiatry [32,38,40,56]. However, the validity of WCST scores for pinpointing lesions in specific brain areas has been questioned [3,13,26,38,41], and neuroimaging studies confirm that the WCST elicits activity from a widespread network of brain areas [10,36,37,42]. All this evidence is consistent with the view that card sorting entails attention and working memory operations [17,18,48], that are best described as dynamic processes subserved by distributed neural networks [16,24,33,47]. Event-related potential (ERP) studies have revealed rapid changes in neural activation over both frontal and non-frontal regions during card sorting [7,8,39]. Two ERP features have been characterised so far within half a second of each card sort: (1) a large P3b wave over mid-parietal areas; (2) a slow negative wave centred in the left frontal-temporal area [7,8]. More importantly, these two ERP features changed significantly from early to late trials within each WCST series.

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Late trials in the WCST series evoke significantly larger P3b waves than early trials, and correct sorts midway in the WCST series evoke P3b amplitudes midway those elicited in early and late trials [7,8]. These early–late WCST P3b effects were originally taken to reflect the gradual updating of a working memory representation for the stimulus category along each WCST series [8,19]. Alternatively, these WCST P3b effects might also reflect subjective probability [55], perceptual (i.e., attentional) closure [57,59], or stimulus-response matching processes [30]. Anatomical sources for the target P3b response have been proposed at temporo-parietal and mesial temporal association cortices [7,27,28,30,33–35,60].

A P3b asymmetry during early WCST trials was originally attributed to the overlap of activation from the left dorsolateral prefrontal (DLPF) cortex during category selection and inhibitory control [8]. More recently, it has been shown that the asymmetry is maximal over temporal areas, and source analyses indicate a plausible contribution from left mesial temporal lobe regions [7]. The asymmetry coexists with a reduced mid-parietal P3b during early WCST trials. Hence, the existing evidence suggests that the asymmetry and the P3b wave reflect two different neurocognitive processes that interact during early WCST trials, whereas only the latter prevails during late WCST trials. However, it is not clear whether attention (i.e., category selection) or memory processes (i.e., the gradual build-up of a category template in working memory) are responsible for these WCST P3b effects. To clarify this issue it would be helpful to isolate the presence of category selection and storage operations within the WCST series.

Early WCST trials demand a shift in attention to a stimulus dimension different from the one reinforced in the previous series. This process has been referred to as extra-dimensional (ED) set shifting [18,50]. Late WCST trials are sorted by the same stimulus dimension that was relevant in previous sorts, and so involve intra-dimensional (ID) set shifting [17,50]. These two processes belong to the realm of category selection, a type of selective attention less studied than either spatial or feature selection [15,21]. Within this framework, the build-up of a memory template for the ongoing stimulus dimension along the WCST series is compatible with ID shifts, but not with ED shifts. Two control tasks were designed to isolate category storage from category selection. One control task required ID shifts like those present during late WCST trials (WID task). A second control task demanded constant ED sorts, and so precluded the storage of any single stimulus dimension (WED task). Therefore, the gradual build-up of a memory template for the stimulus category would be possible in the WID task, but not in the WED task.

The main purpose of this study was to explore the functional meaning of early–late WCST P3b effects, and in particular, the hypothetical association of the WCST P3b and its related asymmetry with category storage and selection, respectively. If the increment in P3b amplitude from early to late WCST trials is due to the gradual development of a template for the stimulus category in working memory, then a gradual increase in P3b amplitude would be expected from early to late WID trials. No such an enhancement in P3b amplitude was expected during WED trials, that are incompatible with the storage of information about any one stimulus dimension. Our WCST adaptation was designed to explore attentional set shifting operations rather than other processes also addressed in the conventional WCST like concept-formation or problem-solving [38,40].

2. Methods

2.1. Subjects

Sixteen right-handed young volunteers (eight women and eight men; mean age = 20.8 years, SD = 2.7, range = 19–28 years) took part in the study. Subjects had normal or corrected to normal vision and no history of neurological or psychiatric disease. They signed a consent form and were paid for their participation.

2.2. Stimuli and procedure

A computer version of the WCST was designed to assess set shifting ability, rather than other aspects of the conventional WCST like concept-formation or problem-solving [38,40]. Thus, subjects were informed about the three possible classification rules, and received 5 min practice before the experimental run. The task also incorporated special features for ERP research [7,8,39]. The coloured geometrical shapes were outlined in black upon a white background to improve visual contrast. Cards were matched in luminance and displayed upon a grey background. Each trial began with the onset of a compound stimulus with the four WCST reference cards on top of one response card, all centred on the computer screen (Fig. 1). The compound stimulus subtended a visual angle of 4° horizontally and 3.5° vertically. Testing took place in an electrically shielded, quiet and dimly illuminated room. Subjects sat in a comfortable armchair 1.5 m away from the video display. Subjects were instructed to match the response card with one of the four reference cards following one of three possible rules: number, colour, or shape. The correct sorting principle was to be determined on the basis of auditory feedback delivered 1.6 s after the response through a

