

Posttraumatic stress disorder is associated with limited executive resources in a working memory task

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Abstract Patients with posttraumatic stress disorder (PTSD) can show declines in working memory. A dual-task design was used to determine whether these impairments are linked to executive control limitations. Participants performed a Sternberg memory task with either one or four letters. In the dual-task condition, the maintenance period was filled with an arrow flanker task. PTSD patients were less accurate on the working memory task than were controls, especially in the dual-task condition. In the single-task condition, both groups showed similar patterns of brain potentials from 300 to 500 ms when discriminating old and new probes. However, when taxed with an additional task, the event-related potentials (ERPs) of the PTSD group no longer differentiated old and new probes. In contrast, interference resolution processes in both the single- and dual-task conditions of the flanker task were intact. The lack of differentiation in the ERPs reflects impaired working memory performance under more difficult, dual-task conditions. Exacerbated difficulty in performing a working memory task with concurrent task demands suggests a specific limitation in executive control resources in PTSD.

Keywords Working memory · PTSD · ERP · Dual task · Executive function · Sternberg memory task

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One critical aspect of executive control is the coordination of multiple cognitive processes. Executive control is required in order to maintain items relevant to current goals in memory and to selectively focus on goal-relevant items (García-Larrea & Cézanne-Bert, 1998). Top-down attention influences the selection of visual stimuli on the basis of previous experience and current goals, while filtering out distractor stimuli (Bledowski, Prvulovic, Goebel, Zanella, & Linden, 2004; Corbetta & Shulman, 2002; Hopf & Mangun, 2000; Lavie, Hirst, de Fockert, & Viding, 2004). Working memory (WM) plays a critical role in guiding these top-down attentional processes by keeping the current goals in mind (de Fockert, Rees, Frith, & Lavie, 2001; Downing, 2000; Soto, Heinke, Humphreys, & Blanco, 2005). The interaction between WM and attention suggests that as WM load increases, attentional capacity decreases, and in turn causes WM performance to decline (Gazzaley, 2011; Pratt, Willoughby, & Swick, 2011).

An ongoing question in cognitive neuroscience is the extent to which different executive control processes can be functionally and neuroanatomically dissociated. For example, factor analysis has demonstrated that response inhibition, set shifting, and WM updating are separable processes (Miyake et al., 2000). Neuroimaging studies have investigated the “unity and diversity” of executive functions, finding both overlapping and distinct patterns of activation for different interference resolution tasks (e.g., Nee, Wager, & Jonides, 2007; Wager et al., 2005). One executive function that has been less investigated in these sorts of studies is dual-task performance (Miyake & Friedman, 2012) or multitasking, a key function in daily life. Studies of patient populations can reveal potential dissociations in performance relative to controls, providing a powerful method for examining the structure of cognition (Henry, 2006; Pantelis & Maruff, 2002). In the present study, we were interested in how an anxiety disorder might influence cognitive control processes. We used a dual-task design with WM and conflict-monitoring

components. By using emotionally neutral stimuli, we can examine whether more general limitations in executive control are seen in individuals with difficulty regulating emotion.

Posttraumatic stress disorder (PTSD) is a specific anxiety disorder that occurs following a traumatic event. PTSD is characterized by three symptom clusters: (1) intrusive memories, such as flashbacks and nightmares, (2) avoidance of activities, people or places as well as general feelings of emotional numbing, and (3) hyperarousal symptoms such as increased startle to unexpected noises, bursts of anger and decreased ability to sleep (DSM-IV; American Psychiatric Association, 1994). These symptoms are often associated with decreased motivation, comorbid depression, and blunt affective disposition (Danckwerts & Leathem, 2003). In addition, individuals with PTSD also show impairments in coordinating, inhibiting, and monitoring cognition and behavior (Koso & Hansen, 2006; Leskin & White, 2007; Swick, Honzel, Larsen, Ashley, & Justus, 2012; Vasterling et al., 2012). These limitations in executive control can lead to impairments in multiple aspects of cognition. However, the effects of PTSD on executive control have not been as consistently documented as the well-known difficulties in regulating emotional memory (e.g., Rauch, Shin, & Phelps, 2006). Some studies have reported deficits in WM and attention in PTSD (Elzinga & Bremner, 2002; Koso & Hansen, 2006; Vasterling, Brailey, Constans, & Sutker, 1998), whereas other studies have shown little to no impairment in performance (Brenner et al., 2010; Neylan et al., 2003). In the present experiment, we set out to determine whether cognitive impairment in WM is linked to executive control limitations by examining performance on a WM task alone and when a secondary attention task was performed during the maintenance period. Exacerbated difficulty while performing a WM task with concurrent task demands would suggest executive control dysfunction in PTSD rather than a general decline in memory (Baddeley, 1996).

