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Event-related potentials index cognitive style differences during a serial-order recall task

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Abstract

Working memory and attentional inhibition processes (jointly symbolized here as WM/I) have been proposed to explain cognitive style differences in Field Dependence–Independence (FDI). FI relative to FD subjects have been found to use more effectively WM/I to operate on task-relevant information. The purpose of this study was to determine whether cognitive style differences are revealed as differences in ERP activity in a novel WM/I task. A serial-order recall task served to manipulate memory load by varying the amount and kind of information to be elaborated and retained in WM in order of temporal appearance (S1, S2); recall demand of the serial-order judgment (S3) was also concurrently varied. FI subjects engaged in deeper WM processing during the high memory load conditions relative to FD subjects; and this was measured as a higher amplitude slow negative wave (SNW), over the centro-parietal scalp extending to the frontal scalp, during the retention interval. In contrast, P300 amplitude was larger for FD subjects in the high memory load conditions following S1, which corresponded with a reduced amplitude SNW. We suggest that inhibitory processes indexed by P300, which FD subjects must mobilize to change their usually global-perceptual (i.e. shallow) attentional strategy for processing task information, may have resulted in less mental-attentional (WM/I) resources available to them during the task's retention phase (Rosen and Engle, 1997). Thus, ERP methods can be used to investigate differences in cognitive style. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Slow negative waves; P300; Cognitive styles; Slow waves

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1. Introduction

The ability to utilize working memory and attentional inhibition (WM/I) for storage and manipulation of task relevant information is needed for the emergence of high cognitive functions such as language, planning, and problem-solving (Pascual-Leone, 1969, 1970; Baddeley, 1986; Shallice, 1988). Although Baddeley's model (Baddeley, 1995) remains descriptively important, our present work adopted a more classic conception of working memory (Pascual-Leone, 2000) which construes WM, in the manner of attention for William James or Hebb, as the currently hyperactivated (i.e. dominant) set of 'software' processes — knowledge units which we interpret as information-carrying schemas or schemes — in the subject's cortical repertoire of these units (Cowan, 1999; Engle et al., 1995; Pascual-Leone, 1970, 1987; Pascual-Leone, in press; Rosen and Engle, 1997). We then posit a number of functional 'hardware' resources in the brain that can update (i.e. adapt to the situation) the functioning of the WM/I mechanism. The two most important resources for our purpose are a mental-attentional activation mechanism that we call mental capacity M, and an attentional inhibition (or I) mechanism that executive processes (schemes) can monitor and allocate to change functioning of WM/I (Cowan, in press; Engle et al., 1999; Pascual-Leone, 2000; Pascual-Leone, in press; Pascual-Leone and Baillargeon, 1994).

There is some agreement that these executive processes include: (a) focusing attention on relevant information and inhibition of irrelevant processes; (b) switching focused attention between tasks; (c) planning a sequence of subtasks to accomplish some goal; (d) updating and checking the contents of WM; and (e) coding representations in WM for time and place of appearance (Smith and Jonides, 1999). Working memory paradigms have been important in revealing individual differences, evidenced both in behavioral studies (Cantor and Engle, 1993; Daneman and Carpenter, 1980; Kyllonen and Christal, 1990) and event-related brain potential (ERP) studies (Nittono et al., 1999; Ruchkin et al., 1990a, 1992).

Working memory and attentional inhibition processes have been proposed to be factors in cognitive style differences found in field dependence–independence (Case and Globerson, 1974; Cochran and Davis, 1987; Pascual-Leone, 1969, 1989; Pascual-Leone and Goodman, 1979). The field-dependence–independence (FDI) cognitive style refers to the cognitive-style disposition, within misleading situations, to process information either in a global perceptual manner (by FD subjects who favor right-hemisphere processing — Pascual-Leone, 1989; Waber, 1989) vs. an actively analytical deeper manner (by FI subjects who favor left-hemisphere processing). We mean by misleading a situation that elicits from the subject habitual global-perceptual schemes that interfere with the task at hand. In contrast, facilitating situations are those where no misleading schemes are activated; in these other situations one may not find performance differences between FD and FI subjects (Pascual-Leone, 1989; Pennings, 1991; Witkin et al., 1954; Witkin and Goodenough, 1981). Analytical/deep processing entails, especially in misleading situations, active segmentation of information into relevant parts and interrelations (Robinson and Bennink, 1978). Global processing, in contrast, is holistic and more passive in character — passive in the sense that it accepts for processing the perceptually salient aspects of the situation, whether they are relevant or irrelevant (as often happens in misleading situations). These styles of processing information have been linked to functional hemispheric dominance (Pascual-Leone, 1989; Silverman, 1991; Waber, 1989) as well as to differences in the WM/I processes (Nahinsky et al., 1979; Pascual-Leone, 1969, 1970, 1989; Pascual-Leone et al., in press). Pascual-Leone and associates call M-space the 'region' of WM where actively analytical/deep processing takes place. If a large amount of the available M-space is allocated to cognitive operations bearing on the visual representation of the input, such processing of perceptual information may leave less space available for other jobs (e.g. elaboration) required by the task. The analytical strategy of FI subjects is more effective than that of FD subjects at optimizing the distribution and allocation of attentional resources; and so they experience less cognitive demands and less need to use attentional inhibition in misleading situations than FD subjects. Pascual-Leone (1969, 1989) reached the conclusion across a variety of tasks that executive schemes of FI subjects adequately control their WM/I resources; in contrast, FD subjects' executive controls are deficient in this regard, although their style has advantages in other situations (Baillargeon et al., 1998; Johnson et al., 2000). Consistent with these views Davis (1991) found that FD and FI performance differences are more apparent under conditions of high information load.

This is demonstrated in the rod and frame task (RFT), a traditional measure of FDI. The RFT presents a misleading situation (Pascual-Leone, 1989, 1995) in which a tilted adjustable rod must be moved to the true vertical position when its surrounding frame is tilted and other visual cues of verticality have been eliminated. Error scores and subject reports (Pascual-Leone, 1989; Witkin and Asch, 1948; Witkin et al., 1954) suggest that FD subjects adopt a global strategy, focused on processing only the salient perceptual features incorporated into a perceptual gestalt. Thus their attention is captured by the salient tilted frame and they feel compelled (a gestaltist effect) to align the rod with a side of this frame, instead of aligning it with the true (gravity's) vertical line as required. Notice that here the tilted frame is misleading because all subjects, FI and FD, have an overlearned habit of judging verticality visually, by aligning objects (e.g. rods) with 'apparently-vertical' lines often found in the immediate urban environment (Witkin and Goodenough, 1981; Messick, 1994; Pascual-Leone, 1989, 1992). This automatized habit of visual evaluation of verticality becomes a potent misleading factor for FD, but not for FI subjects, in this task. FI subjects, unlike FD subjects, can effectively mobilize the WM/I mechanisms and switch mental attention to deeper (proprioceptive, labyrinthic feedback) processing. And so they construct an estimate of verticality that is unaffected by misleading salient cues of 'verticality' (e.g. sides of the tilted frame) offered by the visual display. FD subjects, however, fail to switch attention away from misleading cues, and do not engage WM/I processes to restructure their perception using deeper information. While traditional measures of FDI such as RFT can be seen superficially as perceptual tasks, which exhibit individual differences, they have been found to predict subjects' performance in very diverse cognitive, problem solving and personality tasks (Goodenough, 1986; Messick, 1994; Pascual-Leone, 1989; Pascual-Leone and Goodman, 1979; Witkin and Goodenough, 1981); this suggests that FDI measures are indexing a cognitive style. See Messick (1994) and Johnson et al. (2000) for recent reviews.