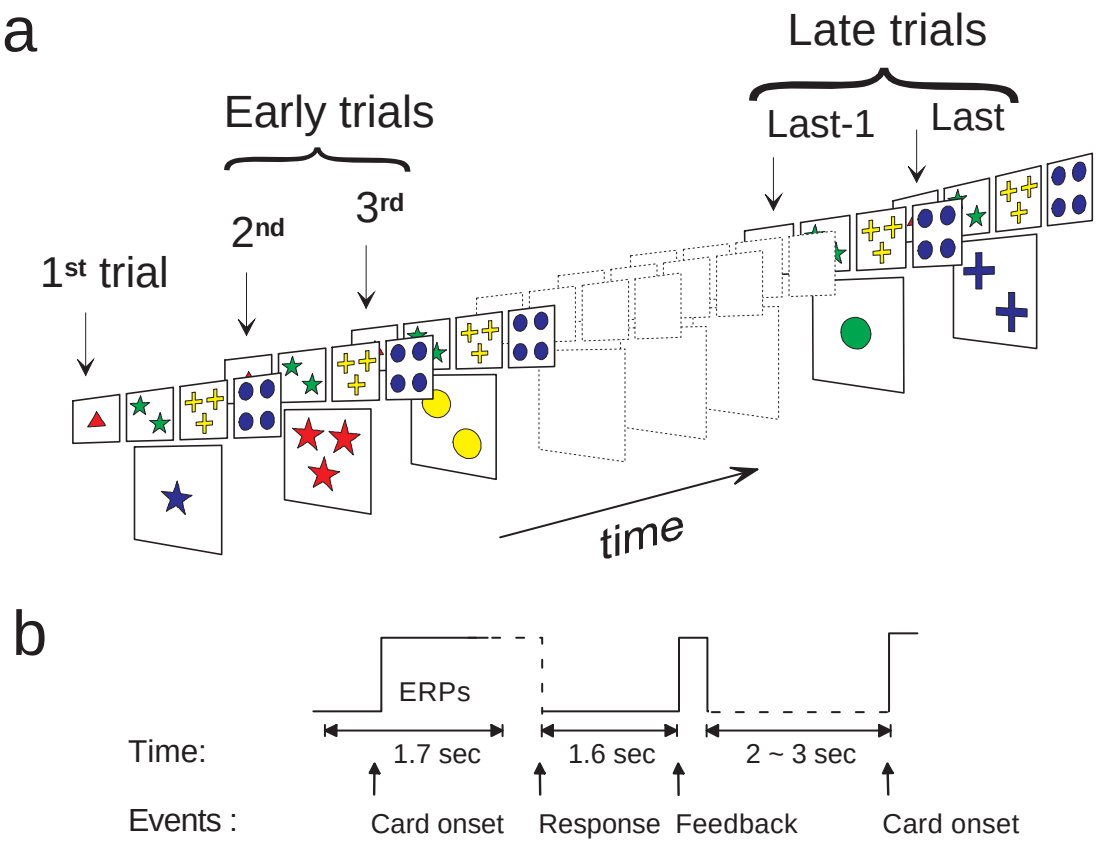

Fig. 1. Schematic example of one WCST series and epoch for ERP analysis. (a) WCST series varied randomly between six and nine trials. Each trial started with the display of the four WCST reference cards on top of one response card, all centred on the computer screen. Subjects used a four-button response panel for sorting, were informed about the task's rules, and had 5 min practice. The task consisted of two runs of 18 series each. (b) ERPs were recorded for 1700 ms locked to the card's onset, including a 200 ms prestimulus baseline. Auditory feedback was delivered 1600 ms after the response (a 2000 Hz tone for correct, a 500 Hz tone for incorrect). The interval between feedback offset and the next WCST card varied randomly between 2 and 3 s.

computer-generated tone (duration = 300 ms; loudness = 75 dB; 2000 Hz for correct, 500 Hz for incorrect). For our fully instructed and trained subjects, a negative feedback was an indication to shift the sorting principle in the next trial. This basically occurred either after the first or second trials in the series (see Fig. 1; Table 1). A negative feedback anywhere else in the WCST series motivated rejection of ERP data from that series. The interval between feedback offset and the next WCST trial varied randomly between 2 and 3 s. Subjects used a response panel with four buttons aligned. The far left button designated the reference card on the far left of the display, the far right button designated the reference card on the far right, and so on. Subjects used their thumbs for responding while holding the response panel with both hands. Tasks required an equal number of presses with each of the four buttons. Subjects were asked to sort briskly and accurately. Trials were ordered semi-randomly with the constraint that the four first response cards in the series could be sorted unambiguously. Elimination of ambiguity eased the scoring of the test and improved the signal-to-noise ratio in the ERPs. Series varied randomly between six and nine trials, so that

Table 1
Mean accuracy scores and reaction times (RT) for the WCST and the two control tasks (standard deviations are in parenthesis)

	WCST	WID task	WED task
Total number of series	36	18	18
Completed series	30.2 (3.5)	16.6 (1.2)	15.2 (2.7)
Total number of errors	27.5 (5.7)	4.1 (2.6)	5.8 (3.5)
Early trials errors	21.0 (4.4)[a]	1.1 (1.6)	1.8 (1.5)
Late trials errors	1.6 (1.8)	1.5 (0.6)	1.6 (1.4)
Anticipations	1.1 (1.0)	–	–
RTs for early trials (s)	1.5 (0.4)	1.0 (0.2)	2.7 (0.6)
RTs for late trials (s)	1.0 (0.2)	1.0 (0.2)	2.6 (0.6)

[a] Mean ± SD of 2nd trial 'efficient errors' = 14.2 ± 1.1 (see section 2).

subjects could not predict the start of a new series. One WCST block consisted of 18 series (i.e., six series per category), and took an average of 14 min to complete. Series were sequenced semi-randomly with the only constraint that the same rule did not apply in consecutive series. A second WCST block was delivered after the two control tasks described below.

The two control tasks used the same general layout as the WCST, including the compound stimulus of four reference cards plus one response card. The length and number of series, timing and structure of trials remained as those for the WCST. Minor changes included the type of instructions delivered to the subjects and the introduction of 12 new response cards. The WID task was designed to explore the effects of intra-dimensional (ID) shifts of attention devoid of the influence of extra-dimensional set shifting. To this end, the first response card of each WCST series was replaced by one which provided the correct sorting category for that series. A set of 12 new response cards was constructed with this purpose. These included four cards with each of the four numerals, four cards with each of the four geometrical shapes, and four plain coloured cards. Shapes and numerals were black drawings upon a white background. These 12 new cards, therefore, clearly denoted the next correct category. The other response cards in the series remained as in the WCST protocol. Subjects were instructed to match the response card to one of the four reference cards according to the target category denoted by the first card.

The WED task addressed the effects of extra-dimensional (ED) shifts of attention in the absence of memory storage of any single stimulus dimension. Subjects were instructed to sort response cards in the pile which shared none of the card's attributes. For instance, one blue star would be sorted in the third pile (see Fig. 1). All trials had a unique correct answer which varied randomly from trial to trial. In this sense, the WED task demanded constant ED shifts of attention and precluded the build-up of a memory template for any single stimulus dimension. The average duration of each control task was 14 min, with a 5 min rest period between the tasks. The order of presentation of tasks was counterbalanced across subjects.

2.3. ERP recording and analysis

The electroencephalogram (EEG) was recorded from 29 tin electrodes positioned according to the extended 10–20 system [2] and referenced to the left mastoid. The EEG was amplified with a band pass from DC to 30 Hz (12 dB/octave roll-off); and digitised at 250 Hz over a 1700 ms epoch including a 200 ms prestimulus baseline. Impedances were kept below 5 kΩ. The electrooculogram (EOG) was also recorded using a bipolar derivation from the supraorbital ridge of the left eye to the outer canthus of the right eye for blink and horizontal eye movement correction [53]. After EOG correction, trials exceeding EEG amplitudes of ± 75 μV at any of the active electrodes, or with residual muscle or movement artifacts, were discarded. Trials with response latencies over 4 s were also discarded.

Only complete WCST series were considered in the ERP averages (see Table 1). A complete series was scored if all three conditions were met that (a) the new sorting rule was not anticipated (i.e., the first trial was sorted by the previous rule and resulted in a negative feedback); (b) the subject found the category either in the second or third WCST trials, and (c) the category was not missed thereafter. Since series were ordered randomly, subjects had to make a guess after the first negative feedback of the new series (Fig. 1). Hence, an ideal subject had a 50% chance to choose the wrong category in the second trial of a new WCST series. These second trial errors can be defined as 'efficient errors', as they involve a shift in category and are followed by correct sorts in all remaining trials of that series [4,5]. Therefore, only one 1st trial error and one 2nd trial efficient error were allowed in complete WCST series (Table 1). As in previous studies, the 2nd and 3rd trials from all complete WCST series were averaged into an Early WCST waveform, and the last two trials were averaged into a Late WCST waveform [7,8]. For the control tasks, early and late trials were also averaged separately. Only series with no errors entered the averages of the control tasks. Averages were not filtered to explore fast ERP activity.

A linked-mastoid reference was computed off-line for the averaged data. Mean amplitudes were measured relative to a 200 ms prestimulus baseline. Measurements were obtained from five latency windows: P1 (100–130 ms), N1 (155–175 ms), P2 (185–215 ms), N2 (305–335 ms), and P3b (450–600 ms). These windows were determined after inspection of individual and group grand averages (see insert in Fig. 2), and correspond with those used in the recent literature [8,33]. Fast extrastriate ERP components were measured for comparison with visual spatial and feature selection studies [9,33], but the present report will focus on P3b activity only.