The severity of PTSD symptomatology is often related to cognitive dysfunction, specifically to a decline in cognitive control and memory performance (Bremner et al., 1993; Drag, Spencer, Walker, Pangilinan, & Bieliauskas, 2012; Elzinga & Bremner, 2002; Vasterling et al., 1998; Vasterling et al., 2012). Bremner et al. (1993) found a significant decline in both immediate and delayed recall in patients with PTSD as compared to military controls using the Wechsler Memory scale. The impairment in WM performance was strongly correlated with symptom severity of reexperiencing the traumatic event (Elzinga & Bremner, 2002). In addition, other studies indicate that reexperiencing is significantly related to impairments in inhibitory control (Swick et al., 2012; Vasterling et al., 1998). Deficits in cognitive control, impulsivity and WM may relate to dysfunction in networks that mediate emotional control (Aupperle, Allard, Grimes, et al., 2012; Etkin & Wager, 2007).

The prefrontal cortex (PFC) is thought to be critical for efficient functioning of executive control (Wager & Smith, 2003). Some evidence suggests that PTSD is related to frontal dysfunction because performance on certain tasks is similar to performance of patients with frontal lobe injury, specifically on memory tasks (Vasterling et al., 1998). Frontal patients may perform well on certain tasks when performed singly, but show difficulty in coordinating multiple processes as evidenced by declines in dual-task performance (Cowey & Green, 1996; Dreher, Koechlin, Tierney, & Grafman, 2008). Other studies have not observed this pattern, however (Andrés & Van der Linden, 2002; Roussel, Dujardin, Hénon, & Godefroy, 2012; Vilkkki, Virtanen, Surma-Aho, & Servo, 1996). Regardless of the neuroanatomical underpinnings, cognitive difficulties in patients with PTSD might not necessarily be apparent when testing only one cognitive domain, but might instead be more prominent in tasks that require coordination of multiple elements. However, no studies have examined dual-task performance in PTSD. Here, we focused on WM retrieval and how it is affected by the performance of a demanding visual attention task during the retention interval.

To determine the nature of the neurophysiological changes that might underlie any memory deficits in PTSD patients, we also examined event-related potentials (ERPs) to the probe stimulus in the WM task. Alteration of a relatively early electrophysiological component in the patients might be indicative of problems with item recognition, whereas later ERP changes could reflect difficulties with decision or postretrieval monitoring processes (Folstein & van Petten, 2011; Wilding & Herron, 2006). A specific neural marker of memory retrieval processes is the ERP old/new effect. This electrophysiological response consists of a positive shift in the waveform to previously presented items that are correctly recognized, relative to new items that are correctly rejected (Rugg & Curran, 2007). Although typically examined using experimental designs such as study–test list learning (Rugg & Doyle, 1992; Smith, 1993) and continuous recognition (Friedman, 1990; Swick & Knight, 1997), the old/new effect has also been examined using WM and Sternberg tasks (Tays, Dywan, Capuana, & Segalowitz, 2011; Tays, Dywan, Mathewson, & Segalowitz, 2008). In those studies, an array of letters or words was presented, followed after a delay by a probe stimulus. A probe that was correctly identified as being contained within the array (“old”) elicited a greater positivity from approximately 350 to 600 ms than did a probe that was not in the array (“new”).