Neuroimaging studies have employed a verbal 2-back task to study storage and executive processes of WM (Cohen et al., 1994; Konishi et al., 1999; Smith and Jonides, 1999). The task visually presents a series of letters, each letter followed by a delay interval. The subject responds indicating whether each letter is the same as the one that occurred two-back in the sequence. Processes engaged during the task include WM storage processes and executive processes for temporal tagging and updating the contents of WM (Braver et al., 1997; Konishi et al., 1999). These WM processes are associated with a phonological storage system in the parietal area, a frontal rehearsal system comprised of Broca's area, the supplemental and premotor areas, and prefrontal executive processes (Smith and Jonides, 1999). ERPs have also been employed to investigate WM processes in paradigms requiring the storage and manipulation of information over a delay period. Ruchkin (Ruchkin et al., 1990a, 1992) manipulated the phonological load by varying the number of consonants in the visual display of a delayed match-to-sample paradigm. ERPs revealed a parietal positive slow wave and a left anterior negativity that increased in amplitude with memory load, as well as a centro-parietal negativity that did not vary with load. The positive slow wave, dominant over the parietal scalp, was associated with long duration encoding processes. The latter two negativities were present during the retention interval and were associated with a phonological rehearsal loop.

The primary purpose of the present study was to determine whether strategy/cognitive style group differences would be revealed as differences in ERP activity in a WM/I task. Functional differences in FD and FI subjects were studied using a delayed-response serial-order recall task that manipulated WM/I processes. The task is similar to the verbal 2-back WM task (Smith and Jonides, 1999) in that it presents multiple stimuli in which verbal information and temporal order must be retained in WM, to respond to a probe requiring a temporal judgment. The serial-order recall task differs from the 2-back WM task in placing a greater demand on coding information from the task stimuli, and in the requirement to remember temporal order stimuli. The serial-order recall task demanded the subject to encode features (single or multiple) from geometric shapes presented with the task stimuli (S1, S2). This information has to be elaborated by forming a memory association and converting the features into letter codes to be retained so as to maintain temporal order for making the serial-order recall response (single or multiple) that the response-cue stimulus (S3) requires. Elaboration instructions varying the memory load were given to the subject at the beginning of each block of trials, asking to memorize via letter codes, either one (low memory load condition) or three (high memory load condition) for each stimulus. This elaboration instruction contradicted, in the case of FD subjects, their habitual tendency to generate passive (salient-feature driven) perceptual processing. Thus, this habitual scheme of FD subjects for passive global processing should transform our serial-order recall task into a misleading situation for them, since the task explicitly required elaboration of letter codes to be memorized, and passive processing is not conducive to it.

The task varied demand on WM/I by manipulating not only the memory load (one vs. three features) to be letter-coded and remembered, but also the number of features to be recalled. Recall demand stipulated that either a single or multiple features be recalled for the serial-order response. It was hypothesized that FI, but not FD subjects, would be able to function equally well across treatment conditions. Furthermore, it was predicted that the global perceptual style of FD subjects would require them to interrupt (i.e. actively inhibit) their habitual scheme for passive and global visual representation of geometric shapes; in particular when multiple features had to be encoded and elaborated during the high memory load conditions. This effort might conflict with FD subjects' WM/I allocation of attention during the task's retention step.

2. Methods

2.1. Subjects

Thirty-one college students (28 right-handed, three left-handed) volunteered (22 males) to participate in the study. Subjects were paid $7.00/h. Mean age was 24.4 years (S.D. = 5.3). All subjects had normal or corrected-to-normal vision. One subject was excluded from the study due to excessive eye artifacts and was not included in the analysis. One subject was re-tested in a second session on one block due to excessive eye blinks when eyes became tired.

2.2. Apparatus

All subjects were tested on two tasks: the portable rod and frame task (PRFT) and a serial-order recall task.

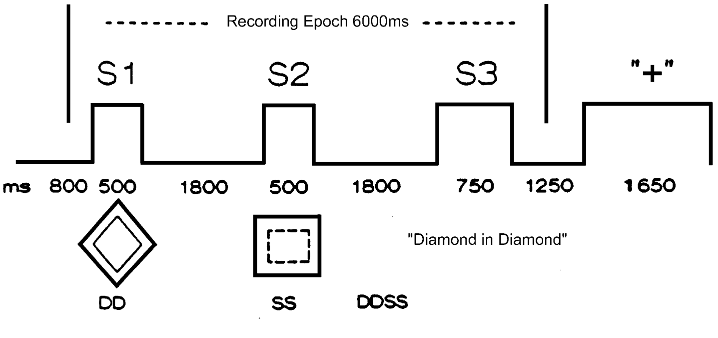
2.2.1. Portable rod and frame task

The version of the PRFT used in this study has been reported to correlate 0.89 with scores on the standard version of the Rod-and Frame test, with Spearman–Brown split-half reliabilities of 0.95 (Oltman, 1968). Subjects were seated and looked through a viewing box that eliminated all cues of verticality in the room. At a distance of 30 inches, a 10 × 10-inch visible black square frame against a white background was tilted either 28° to the left or right. A black rod, 0.5 inches wide and 9 inches in length, was positioned in the center of the frame. The rod could be tilted independently of the frame and was initially tilted either 28° to the left or right. The subject's required response was to align the rod with the objective vertical (the invisible walls of the room).

2.2.2. Serial-order recall task

Subjects were seated comfortably in a dimly lit room facing a cathode ray tube (CRT) at a distance of approximately 114 cm. A trial consisted of an S1, S2, S3 sequence with an 1800-ms interstimulus interval. Task stimuli (S1, S2) presented on the CRT (duration = 500 ms) consisted of an inner geometric shape nested within an outer geometric shape. Stimuli varied on three features: outer shape (square or diamond); inner shape (square or diamond); and line quality of inner shape (dashed or solid). A cue stimulus (S3) consisted of a word or word combination (duration = 750 ms) representing selected feature(s) presented in either S1 or S2 (e.g. 'diamond' or 'square in diamond' or 'dash in solid'), which required a serial-order recall response. A plus sign ('+') was presented for 1650 ms in the center of the screen 1250 ms after the offset of S3. The plus sign indicated the end of that trial and a time when eye blinks were allowed. The offset served as a warning for the beginning of the next trial, and a time to keep from blinking. Task stimuli and trial structure are presented in Fig. 1. All stimuli were presented in the center of the CRT just below eye level. Each outer geometric shape was 8.89 × 8.89 cm with a visual angle subtending 4.45°. All stimuli were displayed in white on a black background. Subjects held RT handles in each hand with thumbs resting on buttons that were used for responding to the cue stimulus.