2.4. Statistical analysis

Three within-subjects ANOVA designs were used to test the hypotheses of this study. The first series of ANOVAs compared early and late trials from each task separately, and involved four within-subject factors, namely, trials (early, late), sagittal (anterior, posterior), hemisphere (left, right) and electrode (six placements). Mid-line electrodes did not enter these analyses. A second ANOVA design

explored the predicted similarities between WCST P3b waves and those evoked by the control tasks. Two planned comparisons were defined between early and late WCST P3b values and their respective control counterparts, with one degree of freedom per contrast. A third ANOVA design assessed, on a trial-by-trial basis, the gradual or discrete nature of those significant early–late P3b modulations observed in the previous series of analyses.

ANOVAs adopted a partial factorial model with the main effects for trials or task and their interactions with the other within-subject factors. ANOVA results are reported with Greenhouse–Geisser adjusted degrees of freedom where appropriate. Tests of main effects are reported using a familywise probability level of 0.05. The latency and accuracy of behavioural responses were assessed through two ANOVAs with task (WCST, WID and WED) and trials (early, late) as within-subject factors.

3. Results

3.1. Behavioural performance

Subjects shifted category efficiently, made few perseverative or non-perseverative errors, and completed 30 out of 36 series on average (Table 1). A complete WCST series was scored if (a) there was no anticipation of the sorting rule; (b) the new correct category was found either in the second or in the third trial, and (c) the category was not missed thereafter (cf. [5,6,8]).

Sorting a WCST card typically took over 1 s, and only 7.5% of all trials were sorted in less than 600 ms. Reaction times in early trials were slower than those in late WCST trials [$F(1,15) = 66.1$, $P < 0.0001$]. Response latencies in early and late trials from the control tasks did not differ significantly. Moreover, reaction times in late WCST trials did not differ from

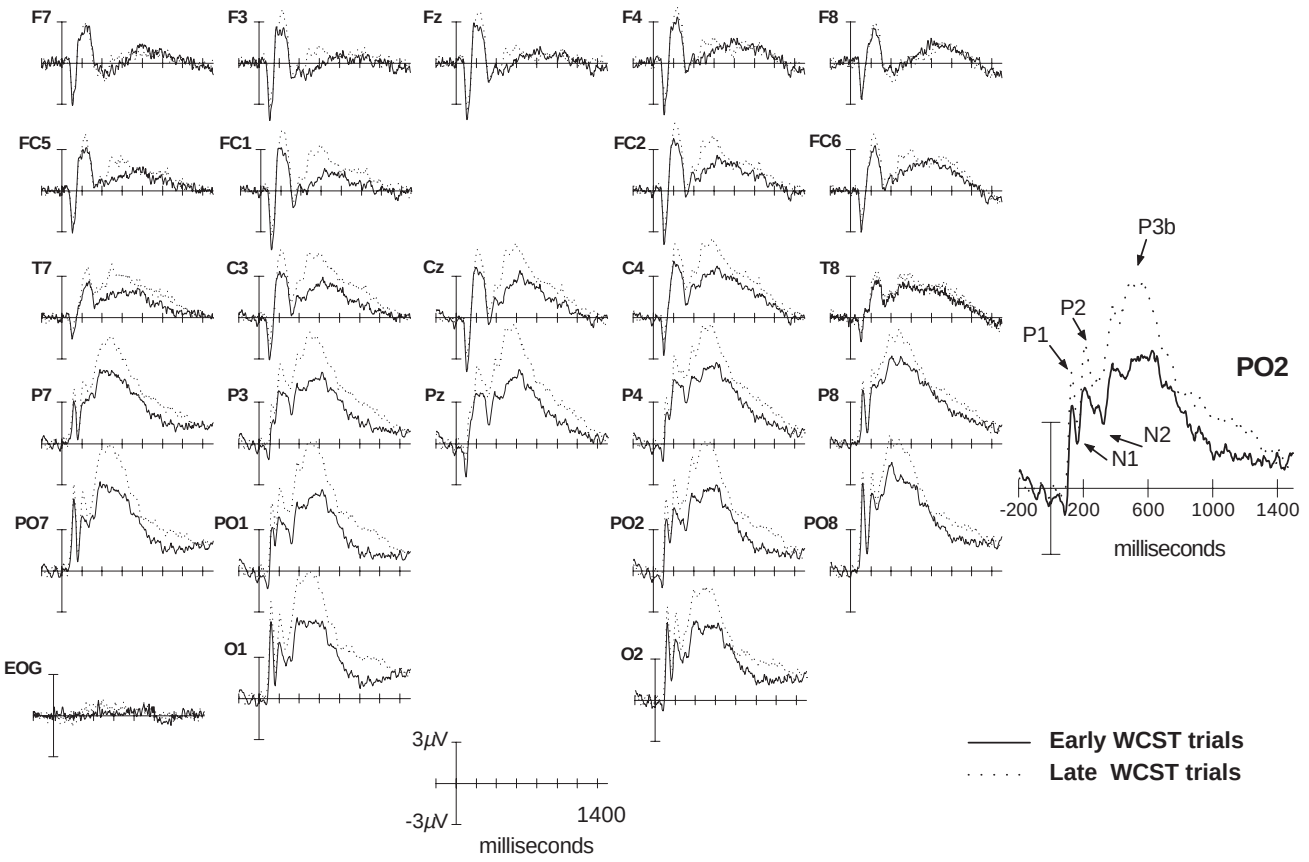

Fig. 2. Early–late WCST P3b effects. *Main panel*: Grand ERP averages for early and late WCST trials at frontal and posterior electrodes. Vertical bars indicate the onset of the reference cards plus response card compound. Waveforms represent linked-mastoid referenced averages from 16 normal subjects. Residual EOG activity after artefact correction is plotted in the lower left-hand corner. *Insert*: Detailed illustration of ERP measurements at PO2.

Table 2
ANOVA *F*-ratios for fast ERPs evoked by early and late WCST trials[a]

Effects	df	P1 (100–130 ms)	N1 (155–175 ms)	P2 (185–215 ms)	N2 (305–335 ms)
Trials (early/late)	1, 15	9.1**	–	9.0**	6.2*
Trials × hemisphere	1, 15	–	–	–	–
Trials × sagittal	1, 15	–	–	5.7*	9.4**
Trials × electrode	5, 75	5.5**	–	4.5*	6.2**
T × H × S	5, 75	–	–	–	–
T × H × E	5, 75	–	–	–	–
T × E × S	5, 75	4.8**	–	–	4.5*
T × H × S × E	5, 75	–	–	–	–

[a] Note: $^{*}P < 0.05$; $^{**}P < 0.01$ (Greenhouse–Geisser).

those in WID trials [$F(1,15) = 0.83$, ns]. In contrast, reaction times in early WCST trials were significantly faster than those in WED trials [$F(1,15) = 105.9$, $P < 0.0001$]. Finally, error rates in late WCST trials did not differ from those of WID trials [$F(1,15) = 2.1$, ns], or WED trials [$F(1,15) = 0.05$, ns] (see Table 1).