Thus far, no studies have examined ERP old/new effects in individuals with PTSD, either under single- or dual-task conditions. In addition to examining verbal WM performance, the present study incorporated a distracting secondary task to tax cognitive control processes while maintaining a smaller or larger memory set. We adjusted the set size by manipulating

the number of items to be remembered (either one or four), and then used a modified version of the Eriksen flanker task (Eriksen & Eriksen, 1974) to engage selective attention and conflict resolution processes. Participants performed both tasks (Sternberg and flanker) alone and in conjunction. We predicted that high WM load would affect attentional performance. Specifically, if items are being maintained in WM, then fewer resources would be available for the flanker task, thereby resulting in decreased ability to resolve response conflict and diminished accuracy to incongruent flankers (Lavie & de Fockert, 2005). We also predicted that PTSD patients would show a disproportionate decline in WM performance in the dual-task condition. Electrophysiological measures were expected to reflect this decline in performance by showing a reduction in the amplitude of the old/new effect in the dual-task condition, suggesting that the secondary task would disrupt WM retrieval processes in PTSD.

Method

Participants

The participants were 18 Iraq and Afghanistan combat veterans diagnosed with PTSD (17 male, one female) and 16 Iraq and Afghanistan control veterans matched in age and gender (15 male, one female). None of the enrolled participants reported significant substance abuse or a history of other psychological disorders, excluding depression (as in Seal et al., 2008). One veteran with PTSD was unable to complete the experiment and was subsequently dropped from analysis leaving the PTSD group at $n = 17$. For the flanker analysis, five participants (three in the patient group and two in the control group) were excluded due to incorrect task performance. These five participants mistakenly responded to the arrow in the center of the flanker array and not to the centrally presented arrow and were therefore excluded. The final analysis for the WM tasks yielded $n = 17$ patients and $n = 16$ for controls, whereas the flanker data yielded $n = 14$ for each group. Fourteen of the 17 participants with PTSD had attended a clinic for traumatic brain injury (TBI); however, all participants had reported no history of TBI involving loss of consciousness greater than 1–2 min or any other preexisting neurological disease. Within the patient group, four participants reported no loss of consciousness, whereas the remaining 13 reported feeling dazed or experiencing a brief loss of consciousness no longer than 1–2 min in duration. A semi-structured clinical interview was conducted, and mild TBI was diagnosed on the basis of patient self-report of the following criteria from the VA/DoD Clinical Practice Guidelines: loss of consciousness for 30 min or less or altered mental status (e.g., feeling dazed, disoriented, or confused), with posttraumatic amnesia less than 24 h (Management of Concussion/mTBI Working Group, 2009).

PTSD diagnosis was based on semistructured clinical interview using DSM-IV criteria. The diagnoses of mTBI and PTSD were corroborated with available VA medical records, to the fullest extent possible.

All participants were given the PTSD Checklist, Military Version (PCL-M) for DSM-IV (Weathers, Litz, Huska, & Keane, 1994) and the Beck Depression Inventory (BDI; Beck, Epstein, Brown, & Steer, 1988). The PCL-M is an accepted diagnostic tool for measuring PTSD (Blanchard, Jones-Alexander, Buckley, & Forneris, 1996). The PCL-M is a 17-item self-report tool that was used to establish the presence of PTSD symptoms in combat-exposed veterans. It has three clusters or subsets: reexperiencing, numbing, and hyperarousal. The BDI is one of the most commonly used self-report screens for major depression that has been validated with well-established psychometric properties (Beck et al., 1988). As expected, the two groups showed highly divergent scores on these questionnaires (Table 1), indicating greater levels of PTSD and depression symptoms in the patients. The groups did not differ significantly in age (PTSD, 33.5 ± 7.2 years; controls, 36.4 ± 8.6 years), $t(31) = 1.070$, $p = .29$. However, we did observe a significant difference in mean years of education (PTSD, 13.7 ± 1.1 ; controls, 14.9 ± 1.9), $t(31) = 2.269$, $p = .03$. See Table 1 for details on the demographic data.