ERPs were recorded with Ag/AgCl electrodes at Fz, Fcz, Cz, Pz, Oz, F3 and F4 (according to the 10–20 system) referenced to linked mastoids with forehead ground. Electrode location Fcz was an interpolation midway between Fz and Cz in order to overlie the supplementary motor area (Lang et al., 1987). The electrooculogram (EOG) was recorded using two Ag/AgCl electrodes, one positioned directly above and the other directly below the right eye. The small visual angle limited stimuli to focal vision minimizing horizontal eye movements. Electrode impedance was less than 5 kΩ. The EEG signals were amplified with Grass Model 12 amplifiers using a 10-s time constant. The amplifiers were set to an upper cut-off frequency (−3 dB) of 35 Hz and a lower attenuation frequency (−3 dB) of 0.01 Hz. The EEG signals



Task Stimuli: * Dashed Line Cue Stimuli by Recall Requirements:

	S1	S2	S3-Single	S3-Multiple
1.	Square * in Diamond	Square in Square	"Square"	"Square in Diamond"
2.	Diamond in Square	Diamond * in Diamond	"Diamond"	"Solid in Solid"
3.	Square in Diamond	Diamond * in Square	"Diamond"	"Diamond in Square"
4.	Diamond in Diamond	Square * in Square	"Square"	"Dash in Solid"
5.	Diamond in Diamond	Square * in Square	"Diamond"	"Diamond in Diamond"
6.	Square in Diamond	Diamond * in Square	"Square"	"Solid in Solid"
7.	Square * in Diamond	Square in Square	"Square"	"Square in Square"
8.	Diamond in Square	Diamond * in Diamond	"Diamond"	"Dash in Solid"

Fig. 1. Schematic representation of the recording epoch for a single trial is presented with sample stimuli. Also listed are the eight task stimuli and cue stimuli combinations used in the study. Task instructions were provided at the beginning of each block of trials to encode and memorize by elaborating as letter codes one feature (low memory load) or three features (high memory load), and to recall either a single feature or multiple features, resulting in four experimental conditions.

were digitized every 10 ms beginning 600 ms prior to S1 onset, serving as the baseline. A calibration pulse was recorded after each session. Data were monitored on-line and stored in digital format on magnetic tape for subsequent quantification and analysis.

2.3. Experimental design

2.3.1. PRFT

This is an excellent instrument for assessing FDI style in terms of subjects' disposition to overcome misleading visual cues of verticality, and elaborate instead valid organismic (labyrinthic) estimates of the objective vertical line (Witkin et al., 1954; Witkin and Goodenough, 1981). We used subjects' score in this task to classify them as FD vs. FI, in the manner proposed by Witkin, so as to define a between-group experimental factor. The process theory of FDI (Pascual-Leone, 1969, 1989) as summarized above, was used to make predictions about FD/FI differences in the ERPs obtained during the serial-order recall task.

2.3.2. Serial-order recall task

Two independent variables defined in this main task, the memory load (low or high) and the recall demand (single recall vs. multiple) afforded a 2 × 2 design, shown in Fig. 2. Memory load instructions varied the number of features to be encoded, elaborated and temporally tagged for retention in WM during the ISI. Recall demand manipulated the number of features previously presented in either S1 or S2 that had to be recalled in serial order to make a correct response.

This within-subjects experimental design permitted the testing of both FD and FI subjects on the following four conditions: low effort (i.e. low memory load, single recall demand); underprepared (i.e. high memory load, multiple recall demand); overprepared (i.e. low memory load, single recall demand); and high effort (i.e. high memory load, multiple recall demand). The underprepared and overprepared conditions were incongruent conditions in that in them the memory load requirements did not match the recall demand. The overprepared condition provided more information (i.e. inner and outer shape plus line quality of inner shape) than was needed for the response (i.e. outer shape). The underprepared condition provided sufficient information (i.e. outer shape) to respond correctly in half of the trials (see Fig. 1). Additional information was available on an incidental basis (line quality of inner shape); this allowed for performance above chance in the other half of the trials.

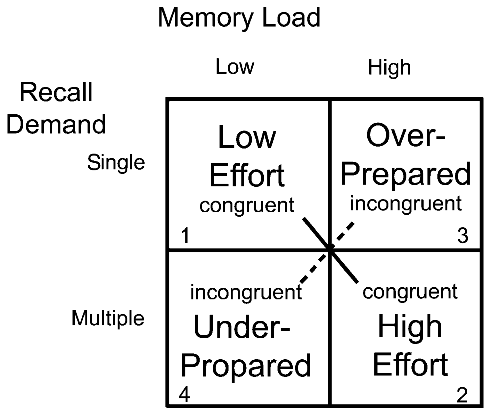


Fig. 2. Representation of the 2 × 2 experimental design with the two independent variables of memory load, with two levels, namely low and high, and recall demand measured by two levels, i.e. single and multiple. Bold numbers in lower quadrant of cells represent the order of presentation of each condition. Two of the four experimental conditions are congruent when memory load and recall demand are matched; low effort (low memory load, single recall demand) and high effort (high memory load, multiple recall demand). Two conditions are incongruent leaving the subject overprepared (high memory load, single recall demand) or underprepared (low memory load, multiple recall demand).

2.4. Procedure

Subjects were tested on the PRFT in a first experimental session. The PRFT was administered in accordance with established testing procedures (Oltman, 1968). The subject was told the rod was to be made vertical by instructing the experimenter when to stop adjusting it. Eight trials were given with the initial frame and rod tilts of 28°, and in the following (left vs. right tilt) frame-and-rod sequence: frame, LLRRLLRR; rod, LRRLLRRL. For all items, the rod was adjusted in increments of 4° by the experimenter, each time asking the subject whether the rod needed further adjustment. Final position of the rod relative to true vertical was recorded. PRFT score was the sum of the absolute deviation in degrees from true vertical over the eight trials. A median split method (Ohnmach, 1966) was used to group subjects into FD and FI groups, yielding 15 subjects in each group.

In a second experimental session electrodes were applied to the scalp and subjects were tested on the serial-order recall task. Subjects were instructed at the beginning of each block to encode and memorize, by elaborating as letter codes, one feature (in the low memory load conditions — outer shape) or three features (in the high memory load conditions — inner shape, outer shape, and line quality of inner shape) from stimuli S1 and S2; and were instructed to rehearse them in the appropriate order following S2. Each of the eight trial types shown in Fig. 1 were equi-probable in presentation. The response–cue stimulus (S3), which presented either a single feature or multiple features seen previously in either S1 or S2, stipulated the number of features to be recalled and requested a serial-order response. The subject was informed in advance whether in that block of trials a single or multiple feature serial-order recall was required. Subjects responded by pressing a button with the left hand if the feature(s) identified in the cue stimulus appeared in S1 or the right hand if it appeared in S2. Note that subjects had to perform the cognitive operations of recalling the stimuli presented with the cue and determine serial order prior to performing the motor response. Motor response requirements were held constant across all experimental conditions. Memory load instructions to code feature(s) by letter codes (e.g. 'd' for diamond or 'sd' for square in diamond) provided a mnemonic aid to remember the serial order of feature(s) in preparation to respond to the cue stimulus. It also constrained subjects to use consistent elaboration strategies. Subjects were presented one block of 64 trials for each of the four experimental conditions: low effort; high effort; overprepared; and underprepared. This fixed sequence was followed for all subjects with a modified sequence presented to six subjects (underprepared, overprepared, low effort, and high effort) to test for effects of sequence. A practice block of nine trials was presented prior to the first two experimental blocks (one low and one high memory load) to practice subjects on strategy instructions. Subjects were instructed to 'respond promptly, but to favor accuracy'. The instructions emphasized accuracy because ability to organize information correctly was considered of primary importance. Subjects were also instructed to minimize eye blinks during the recording epoch by focusing on the task and blinking briefly, momentarily resting the eyes, when the plus sign ('+') was presented on the screen.