3.2. P3b activity in early and late WCST trials

Grand ERP averages displayed in Fig. 2 are consistent with results from previous reports [4,7,8], and reveal a large P3b wave over the mid-parietal region and a slight asymmetry across temporal areas. The analysis of P3b amplitudes yielded significant main effects for trials [$F(1,15) = 23.3$, $P < 0.002$], trials and sagittal [$F(1,15) = 15.9$, $P < 0.001$], trials and electrode [$F(5,75) = 20.5$, $P < 0.0001$, $\epsilon = 0.42$], and trials, electrode and sagittal [$F(5,75) = 5.9$, $P < 0.002$, $\epsilon = 0.58$]. These effects reflected significantly larger P3b amplitudes for late than for early WCST trials at central [at Cz: $F(1,15) = 14.1$, $P < 0.002$], left temporal [$F(1,15) = 9.23$, $P < 0.01$], and all posterior leads [at Pz: $F(1,15) = 45.3$, $P < 0.0001$]. Only one significant trial × hemisphere × sagittal × electrode interaction [$F(5,75) = 3.47$, $P < 0.05$], indicated a larger P3b in late as compared to early WCST trials at the T7 [$F(1,15) = 8.75$, $P < 0.01$], but not the T8 electrode (Fig. 2).

These analyses also revealed significant differences between early and late WCST trials in fast ERP components P1, P2 and N2 over posterior sites. In all these cases, late WCST trials evoked more positive ERP amplitudes than early WCST trials, with no significant differences between hemispheres (see Table 2; Fig. 2). These fast ERP effects will be described further elsewhere.

3.3. P3b activity in control tasks

Early and late trials from the WID and WED control tasks did not elicit significantly different P3b amplitudes in any of the electrodes explored [for WID at Pz: $F(1,15) = 0.75$, ns; for WED at Pz: $F(1,15) = 0.42$, ns] (see Fig. 3). Neither the WID task [$F(1,15) = 1.12$, ns] nor the WED task [$F(1,15) = 0.08$, ns] evoked any hemispheric asymmetry in P3b activity across temporal electrodes. Therefore, early and late trials from each control task were collapsed into one waveform for the remaining series of analyses.

Two main ANOVAs compared P3b activity evoked by early and late WCST trials with their respective control counterparts. Grand ERP averages from midline electrodes in each of the three tasks are shown in Fig. 3. Late WCST trials and WID trials evoked similar P3b waves across all posterior sites [at Pz: $F(1,15) = 3.85$, ns]. In contrast, a significant task × electrode interaction [$F(5,75) = 13.2$, $P < 0.0003$, $\epsilon = 0.30$], indicated that the WED task evoked reliably larger P3b waves than early WCST trials at mid parietal electrodes (see Fig. 3). To test whether these differences in P3b amplitude could be attributed to significant differences in reaction times between the tasks, WED trials were split up into those associated with a fast (less than 2.2 s) or a slow (2.5–4.0 s) response. Mean reaction times and standard deviations for fast and slow WED trials were 1.8 ± 0.28 s and 3.3 ± 0.14 s, respectively. However, peak P3b latencies associated with

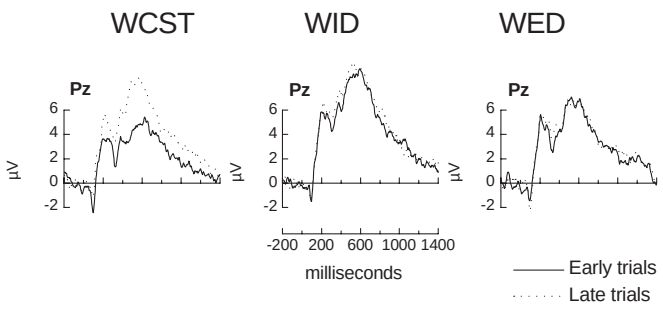

Fig. 3. Grand ERP averages for early (2nd and 3rd) and late (Last-1 and Last) trials from the WCST, WID and WED tasks. Waveforms from the Pz electrode are plotted from −200 to 1400 ms relative to the onset of the reference cards plus response card compound. Early and late trials from the control WID and WED tasks evoked similar P3b waves in all the electrodes explored.

slow and fast WED trials did not differ significantly [at Pz: $F(1,15)=0.3$, ns] (Fig. 4).

3.4. P3b activity in shift and non-shift WCST trials

The foregoing analyses suggest that both the attenuation and the asymmetry of the P3b response are related to a mechanism not shared with either the WID or the WED tasks. Furthermore, WID task data suggest that the mechanism responsible for the early–late WCST P3b modulation mainly affects early WCST trials. Perhaps the most distinctive feature of the WCST is the requirement to internally shift the sorting rule and to guess the next new one [40]. In contrast, none of the two control tasks demanded such a type of shift. The WED task involved the same fixed sorting rule in all trials. In the WID task, the new sorting rule was externally prompted at the start of the new series. On these grounds, it would be interesting to explore the gradual vs discrete nature of WCST P3b effects on a trial-by-trial basis with the shift and non-shift trials aligned.

To assess the early–late WCST P3b modulation in relation to the shift in category, the trial factor of our main ANOVA design was split up into eight levels, with pre-shift, shift and non-shift trials arranged by trial order. Shift trials were defined as those preceded by a negative feedback, and consisted of all of 2nd trials and half of 3rd trials from complete WCST series (see Fig. 5). Non-shift trials were preceded by positive feedback, and consisted of half of 3rd trials plus all ensuing trials from complete WCST series. Since the 1st trial of each WCST series was cognitively, behaviourally and physiologically equivalent to the last non-shift trial (see Table 1 and Fig. 5), it was used as a pre-shift baseline. Note that all 2nd trials from complete WCST series evoked similar P3b amplitudes regardless of whether they resulted in a correct sort (Fig. 5a) or in an 'efficient error' (Fig. 5b). They both reflect an efficient shift in set after a negative feedback (see section 2). Likewise, the *n*th non-shift trial evoked similar P3b amplitudes regardless of whether the correct category was found in the 2nd (Fig. 5a) or the 3rd trial of the series (Fig. 5b). Therefore, mean P3b amplitudes were obtained for the 1st, 2nd, 4th, 5th, last-1 and last trials across all complete WCST series. In contrast, correct 3rd trials were preceded by either a negative or a positive feedback (Fig. 5a and b). Therefore, correct 3rd trials were split up into 3rd shift and 3rd non-shift trials for the trial-by-trial analysis of P3b amplitude. Fig. 6 illustrates the ERPs elicited by shift and non-shift 3rd correct trials. The number of left-hand and right-hand responses was balanced in these averages. Mean P3b amplitudes were subjected to a within-subject ANOVA design with trial (1st, 2nd, 3rd shift, 3rd non-shift, 4th, 5th, last-1, last), hemisphere and electrode (temporal, temporo-occipital, lateral parietal, parietal, parieto-occipital and occipital). Two a priori orthogonal contrasts were defined for the Trial factor between every pair of consecutive trials (design 1), as well as between each trial and the last trial in the series (design 2). Fig. 7 shows grand mean P3b amplitudes and significance levels of simple tests of effects for the eight levels of the trial factor.