The Institutional Review Board of the VA Northern California Health Care System approved the experimental protocol, and all participants gave informed consent prior to beginning the experiment. They were paid for transportation plus \$20/h for their participation.

Stimuli and tasks

Single-task condition (Sternberg memory task) Participants were seated in a darkened, sound-attenuated room and were instructed to limit blinking and fixate at the center of a screen. Participants were asked to remember either one consonant (presented for 2,000 ms) or four consonants (presented for 3,500 ms). After an 8,500-ms delay, another consonant was presented (probe). Participants responded with a buttonpress to indicate whether the probe was part of the previous memory set (old) or whether the probe was not part of the memory set (new). For each trial, the set size (one or four) as well as the probe type (old or new) was determined randomly with equal probabilities. Ten blocks of ten trials each were presented (100 total).

Single-task condition (arrow flanker task) Participants were instructed to respond with a buttonpress to indicate, as quickly and accurately as possible, whether the central arrowhead pointed to the left or the right. Flanking arrows, positioned either above, below, or both above and below the central arrow, could point in either the same (congruent) direction

Table 1 Demographic information and self-rating scores for the PTSD patients and the controls

	Patients ($n = 17$)	Controls ($n = 16$)
Age (yrs)	33.5 ± 7 (n.s.)	36.4 ± 7
Education (yrs)	13.68 ± 1.10**	14.94 ± 1.95
Handedness	16 R, 1 L	15 R, 1 L
Deployed (n)	17	6
Combat (n)	17	2
PCL-M	57.1 ± 13.0***	24.8 ± 7.3
BDI	18.5 ± 7.6***	4.8 ± 5.4

The mean ± standard deviation are given for age, education, PTSD Checklist, Military Version (PCL-M), and Beck Depression Inventory (BDI). n.s. = not significantly different from controls. ** Significantly different from controls at $p < .005$. *** Significantly different from controls at $p < .0001$. R = right, L = left

(40 % of trials) or in a different (incongruent) direction (60 % of trials). Each flanker stimulus was presented for 200 ms, with the next trial beginning 300 to 500 ms after a response was made. If no response was registered, the next trial began 900 ms after stimulus onset. Each participant completed ten blocks of 60 flanker trials.

Dual-task condition (Sternberg memory task + arrow flanker) In the dual-task condition, participants were required to perform the arrow flanker task during the delay interval of the Sternberg memory task. Nine flanker trials began 300 to 500 ms following the presentation of each Sternberg memory set. The stimulus parameters were the same as for the single-task flanker condition described above. The Sternberg probe was then presented 500 ms following the final flanker trial, and participants responded with a buttonpress to indicate whether this item was in the previous memory set. Each of the ten blocks contained ten Sternberg trials, each with nine flanker trials embedded during each delay interval, for a total of 100 Sternberg trials and 900 arrow flankers. The task order was counterbalanced across participants.

EEG recording

Continuous EEG was recorded from 64 scalp electrodes and two electrodes on the left and right mastoids using the ActiveTwo Biosemi electrode system (BioSemi, Amsterdam, The Netherlands). Four electrodes placed lateral to and below the right and left eyes recorded blinks and eye movements. The EEG was sampled at 512 Hz. Offline analysis was completed using the Brain Vision Analyzer software (Brainproducts, Munich). Data were re-referenced to the averaged mastoids and bandpass filtered from 0.1 to 30 Hz. The EEG was segmented for each trial from 100 ms prestimulus to 900 ms post-stimulus-onset. EEGs were corrected for blinks, and eye

movements and extraneous artifacts exceeding $150\mu V$ were rejected.

Statistical analysis

Behavioral performance Behavioral analyses examined reaction time (RT) and accuracy using repeated measure analyses of variance (ANOVAs). Only correct responses to Sternberg probes were used in the RT analysis. The RT data were analyzed using a $2 \times 2 \times 2 \times 2$ design with the within-subjects factors Task (single or dual), Set Size (one or four), and Probe (old or new), and the between-subjects factor Group (PTSD or control). The accuracy analysis examined percentage of correct responses using the same factor design as the RT analysis. The flanker data were analyzed using a 2×3 factor design: Congruence (congruent or incongruent) \times Load (single flanker, set size 1, or set size 4). In addition, any significant group effects were also followed up with an analysis of covariance to evaluate the effect of education.