2.5. Data reduction and analysis

All saturated trials due to eye blinks and incorrect responses were excluded from the averaging process. A method used by Gratton et al. (1983) corrected for artifacts in the EOG off line. A criterion of a minimum of 25 trials/block for averaging was adopted. The lowest average number of trials per block for analysis occurred in the underprepared condition yielding 48.8 and 53.3 trials for FD and FI subjects, respectively.

Peak amplitudes at Pz were identified for each subject within each condition, which established the general latency range used for the P300. The average amplitude was taken for the P300 component within the following epochs: S1–S2 interval, (260–560 ms) referenced to 600-ms baseline prior to S1 (mean amplitude of the sample points in the 600 ms period before S1); and S2–S3 interval, (230–560 ms) referenced to a 200-ms baseline prior to S2. Slow wave component amplitudes were measured by computing the average amplitude within the following latency ranges. An early slow wave measure following the P300 was analyzed in the following epochs: S1–S2 interval, (560–950) referenced to a 600-ms baseline prior to S1; and S2–S3 interval, (560–950 ms) referenced to a 200-ms baseline prior to S2. Two slow wave measures, well after the offset of the task stimulus, identified as early and late retention intervals (Ruchkin et al., 1992), were measured in the following epochs: S1–S2 interval, early retention (1300–1800 ms), late retention (1800–2300 ms); S2–S3 interval, early retention (1300–1800 ms), late retention (1800–2300 ms). All of the retention interval components were referenced to a 600-ms baseline established before S1. This method of establishing the baseline prior to S1 for the slow negative wave served to distinguish tonic slow negative waves across the processing sequence of S1–S3 from phasic processing requirements at each task stimuli (S1, S2) (McCallum et al., 1988). Data analysis included a repeated measures analysis of variance (ANOVA) including three within factors (memory load × recall demand × electrode) and a between factor (FDI). Post hoc analyses were conducted using paired comparisons or ANOVA including two within factors (memory load × recall demand) and a between factor (FDI) for separate electrode sites or site combinations. To ensure that the relative topography of the slow-wave pattern was confined to shape alone (McCarthy and Wood, 1985), a separate analysis was conducted by rescaling the raw amplitudes for each subject and measurement epoch so that the amplitudes had a mean of 100 and an S.D. = 15 over all electrodes (Rosler et al., 1995). The rescaled data was then analyzed using the same repeated measures ANOVA with three within factors and one between factor. These results were used to report all main effects for electrode and electrode interactions, as well as post-hoc analyses on electrode sites. To control for an increase in type I error, the degrees of freedom of F tests were adjusted by means of the estimated Greenhouse and Geisser (1959) coefficient. The adjusted P-values are presented in the text with the epsilon ε, value.

3. Results

The PRFT results yielded scores that ranged from 7 to 141° deviation ($\bar{X} = 29.6$, S.D. = 28.01). Scores of less than 25° deviation (median score) served as the cutoff for the FI group and produced 15 subjects in each group. Our results, using a smaller sample, exhibited less variance in performance than the study of Oltman (1968) ($n = 163$) in which he reported PRFT scores ranging from 0 to 219° with means and S.D.s reported for females ($\bar{X}^* = 52.4$, S.D. = 41.0) and males ($\bar{X}^* = 45.8$, S.D. = 36.9).

Table 1 summarizes results for the serial-order recall task for reaction time (RT) and accuracy for the four experimental conditions. All subjects were significantly slower when recall demand was high [$F(1,29) = 108.79$, $P < 0.001$]. Subjects took longer to respond, and were less accurate when they were underprepared, as indicated by a significant memory load × recall demand interaction for RT [$F(1,29) = 5.24$, $P < 0.05$] and for accuracy [$F(1,29) = 25.50$, $P < 0.001$]. These results suggest subjects followed memory load instructions, otherwise RT and accuracy would be similar for both the underprepared and high effort conditions. FI subjects were more accurate in all four conditions compared to FD subjects, as seen in Table 2. These differences, however, did not reach statistical significance. High accuracy rates of 90% for all subjects suggest a ceiling effect, and indicate subjects could perform the task accurately, even when demand on working memory was high.

3.1. Event-related potentials

3.1.1. Overall ERP profile

Figs. 3 and 4 present grand average ERPs for FD and FI subjects, respectively, compared on low and high memory load.

Both groups exhibited a P300 following the presentation of S1 and S2. A slow negative wave

Table 1
Mean accuracy and mean reaction time (RT) as a function of memory load and recall demand for all subjects ($N = 30$) for the four higher order conditions

Recall demand	Accuracy Memory load		RT Memory load	
	Low	High	Low	High
Low	94% (3.4)[a]	91% (6.8)	812 ms (232.3)	836 ms (191.9)
High	83% (9.2)	91% (6.2)	1124 ms (145.6)	1065 ms (155.2)

[a] S.D.

Table 2
Mean accuracy and reaction times (RT) for field independent ($N = 15$) and field-dependent ($N = 15$) for the four higher order conditions

Recall demand	Field-dependent Memory load		Field independent Memory load	
	Low	High	Low	High
Low				
acc	92.5% (3.9)[a]	90.1% (8.6)	94.5% (2.5)	92.6% (4.2)
RT	891 ms (243.6)	877 ms (195.3)	732 ms (197.3)	794 ms (185.6)
High				
acc	82.9% (7.6)	90.4% (7.1)	83.5% (11.0)	91.9% (5.1)
RT	1114 ms (139.0)	1072 ms (170.4)	1134 ms (156.1)	1059 ms (144.2)

[a] S.D.

occurred in the S1–S2 and S2–S3 retention intervals beginning early in the former interval at approximately 1300 ms following the onset of S1, with a slightly delayed onset in the latter interval. The slow negative wave continued throughout the remainder of each retention interval. The slow