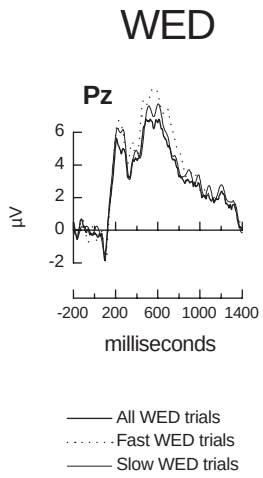

Fig. 4. Grand ERP averages for the WED task compared with two WED sub-averages of either fast (RT < 2.2 s) or slow (2.5 s < RT < 4.0 s) responses. Mean reaction times (RT) and standard deviations for fast and slow WED trials were 1.8 ± 0.28 s and 3.3 ± 0.14 s, respectively. Each sub-average contains one third of the trials in the WED grand average. Waveforms from Pz are plotted from −200 to 1400 ms relative to the onset of the reference cards plus response card compound.

The main effect for trial [$F(7,105)=13.6$, $P < 0.0001$, $\epsilon=0.51$], was due to a sharp reduction in P3b amplitude from pre-shift to shift trials in the series, followed by a gradual build-up during the ensuing non-shift trials. This build-up was so smooth that only the comparison between 3rd shift and 3rd non-shift trials yielded significant differences at central, temporo-parietal and left temporal sites (see Figs. 5–7). When compared with the last non-shift trial in the series, P3b amplitudes remained significantly reduced during the 3rd, 4th and, at some posterior sites, even the 5th non-shift trials of the series (see Figs. 5 and 7). Significant trial × hemisphere [$F(7,105)=2.96$, $P < 0.03$, $\epsilon=0.63$], and trial × hemisphere × electrode interactions [$F(35,525)=2.85$, $P < 0.02$, $\epsilon=0.19$], indicated that the P3b asymmetry was confined to T7/T8, P7/P8 and PO7/PO8 sites during the 2nd shift and 3rd shift trials. In all these cases, P3b amplitudes were significantly reduced at left hemisphere electrodes. No hemispheric asymmetry was apparent during 3rd non-shift, or later non-shift trials (see Figs. 5–7).

Two behavioural indexes were also plotted and analysed in a trial-by-trial fashion along the WCST series

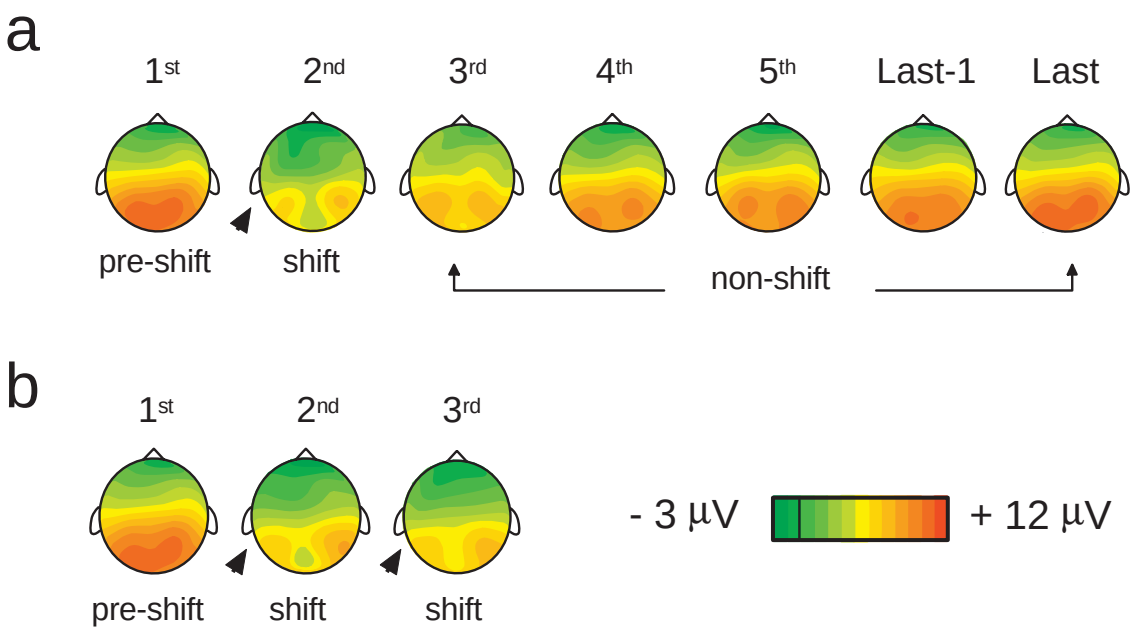

Fig. 5. Voltage maps showing the topographical distribution of mean P3b amplitudes in shift and non-shift trials within each WCST series. Arrowheads mark those trials that were preceded by a negative feedback (i.e., shift trials). (a) Series with one shift trial. (b) Series with two shift trials (post-shift trials not shown). The 2nd shift trials and the *n*th non-shift trials across series (a) and (b) evoked similar P3b responses. In contrast, mean P3b amplitudes differed significantly between 3rd shift and 3rd non-shift trials. A gradual build-up in the amplitude of the P3b response was observed during post-shift WCST trials.

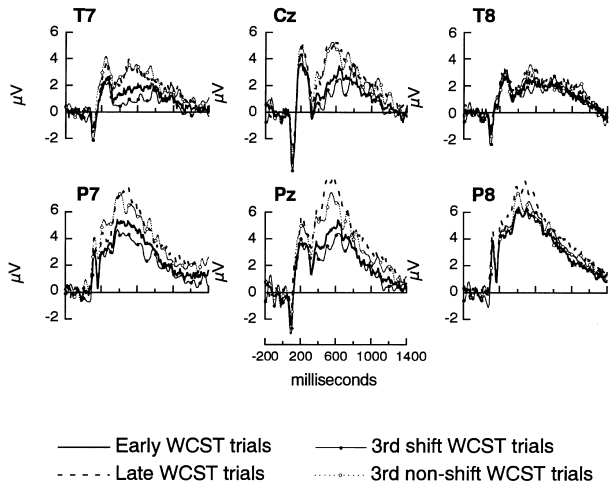

Fig. 6. Shift vs non-shift 3rd WCST trials. Grand ERP averages for early and late WCST trials are compared with 3rd shift trials and 3rd non-shift trials (cf. Fig. 5). Only 3rd correct trials from complete WCST series were considered in these sub-averages. Each subject contributed with 10 trials to each sub-average, with the same number of left- and right-hand sorts per sub-average. Waveforms from midline Cz and Pz, and lateral T7/T8 and P7/P8 electrodes are plotted from −200 to 1400 ms relative to the onset of the reference cards plus response card compound. 3rd shift trials evoked reliably smaller P3b amplitudes than 3rd non-shift trials at left lateral electrodes [$P < 0.01$], but not at right lateral electrodes.

(see Fig. 7, closed axes). Mean reaction times were slower during the 2nd and 3rd trials than during the last trial in the WCST series [$F(1,15) = 11.7$, $P < 0.005$]. In particular, 3rd non-shift trials were sorted faster than 3rd shift trials [$F(1,15) = 5.7$, $P < 0.03$], but not so fast as the last trial in the WCST series [$F(1,15) = 5.1$, $P < 0.04$] (see Fig. 7). The analysis of errors from failed series suggested that subjects were more prone to making sorting errors in 3rd shift trials than in 3rd non-shift trials [$F(1,15) = 42.9$, $P < 0.0001$]. Finally, subjects were also more likely to miss the category in 3rd non-shift trials than in the last trial of the series [$F(1,15) = 19.7$, $P < 0.001$] (Fig. 7).

4. Discussion

This study explored the functional meaning of early–late WCST P3b effects in relation with two specific hypotheses about the discrete selection or the gradual storage of memory templates of stimulus categories. As in previous studies, late WCST trials evoked reliably larger P3b amplitudes than early WCST trials, and a P3b asymmetry was apparent between left and right temporal areas [7,8]. Early and late WCST ERPs did not differ over frontal or frontopolar areas, but significant differences were observed in

fast extrastriate ERP activity. In the following sections, behavioural and P3b data from the WCST and the two control tasks are interpreted from current neurocognitive models of attentional set shifting [14,48,52,54] and context updating in working memory [19,20,35,57,59].

4.1. WCST P3b effects are both discrete and gradual

The modulation of the target P3b response across WCST trials is a statistically robust and a highly consistent result [4,7,8]. This finding is relevant for several reasons: (a) early and late WCST trials involve similar target stimuli, but different set shifting demands; (b) only a few studies have explored P3b modulations associated to shifts in set [39]; (c) brain sources for the P3b response have been postulated at posterior association cortices [27,28,30,33], but the WCST has been historically linked to the assessment of frontal function [32,40,56]. Information gathered from the two control tasks shed new light on the cognitive meaning of WCST P3b effects. Early and late trials from the WID task evoked P3b waves similar to those evoked by late WCST trials (Fig. 3). The WID task was similar to the WCST task, except for the first card of each WID series that announced the new correct category. This suggests a discrete development of the full-blown P3b after the subject saw an exemplar of the new category, but a gradual build-up of the P3b response when the shift was endogenously generated by the subject. Neither of the two control tasks showed any signs of a P3b modulation as a function of trial order. One of the most distinctive features of the WCST is that it demands an endogenous shift in set at the beginning of each new series [14,38,40,51,54]. In contrast, none of the two control tasks required such a type of shift. In the WID task, the new sorting rule was externally prompted at the start of each series. In the WED task, the same fixed rule was used throughout. As a consequence, results from the control tasks suggest that the

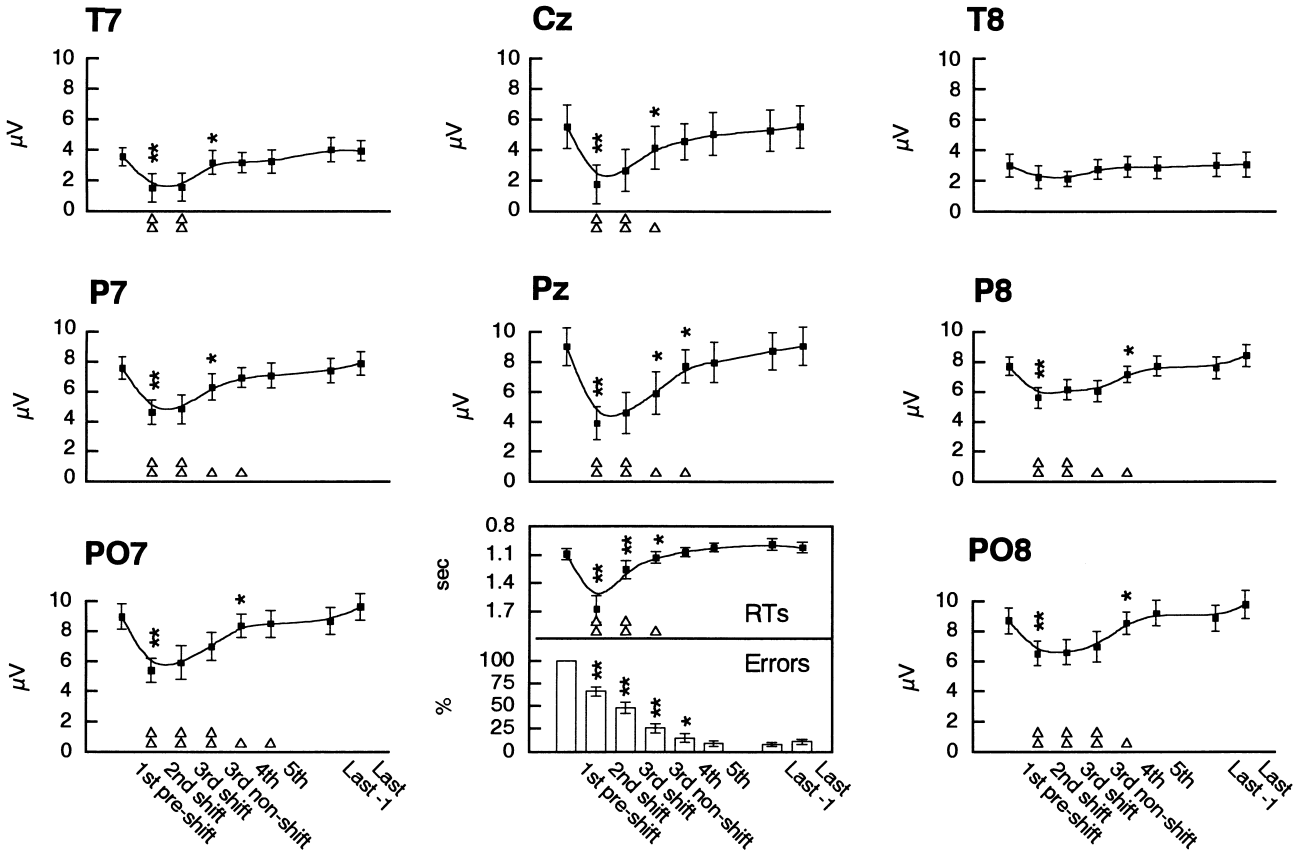

Fig. 7. Physiological and behavioural WCST shift costs. *Open axes*: Grand mean P3b amplitudes for shift and non-shift WCST trials are plotted as a function of trial order. Note that 3rd shift and 3rd non-shift trials were drawn from different series (cf. Fig. 5). Mean P3b values from Cz, Pz, T5, T6, P7, P8, PO7 and PO8 electrodes are shown. Vertical lines indicate standard error of the mean. A non-linear b-spline function was used to connect trial-by-trial changes in mean P3b amplitude. *Closed axes*: (Upper panel): grand mean reaction times from complete WCST series are plotted as a function of trial order. (Lower panel): Mean percent of errors from failed WCST series are plotted as a function of trial order. Vertical lines indicate standard error of the mean. Asterisks indicate significant differences with the previous trial in the series; $^{*}P < 0.05$; $^{**}P < 0.01$. Triangles indicate significant differences with the last trial in the series; $\triangle P < 0.05$; $\triangle\triangle P < 0.01$.

reduced P3b amplitudes of early WCST trials are related to the endogenous shift in set, as compared to a stimulus driven shift in rule (WID), or the consistent use of the same extradimensional sorting rule (WED). This hypothesis was addressed further with a finer analysis of WCST trials.

WCST trials were split up into shift and non-shift trials, and P3b amplitudes were analysed as a function of trial order. This analysis revealed two new pieces of information. Firstly, the sharp reduction in P3b amplitude from pre-shift to shift trials was followed by a gradual P3b build-up during the ensuing post-shift trials. Significant differences in P3b amplitude were observed between 3rd shift and 3rd non-shift trials at many posterior electrodes (Figs. 5 and 6). However, those differences did not account for the full size of P3b waves observed in late trials (cf. Figs. 6 and 7). Hence, even if subjects had learned the new correct category after the 2nd trial feedback, it took them another two or three extra trials to reach the full-blown P3b amplitudes of late WCST trials. Secondly, the P3b asymmetry was apparent during early shift trials, but not during early non-shift or later trials (Figs. 5–7).