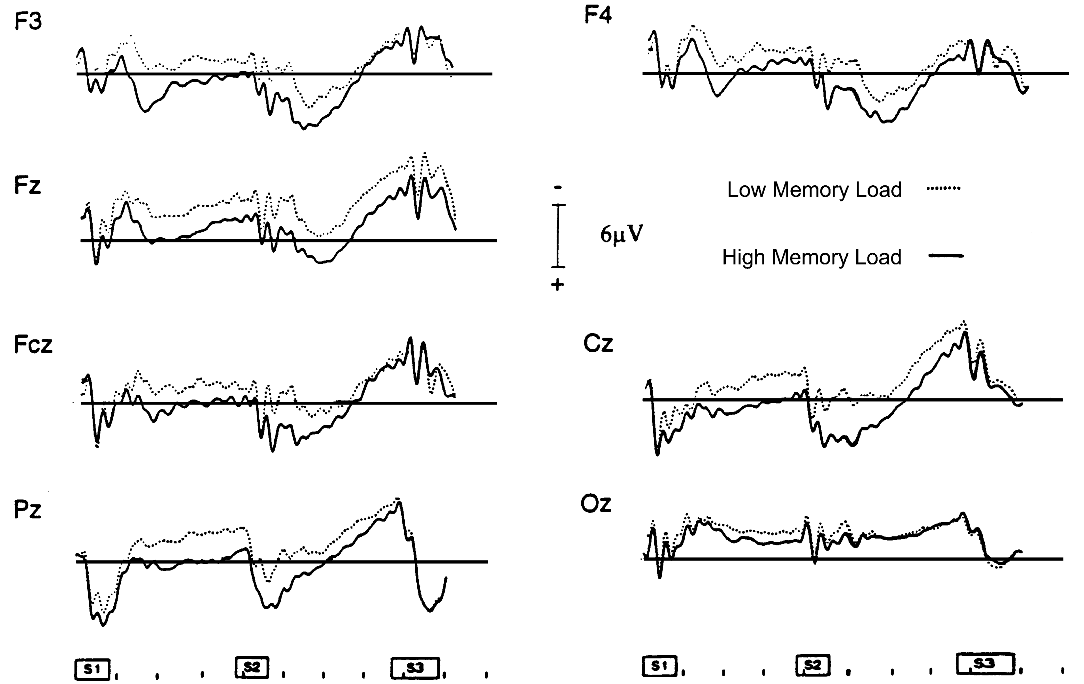


Fig. 3. Average ERPs for field-dependent subjects ($n = 15$) comparing low memory load (dotted line) and high memory load (solid line) conditions for all electrode sites: F3; F4; Fz; Fcz; Cz; Pz; and Oz. Stimulus presentation is indicated at the bottom of the figure with onset of S1 at time zero (500-ms duration), onset of S2 at 2300 ms (500-ms duration), and cue stimulus (S3) onset at 4600 ms (750-ms duration).

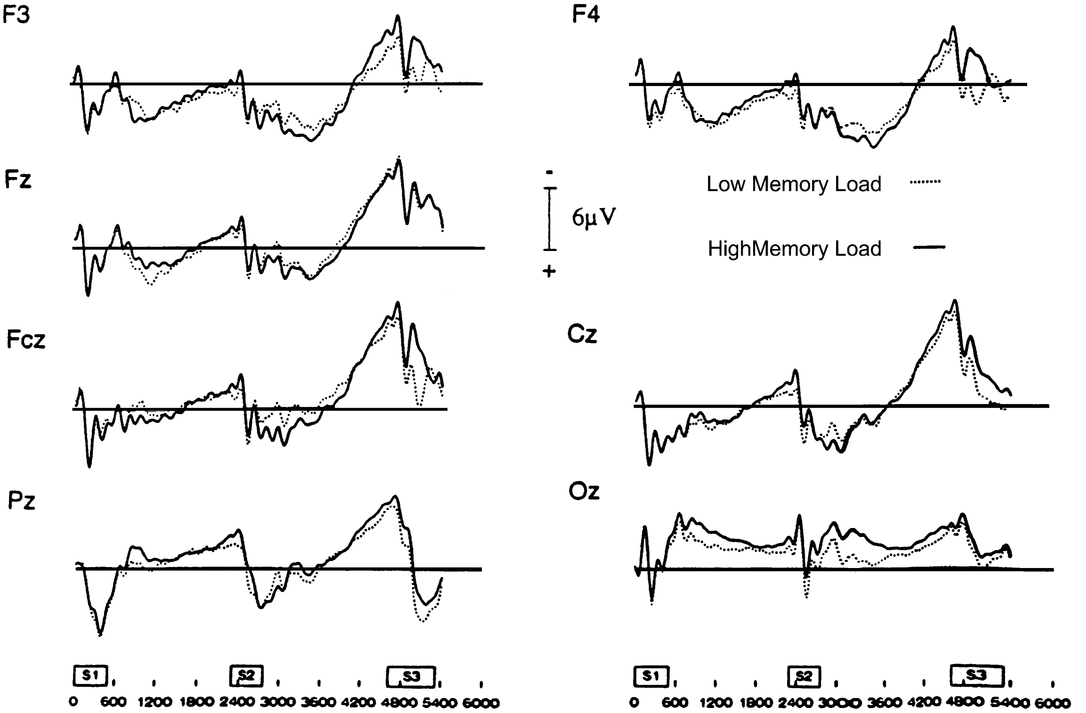


Fig. 4. Average ERPs for field independent subjects ($n = 15$) comparing low memory load (dotted line) and high memory load (solid line) conditions for all electrode sites: F3; F4; Fz; Fcz; Cz; Pz; and Oz. Stimulus presentation is indicated at the bottom of the figure with onset of S1 at time zero (500-ms duration), onset of S2 at 2300 ms (500-ms duration), and cue stimulus (S3) onset at 4600 ms (750-ms duration).

negative wave was seen in both intervals at parietal, central and frontal sites, generally maximal across the two cognitive style groups at the central and parietal sites. The slow negative wave occurred in the retention intervals when information from the task stimuli and serial order must be held in WM. A different pattern is seen at Oz as a prolonged negative slow wave with an earlier onset beginning approximately 500 ms following the onset of S1 and S2. It also had a flatter gradient compared to the slow negative wave seen at the parietal, central and frontal sites. Cognitive style group differences in the slow negative wave are most pronounced in the retention intervals prior to S2 and S3 in the high memory load condition; the FI group exhibited higher amplitudes relative to the FD group extending from the centro-parietal scalp anteriorly to the supplementary motor area at Fcz and the frontal scalp at Fz. The slow negative wave was at a maximum for FD subjects in the low memory load condition. ERPs for the subsample of subjects ($N = 6$) tested using a modified sequence exhibited a similar pattern in the slow negative wave compared to the complete sample, suggesting learning effects did not significantly influence the results.

3.2. ERPs in the S1–S2 interval

3.2.1. P300

The P300 was larger in amplitude in the high memory load conditions when multiple features were processed from the task stimuli at S1. This was reflected in a main effect for memory load [$F(1,28) = 7.15$, $P = 0.012$]. However, FD subjects appeared to allocate more cognitive resources for processing perceptual information from S1 (possibly in the attentional inhibition of a habitually global perceptual scheme, to enable in them a more analytical perception) compared to FI sub-