In the light of this evidence, early–late WCST P3b effects seem to reflect three different processes: (1) a sharp reduction in P3b amplitude; and (2) a slight P3b asymmetry during shift trials; plus (3) a gradual post-shift P3b build-up extending over several non-shift trials. The mechanisms responsible for such a modulation are not shared with either the WID or the WED tasks. These results are consistent with our original interpretation in terms of attentional set shifting and the updating of working memory templates for perceptual categories [8,19]. However, the new evidence can help us refine the description of the processes involved in line with current neurocognitive models of task-set shifting [14,48,51,54]. In the ensuing discussion we propose that endogenous shifts in set are responsible for the sharp attenuation and the slight asymmetry in P3b activity during early WCST trials. On the other hand, the gradual post-shift P3b build-up may be a physiological concomitant of the reconfiguration of the attentional set [1,52]. Let us first consider alternative interpretations of these effects from existing models of the P3b response.

4.2. Uncertainty, expectancy and subjective probability

Uncertainty, expectancy, and subjective probability are cognitive constructs often used to account for the changes in P3b amplitude to tasks and stimulus variables [19,20,55,57,59]. Shift and non-shift WCST trials likely conveyed varying degrees of uncertainty and subjective probability. The contribution of these variables to the WCST P3b modulation can be empirically estimated in our experimental design. Subjects were instructed to shift category efficiently, and they knew that they had two categories left to choose from after the first negative feedback. If their first choice was incorrect (i.e., a 2nd trial 'efficient error' [4]), the remaining category was systematically chosen in the 3rd trial. Therefore, the uncertainty associated with shift and non-shift trials can be empirically estimated. For all complete WCST series used in the P3b averages, the probability of hitting the correct category was $P = 0.47$ in the 2nd trial, and $P = 1$ in the 3rd and following trials (see section 2 and Table 1). This suggests that WCST P3b responses varied independently from empirical estimates of expectancy, uncertainty, or subjective probability. If P3b responses were directly related to uncertainty, WCST P3b amplitudes from late trials would be the smallest in size. In contrast, if P3b amplitudes were inversely related to uncertainty, then 3rd and 4th WCST trials would evoke similar P3b responses to those evoked in late trials. Neither of these two predictions are met by the present WCST P3b results. This conclusion is consistent with recently published views that conscious expectancies do not always govern the amplitude of the P3b response [20,55].

On the other hand, the behavioural and physiological data shown in Fig. 7 are consistent with an account in terms of shift costs and the effects of proactive interference from the previous set [1,51,54]. Reaction times from complete WCST series did not plateau until the 4th trial. Also, error rates from failed WCST series indicated that subjects were more prone to missing the category in the early post-shift trials than in the last trials of the WCST series. Therefore, WCST P3b effects seem to parallel the costs in response speed and accuracy that are known to accompany set shifting in normal subjects [1,54]. An account of WCST P3b effects in terms of attentional set shifting is consistent with a large data base of clinical and experimental research both in humans [25,31,32,37,40,44,52], and in animals [17,18,49], as well as with formal neural network models of executive functions [14,15].

4.3. Stimulus dimensions vs perceptual rules

The control WED task evoked reliably larger P3b responses than early WCST trials over posterior and mid-parietal areas (Fig. 3). This evidence suggests that the WED task was not as good a control for early WCST trials as the WID task was for late WCST trials. Nevertheless, two important corollaries can be derived from the WED task. Firstly, WED trials were incompatible with the selection or the storage of information for any single stimulus dimension. They required extradimensional sorts in the sense that no

particular stimulus dimension was targeted for selection or memorisation. And yet WED trials did not evoke any P3b modulation like that observed in early WCST trials[1]. This evidence suggests that perceptual rules, rather than stimulus features or dimensions, are important for explaining WCST P3b effects. Whereas the same perceptual rule was used in all WED trials, the rule changed in early WCST trials. In this respect, neural network models of the WCST predict a distinct, supraordinate role of rule-coding neurons as compared to feature-coding, or memory-coding neurons [14,15,54]. Secondly, response latencies in WED trials were over one second longer than those observed in early WCST trials. In contrast, P3b peak latencies remained unaltered despite large variations in reaction times between different task conditions (cf. Figs. 3 and 4). If the WCST P3b response is the outcome of some template matching mechanism [19,33,35], then peak latency data from Figs. 3 and 4 suggest that the P3b response must be triggered at the outset, rather than at the end, of the template matching process. This finding provides support for the view that the P3b wave does not always correlate with completion of response-related processing [58,59]. Instead, it might reflect some initial stage in the matching of stimulus or response templates in working memory [30,59].

4.4. An elusive WCST P3b asymmetry

In line with previous studies, early WCST trials were associated with a more marked P3b reduction over the left temporal and temporo-occipital regions [7,8]. No such an asymmetry was apparent in the control tasks. The breakdown of early WCST trials into shift and non-shift trials confirmed that the asymmetry was linked to shift trials, and was not observed during the gradual post-shift build-up of the P3b response (Figs. 5 and 6). This effect was seen at lateral rather than medial temporo-occipital electrodes, and amounted to near 1 μV mean difference across hemispheres out of an overall 5 μV P3b reduction at mid-parietal sites (see Figs. 2, 5, and 6). This modest P3b asymmetry may go unnoticed if brain activity is averaged across shift and non-shift trials.

This asymmetrical modulation of the P3b response is consistent with clinical reports that endogenous shifts in set involve the co-ordinated action of different brain mechanisms [25,29,31,44,46]. At least two operations could be postulated in relation with this asymmetry. One is the moving of attention to a previously irrelevant category [47]. The other one is the inhibition of proactive interference from a previously relevant category [31,44,52]. Based on available evidence, we propose that the P3b asymmetry reflects the overlapping activation of left mesial temporal lobe structures during inhibition of interference from a previously relevant set. Firstly, the topography of the P3b asymmetry is consistent with far-field activity from deep left temporal lobe generators (Fig. 6; [7]). Secondly, mesial temporal lobe lesions are known to compromise WCST performance [13,26]. Thirdly, hippocampal and parahippocampal cortices are known to play an important role in reversal learning and inhibition of interference [22].

To our knowledge, no previous studies have reported P3b asymmetries during attentional set shifting tasks in normal subjects. In contrast, schizophrenic patients have been shown to evoke reduced P3b amplitudes at left-temporal areas in simple target detection 'oddball' tasks [43]. Although oddball tasks do not demand any shift in set, it is feasible that schizophrenic patients unduly shift their classification rule for targets and non-targets. This hypothesis would be consistent with reports that schizophrenic patients show "fluctuating attention or strategies" [23], and have impaired set shifting ability [39,45]. For the time being, such a hypothesis awaits appropriate empirical testing.