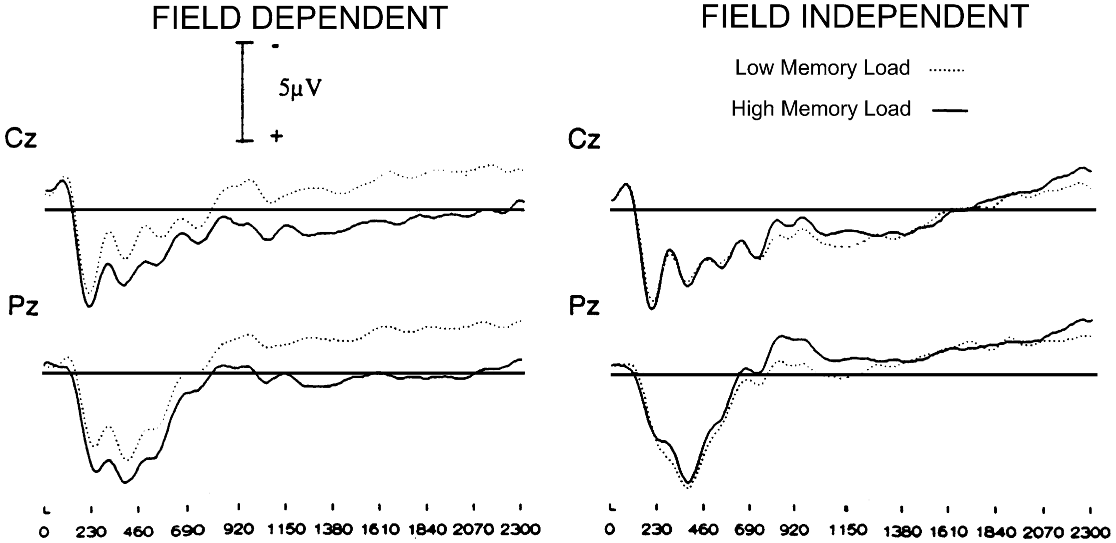


Fig. 5. Average ERPs for field-dependent subjects (left) and field independent subjects (right) at Cz and Pz for the P300 in the S1–S2 interval during low memory load (dotted line) and high memory load (solid line) conditions; S1 onset is at time 0. Baseline was established 600 ms prior to S1. P300 was calculated as average amplitude measure within a 260–560-ms latency window following onset of S1.

jects. This higher demand of resources is indexed by a larger P300 amplitude in FD subjects for the high memory load condition (see Fig. 5). This interpretation is supported by a significant memory load × FDI interaction [$F(1,28) = 8.26$, $P = 0.008$]. A main effect for electrode [$F(6,168) = 16.11$, $P < 0.001$, $\varepsilon = 0.38$] supported the observation that the P300 was maximal at Pz.

3.2.2. Early slow wave

Following the P300 at approximately 500 ms after the S1 onset, there is a negative slow wave predominant over the occipital site. This was revealed in a main effect for electrode [$F(6,168) = 9.89$, $P < 0.001$, $\varepsilon = 0.44$]. The slow wave at Oz is higher in amplitude in FI subjects in the high memory load condition. This observation is supported by a memory load × electrode interaction [$F(6,168) = 3.31$, $P = 0.026$, $\varepsilon = 0.48$] and a memory load × FDI interaction [$F(1,28) = 5.87$, $P = 0.022$]. Post-hoc analyses indicated that the negative slow wave at Oz increased with memory load [$F(1,29) = 4.41$, $P = 0.044$] and that there were cognitive style differences related to memory load at Oz [$F(1,28) = 7.38$, $P = 0.011$].

3.2.3. Early retention interval slow negative wave

FI subjects exhibited a rising slow negative wave beginning in the early retention interval over the parietal, central and frontal scalp, seen in both the low and high memory load conditions. FD subjects exhibited a different pattern in which the slow negative wave was larger in amplitude at F3, F4, Fz, Fcz, Cz and Pz in the low relative to the high memory load conditions. Group differences were significant in a memory load × FDI interaction [$F(1,28) = 4.53$, $P = 0.042$]. The cognitive style groups exhibited a different scalp distribution, as the slow negative wave was maximal over the parietal scalp in the high memory load condition for FI subjects, and maximal over the frontal scalp for FD subjects in the low memory load condition. This observation was supported by a main effect for electrode [$F(6,168) = 5.67$, $P = 0.003$, $\varepsilon = 0.39$] and an electrode × FDI interaction [$F(6,168) = 3.52$, $P = 0.029$, $\varepsilon = 0.39$]. A post-hoc analysis revealed that group differences on memory load were significant at F3 [$F(1,28) = 5.68$, $P = 0.024$]. Higher amplitudes frontally (F3, F4, Fz and Fcz) and lower amplitudes posteriorly (Cz and Pz) in the high recall condition were found when both groups were combined. This was seen in a significant recall × electrode interaction [$F(6,168) = 3.93$, $P = 0.009$, $\varepsilon = 0.55$], and supported by a post-hoc test in which frontal electrodes (Fz, F3 and F4) were compared to posterior electrodes (Cz, Pz and Oz), revealing a highly significant effect for recall × electrode [$F(1,89) = 24.24$, $P < 0.001$].

3.2.4. Late retention interval slow negative wave

Group differences in the slow negative wave associated with memory load that began in the early retention interval were statistically stronger in the late retention interval, as indicated by a significant memory load × FDI interaction [$F(1,28) = 5.59$, $P = 0.025$]. The slow negative wave was maximal over the centro-parietal scalp for FI subjects in the high memory load conditions and minimal for FD subjects. The slow negative wave was maximal over the frontal scalp for FD subjects in the low memory load condition. These cognitive style differences in topography were significant as indicated by an electrode × FDI interaction [$F(6,168) = 3.44$, $P = 0.018$, $\varepsilon = 0.53$]. A post-hoc analysis revealed significant group differences with memory load at Cz [$F(1,28) = 4.38$, $P = 0.045$], Pz [$F(1,28) = 6.91$, $P = 0.014$], and F3 [$F(1,28) = 4.40$, $P = 0.045$]. Frontal electrodes (F3, F4, Fz and Fcz) were higher, and electrodes at Cz and Pz were lower in amplitude in the high recall condition, across all subjects. This was seen in a significant recall × electrode interaction [$F(6,168) = 4.13$, $P = 0.004$, $\varepsilon = 0.65$] and a three-way interaction for memory load × recall × electrode [$F(6,168) = 3.78$, $P = 0.008$, $\varepsilon = 0.62$]. A post-hoc analysis revealed a highly significant ANOVA for recall × electrode [$F(1,89) = 15.42$, $P < 0.001$] and memory load × recall × electrode [$F(1,89) = 15.99$, $P < 0.001$] when frontal electrodes (Fz, F3 and F4) were compared to posterior electrodes (Cz, Pz and Oz).