4.5. Neurocognitive models of attentional set shifting

We have made an effort to integrate accepted views of the P3b response as a context updating mechanism in working memory [19,35], with formal models of visual attention [12,16,21], and attentional set shifting in the WCST [1,14,15,48,54]. Neurocognitive models of attentional set shifting assume a hierarchical organisation of layered representations between stimulus inputs and motor outputs [15,16,24,54]. At the lowest sensory level, items in the visual scene are encoded by feature detectors in the visual cortex. Visual selection entails the temporary activation of feature detectors that encode the sought-after item (i.e., red). This short-term activation of feature-coding neurons has been referred to as an *attentional template* [16,30], and relates to increased firing rates in the corresponding visual association cortices [16,47]. Attentional templates formed by single sensory representations may account for results in simple feature selection tasks. However, the present WCST results are best described in terms of *perceptual categories* [21]. Bundesen [12] defined a perceptual categorization as a computation of the form "*x* belongs to *i*", where *x* is a perceptual item in the visual field and *i* is a perceptual category. Accordingly, a *category template* or perceptual cat-

[1] Note that our operative definition of an extradimensional sort differed from the original one proposed by Roberts et al. [50]. In their case, a shift in the stimulus dimension was equivalent to a shift in the sorting rule. In our case, extradimensional sorts do not imply any shift in the sorting rule: the same rule was consistently applied in all WED trials.

egory can be defined as the rule that determines inclusion in the class *i* of perceptual items (i.e., either red, or green, or yellow, or blue). For our purposes, these rules are usually fixed with the task's instructions [51].

The distinction between simple attentional templates and category templates is germane to the interpretation of WCST P3b effects. A supraordinate class of working memory representations has been proposed to account for category selection effects in set shifting tasks [14]. Dehaene and Chageux [14,15] proposed the existence of *rule-coding clusters* of neurons that combine subsets of feature coding neurons to allow for rapid shifts of activation among entire sets of sensory memory representations [15]. Rule-coding clusters connect sensory memory representations with motor programs to establish stimulus-response mappings in working memory (see also [24]). Therefore, a rule-coding cluster is synonymous with an *attentional set* [24,31], and can be formally defined by adding a response process to the outcome of the category selection process: "if *x* belongs to *i*, then *y*, else *z*", where *y* and *z* designate different motor programs [12]. One corollary of this model is that any change in the category template would also involve a reconfiguration of the entire attentional set in working memory [21,31,44,52].

4.6. Endogenous vs exogenous shifts in set

It is now possible to interpret WCST P3b effects in terms of attentional set shifting mechanisms. In the WED task, the attentional set combined three perceptual items that set up the exclusion criteria for response selection (i.e., "select the reference card with neither the star, nor blue, nor one items"; see Fig. 1). Every new card in the WED task refilled the values in the rule's variables, but the rule itself did not change. On the contrary, both the WCST and WID tasks demanded shifts between three different sets (i.e., colour, number, or shape), each with a different stimulus-response mapping. However, whereas WID shifts were visually prompted by the first card in the series, subjects had to guess the new WCST category. It can be argued that having to guess the category, subjects were temporarily uncertain about the next category template. But task uncertainty alone cannot account for the discrepancy between WID and WCST P3b results. In fact, subjects used the feedback very efficiently to find the next correct category, which suggests that uncertainty was dispelled after the 2nd trial feedback (Table 1).

A more plausible explanation for the discrepancy between WID and WCST P3b results is that different brain mechanisms underlie externally driven and endogenously generated shifts in set. Extensive neuropsychological evidence provides support for this idea [51,52,54]. For instance, both Parkinson's disease and prefrontal patients have difficulties in shifting set, but only when they have to rely on 'internal' as opposed to 'external' cues [11,29,31,40,46]. It has been shown that after an endogenous shift in set normal subjects need to use the new set for a number of trials before reaching pre-shift efficiency levels [1,51]. Behavioural results from Fig. 7 are consistent with a progressive post-shift improvement in response speed and accuracy, that was paralleled by a post-shift build-up in P3b amplitude. Accordingly, we propose that the post-shift build-up of the WCST P3b response reflects gradual strengthening of the newly established set in working memory. The gradual rather than discrete updating of the new set may be partly due to the protracted effect of proactive interference from previously active sets [1,31]. Interference is particularly strong when the new stimuli contain elements associated with the previously relevant but currently irrelevant set [44,51].

The hypothesis that a weak or unstable attentional set will elicit a reduced WCST P3b response is consistent with current views that fluctuating attentional strategies attenuate P3b responses [19,23,57]. However, the present evidence also indicates that P3b amplitudes should not be taken as a direct index of the integrity of cognitive processing in the absence of other behavioural or physiological indicators. In our sample of healthy subjects, a temporarily reduced P3b indicated that the set was being shifted efficiently. In contrast, a 'normal' P3b response would be expected when subjects fail to update the old set in the presence of changing contextual cues (i.e., after a negative feedback). This is exactly what has been observed when either normal subjects [4], or DLPF patients commit a perseverative error [6].

4.7. Implications for neuropsychological assessment

In line with neuroimaging studies, the present results confirm that card sorting modulates brain activity over a widespread neural network [10,37,42]. The most conspicuous of these ERP modulations influenced the target P3b response, whose putative generators have been proposed at temporo-parietal and mesial temporal association cortices [7,27,28,30,33–35]. This is consistent with reports that temporo-parietal lesions impair WCST performance [3], and severely reduce the amplitude of the oddball P3b [34,60]. A few fMRI studies have observed bilateral fMRI activation of the DLPF cortex linked to specific set-shifting operations [36,37], but most studies have not analyzed shift and non-shift periods separately [10,42]. Varying amounts of activation have been reported at posterior association cortices. The present ERP results complement fMRI data

with real time measurements of the rapid physiological changes that accompany attentional set shifting.

Early and late WCST trials evoked similar ERP patterns over frontal areas (Fig. 2). However, this should not discard a likely contribution from prefrontal cortex to the present WCST P3b modulation. Firstly, ERP measures might not be sensitive enough to the type of sustained modulation exerted by prefrontal cortex upon stimulus-locked responses from posterior association cortices. Thus, patients with focal lesions to the DLPF cortex show impaired phasic extrastriate ERPs to visually attended stimuli, but normal ERPs over the lesioned frontal area [9,33]. Secondly, the rule-coding neurons proposed to model set shifting in the WCST were derived from the ability of DLPF neurons to maintain a sustained level of firing over extended periods of time [15]. Finally, lesions to the DLPF cortex do not abolish neither the oddball P3b [9,33], nor the WCST P3b, but do disrupt early–late WCST P3b effects and the ability to shift the attentional set [5,6,31,40,52].

It has been proposed that the efficiency of the new set for filtering irrelevant information and selecting appropriate responses depends on the strength of the newly updated stimulus-response representations in working memory [31,51]. The present WCST P3b effects point to the involvement of both discrete and gradual working memory mechanisms linked to the endogenous shift in set. The present account of WCST P3b effects offers solid grounds for integrating the context updating model of the target P3b response [19,20,55,57,59], with formal models of visual attention and attentional set shifting [1,12,14–16,21,48,51,54]. Most past P3b research has used simple oddball tasks with a fixed, pre-established set [19,20,23,55,57,59], but there have been few previous attempts to measure P3b changes linked to shifts in set [8,39]. The present WCST P3b results suggest that the reconfiguration of stimulus-response mappings in working memory (i.e., the updating of an attentional set) constitutes one important modulatory source for the target P3b response.

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