3.3. ERPs in the S2–S3 interval

3.3.1. Early slow wave

A negative slow wave is apparent over the occipital scalp following the P300. Activation over selected cortical areas is supported by a main effect for electrode [$F(6,168) = 11.92$, $P < 0.001$, $\varepsilon = 0.40$]. A significant memory load × electrode interaction suggested that the slow wave is larger with high memory load [$F(6,168) = 4.05$, $P =$

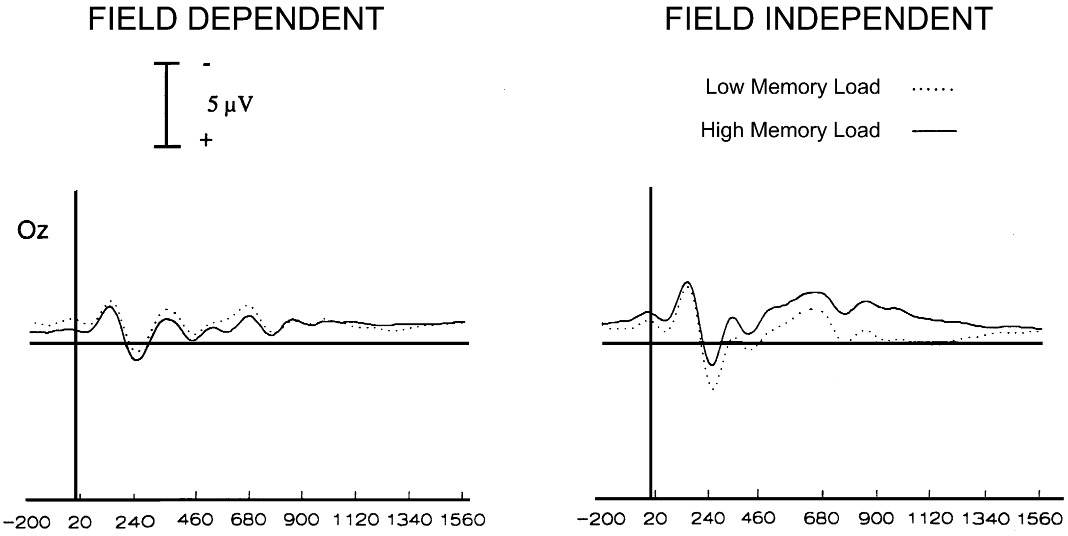


Fig. 6. Average ERPs for field-dependent subjects (left) and field independent subjects (right) at Oz for slow negative wave in the S2–S3 interval during the low memory load (dotted line) and high memory load (solid line) conditions. ERPs include the adjusted baseline established 200 ms prior to S2 with S2 onset at time 0 indicated by the vertical line. The slow negative wave was calculated as average amplitude measure within a 560–950-ms latency window following onset of S2.

0.021, $\varepsilon = 0.35$]. A post-hoc analysis revealed that the slow wave was significant at Oz with high memory load [$F(1,28) = 15.23$, $P = 0.001$] (see Fig. 6). However, the slow wave was also larger with high recall requirements seen as a significant recall × electrode interaction [$F(6,168) = 3.41$, $P = 0.025$, $\varepsilon = 0.45$], and supported by a post-hoc analysis indicating the amplitude at Oz increased with high recall requirements [$F(1,28) = 9.15$, $P = 0.005$].

Inspection of Fig. 6 shows that the tracings are not aligned at time 0. This indicates that the baseline adjustment did not correct completely for the long lasting negative waves preceding the presentation of S2. As a precaution to ensure independence of the measurements of phasic phenomena of the early slow wave and the P300 from baseline shifts, correlations between peak amplitudes and baseline parameters were calculated, and only those amplitudes were considered for interpretation that proved to be statistically independent from baseline trends (Rosler, 1991). Results revealed that the P300 phasic component was significantly correlated with the baseline trends, and the results of the P300 are not further considered. The correlation dropped to non-significance when the early slow wave was compared to baseline trends. This suggests that the phasic phenomenon measured by the early slow wave was statistically independent of baseline trends.

3.3.2. *Early retention interval slow negative wave*

Delayed onset of the slow negative wave was apparent in the S2–S3 early retention interval, relative to the S1–S2 interval. This occurred at a time in the task when subjects were required to combine the verbal codes from S1 and S2 in the temporal order of appearance. Cognitive style differences in the slow negative wave related to memory load were not significant in the early retention interval [$F(1,28) = 3.55$, $P = 0.07$]. The slow negative wave over the prefrontal cortex might be lateralized to the left, since F3 was larger in amplitude compared to F4. An ANOVA was conducted, excluding the three left-handed subjects, resulting in a main effect for electrode [$F(6,150) = 6.62$, $P = 0.001$, $\varepsilon = 0.48$]. A paired comparison post-hoc analysis confirmed that the amplitude at F3 was significantly larger than F4 [$t(1,107) = -2.37$, $P = 0.019$]. The high recall condition again revealed higher amplitudes in frontal electrodes (F3, F4, Fz and Fcz) compared to electrodes at Cz and Pz, across all subjects. This was supported by a recall × electrode interaction [$F(6,168) = 3.18$, $P = 0.033$, $\varepsilon = 0.45$] and a post-hoc analysis, which found frontal electrodes (Fz,F3 and F4) to be significantly larger in amplitude in the high recall condition relative to posterior electrodes (Cz, Pz and Oz) [$F(1,89) = 21.98$, $P < 0.001$].

3.3.3. *Late retention interval slow negative wave*

A steep-gradient slow negative wave in the late retention interval revealed distinct cognitive style differences. FI subjects exhibited a higher amplitude in the high memory load condition, relative to FD subjects. This is reflected in a significant memory load × FDI interaction [$F(1,28) = 5.94$, $P = 0.021$]. A pattern emerges across the S1–S2 and S2–S3 intervals indicating that the largest cognitive style differences in amplitude in the centro-parietal dominant slow negative wave are found in the late retention interval. The slow negative wave might be left lateralized frontally, F3 having a larger amplitude than F4. This is supported by a main effect for electrode [$F(6,150) = 5.95$, $P = 0.001$, $\varepsilon = 0.53$], in an analysis excluding left-handed subjects. A paired samples comparison confirmed that the F3 amplitude was larger than F4 [$t(1,107) = -4.28$, $P < 0.001$].

4. Discussion

4.1. *P300*

P300 amplitude following S1 was larger for FD subjects only, as demand increased in the high memory load conditions. This finding is consistent with Pascual-Leone's organismic model of field dependence independence (Pascual-Leone, 1969, 1989, 1992; Pascual-Leone and Mora, 1991; Messick, 1994; Niaz, 1994; Johnson et al., 2000). According to this model FD subjects should in our task experience the need, as processing demands increase, to actively inhibit their tendency to notice only salient aspects of the stimulus compound thus missing the non-salient ones. The finding is also consistent with past research indicating that P300 is sensitive to strategy differences (Hamstra, 1989; Stieben, 1994; Ruchkin et al., 1990b; Wascher et al., 1996).

It has been proposed that the P300 amplitude reflects the degree to which a change occurs in the context updating process (Donchin and Coles, 1988). The larger P300 amplitude in FD subjects (relative to FI subjects) in the S1–S2 interval, should reflect a greater change for FD subjects in the representational model of the stimulus situation. Indeed, the known global perceptual style of FD subjects suggests that geometric-shape stimuli presented were processed by them as a global perceptual whole. And we assume that 'context updating' involves the subject's mental updating of task processes and elements that together construct the representation of stimuli or situation; these processes or elements are represented by discrete schemes that must be boosted or inhibited in the updating process (Pascual-Leone et al., 1990). The high memory load conditions required the extraction of multiple features (even the less salient ones) from each geometric shape. The larger P300 amplitude in the high memory load condition, seen only in FD subjects presumably corresponds to the process of effortful inhibition (I) that FD subjects must apply at S1 in order to suppress their habitual scheme of global, passive perception; and instead apply the more analytical feature-extraction approach demanded by the task — a mental updating process. So interpreted, the process indexed by the P300 should indeed be of greater magnitude in FD subjects relative to FI subjects. This explanation of results, suggested by Pascual-Leone's model of FDI and congruent with other findings (Pascual-Leone et al., 1990), is supported by findings that interpret P300 amplitude as indexing inhibitory processes (Bakay et al., 1998; Halgren, 1993; Rockstroh et al., 1997). Furthermore, because the WM/I mechanism is a limited resource, if FD subjects allocate a large amount of processing resources in their context updating process (Isreal et al., 1980), then less resources in the limited capacity system may be available for holding and applying task-relevant schemes of information storage, temporal tagging, and updating, during the retention interval.

4.2. Early slow negative wave

This slow wave at Oz following the P300 in both the S1–S2 and S2–S3 intervals (Fig. 6) exhibited a different pattern compared to the slow negative wave at the parietal, central and frontal sites (Figs. 3 and 4). It was a prolonged negative wave with an earlier onset beginning approximately 500 ms that peaked at approximately 700–800 ms with a flattened gradient through the remainder of the retention interval. Ruchkin et al. (1997) presented subjects with visual object information to be retained in WM and found a negative slow wave activity over the temporal-occipital cortex; with an earlier onset and a flattened gradient, relative to later developing slow negative waves over the central-parietal to frontal scalp. The temporal-occipital negative slow wave was attributed to different brain processes than the later developing slow negative waves based on differences in topography and sensitivity to memory load. The negative slow wave at Oz in the present study increased in amplitude with memory load for FI subjects (Fig. 6). This slow wave at Oz may be subject to strategy differences, as revealed by cognitive style differences in the S1–S2 interval; and also by the fact that it was also found to increase in amplitude with recall demand in the S2–S3 interval. While we must be cautious in interpreting the function of the slow wave at Oz because of our limited electrode placements, the distinct pattern of the negative slow wave at Oz, and its increase with load, suggests that it has a neural generator that is different from the slow negative wave at the parietal, central and frontal scalp. The task's requirement to process analytically visual information from geometric shapes, and the similarity in onset and slow wave pattern with prior research (Ruchkin et al., 1997) suggests that the slow wave may be indexing further processing of visual information in the task. This interpretation is consistent with the finding that FI subjects exhibit higher slow wave amplitude at Oz during high memory load. It is, since Pascual-Leone (1969, 1970, 1989, 1992) has proposed, and others have also reported, that FI subjects tend to process information more deeply than FD subjects — unless they run out of capacity in their WM/I system (Baillargeon et al., 1998).

4.3. Slow negative wave

Later in the ERP record we found a slow negative wave of significantly higher amplitude for FI subjects than for FD subjects. FI subjects displayed a large slow negative wave in the S1–S2 and S2–S3 retention intervals, over parietal, central and frontal scalp, in both memory load conditions, which was slightly higher in amplitude in the high load conditions. This slow negative wave was lateralized to the left at F3 in the S2–S3 interval. In contrast, FD subjects exhibited their larger slow negative wave over the parietal and central scalp and during the low memory load conditions. Thus, distinct cognitive style differences appeared in both memory load conditions; with high memory load the slow negative wave was lower in amplitude for FD than for FI subjects, over the parietal, central and frontal scalp. We interpret this finding as indexing the deeper processing of information that FI subjects are known to exhibit in tasks that involve non-salient or conflictive cues — as we have explained in Section 1. In addition, there is evidence to suggest that the minimal negativity for FD subjects in the high memory load conditions may reflect a diversion of limited resources to context updating processes. The larger P300 amplitude in FD subjects in the high memory load conditions in the S1–S2 interval corresponded with a decrease in the slow negative wave over the parietal, central and frontal scalp. We attribute the larger P300 amplitude in FD subjects to strategy differences associated with their global processing style, and suggest that allocation of processing resources to context updating processes may have resulted in less processing resources available in the limited capacity processing space for storage and manipulation processes in the retention interval. This was expressed as a reduced amplitude slow negative wave in FD subjects. Previous memory studies, using a different paradigm that did not require WM processes during the delay interval, found slow negative waves to decrease in amplitude with increased memory load (Roth et al., 1975; McCallum et al., 1988).

4.4. Concluding remarks

The serial order recall task manipulated WM/I processes and executive processes by requiring subjects to retain feature information elaborated as verbal codes to make a temporal-order judgment about the probe. The scalp distribution in the present study is consistent with findings of neuroimaging studies that employed a verbal 2-back task, which is functionally similar to the serial order recall task. In this case, activated regions of the brain were associated with a phonological storage system in the parietal area, with a frontal rehearsal system (left-lateralized), and with prefrontal executive processes (Smith and Jonides, 1999). Executive processes were associated with temporal tagging and the updating of WM (Braver et al., 1997; Konishi et al., 1999). The cognitive style differences in our study were associated with WM retention processes, since the slow negative wave followed components associated with processing the task stimuli; and group differences were found to increase with memory load, and not with recall requirements, in the late retention interval.

The shifting allocation of resources to either stimulus evaluation or to planning/anticipatory processes, has been identified as an executive function of the prefrontal cortex (Garcia-Larrea and Cezanne-Bert, 1998). This is important because theories about FDI (Dempster, 1992; Pascual-Leone, 1989; Waber, 1989), and the task analysis of the RFT discussed above, suggest that executive processes of FD subjects (possibly localized in the prefrontal lobe — Pascual-Leone, 1989) are less effective than those of FI subjects in shifting mental attention away from perceptual processes and into structuring of the task solution.

FD subjects exhibited a higher amplitude slow negative wave over the frontal scalp in the underprepared condition, and a reduced amplitude slow negative wave over the centro-parietal scalp in the high effort condition. These two conditions comprise the high recall condition. We interpret the heightened frontal activity in FD subjects during the underprepared condition as expression of the subjects' executive attempt to retrieve, from the initial global-perceptual information that they extracted from S1 and S2, the additional information needed to answer the question posed by S3. Previous studies have found frontal maximal slow negative waves to be associated with processes of anticipation (Simons et al., 1983), particularly in response to emotionally arousing stimuli (Klorman and Ryan, 1980). The reduced slow negative wave of FD subjects in the high effort condition, we interpret as reflecting the tendency toward lesser depth of processing in FD relative to FI subjects.

This is the first study to use theories about FDI cognitive style differences to make predictions about differences in ERP activity in a WM task. The FD global strategy and the FI analytical strategy have been linked to functional differences in WM/I processes. While the present study found a higher amplitude slow negative wave in FI than in FD subjects — a wave associated with WM retention processes under high load conditions — additional research is needed to understand neuropsychologically how FDI strategies relate to WM/I processes. One promising area for future research is based on the consistent findings in a number of studies that FD subjects exhibit poorer performance on concept formation tasks, relative to FI subjects (Davis, 1991). Davis and Frank (1979) reviewed evidence showing FD subjects to be less efficient in using short-term memory to process feedback information and sample working hypotheses during concept formation. And in recent neuroimaging and ERP studies, WM and executive processes were found to be critical during concept formation (Konishi et al., 1998; Lang et al., 1987). Furthermore, individual differences in activation associated with these processes seem to correlate with performance (Lang et al., 1988).

The ERP methodology and neuroimaging techniques are valuable tools to further explore the psychological construct of FDI, and the functional brain systems underlying cognitive style differences.

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