Electrophysiological analysis The old/new effect was analyzed in 100-ms intervals. The Sternberg probe ERPs were analyzed by taking the mean amplitude of six midline electrodes over time windows of 300–400, 400–500, 500–600, and 600–700 ms, with the factors Task (single or dual), Set Size (one or four), Probe (old or new), Electrode (Fz, FCz, Cz, CPz, Pz, or POz), and Group (controls or PTSD) for correct responses only. To ensure that each averaged ERP represented a sufficient number of artifact-free segments (mean > 40, minimum > 20), effects of set size were examined in analyses that collapsed across probe, and effects of probe were examined in analyses that collapsed across set sizes. Therefore, we performed two analyses at each time interval using a four-way ANOVA (1: Task \times Set Size \times Electrode \times Group; 2: Task \times Probe \times Electrode \times Group).

Results

Behavioral results

Sternberg Individuals with PTSD were less accurate than controls on the Sternberg WM task, and their performance was disproportionately impaired in the dual-task condition (Fig. 1). This was supported by a main effect of group [$F(1, 31) = 5.55, p = .03$] and a Task \times Group interaction [$F(1, 31) = 4.42, p = .04$]. The PTSD patients were not significantly different from controls in the single-task condition [$F(1, 31) = 2.49, p = .12$] but were significantly less accurate on the Sternberg task in the dual-task condition [$F(1, 31) = 6.42, p = .02$], when the demanding flanker task occurred during the WM delay (Fig. 1). Accuracy in the PTSD

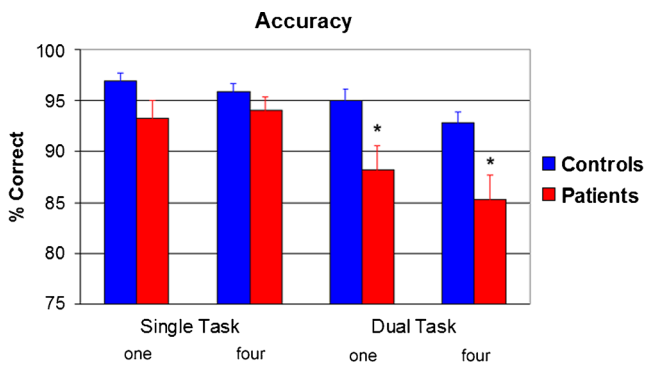


Fig. 1 Mean percent correct responses to Sternberg probe items, as a function of task (single, dual), set size (one, four), and group (controls, patients). Individuals with PTSD were less accurate than controls at classifying Sternberg probes as old versus new, particularly for the dual task ($p < .05$ is indicated by an asterisk)

patient group dropped from 93.7 % in the single task to 86.7 % in the dual task [$F(1, 16) = 13.49, p = .002$]. The controls also showed a decline in accuracy, yet the decrease in performance was smaller (single task, 96.5 %; dual task, 93.9 %) [$F(1, 15) = 11.79, p = .004$]. In addition, participants were less accurate in the dual task than in the single task and for new probes than for old probes (Table 2), as indicated by significant main effects of task [$F(1, 31) = 20.81, p < .0001$] and probe [$F(1, 31) = 8.97, p = .005$]. The main effect of set size ($p = .11$) and the Set Size \times Group interaction ($p = .74$) were not significant.

To account for the discrepancy in education between the groups, a covariance analysis was used to examine differences in accuracy in the dual-task condition. After adjusting for education, we observed a marginal effect between groups

Table 2 Accuracy (percent correct \pm SEM) and response times (mean \pm SEM, in milliseconds) for the controls ($n = 16$) and the participants with PTSD ($n = 17$) in the Sternberg task

	Set Size 1 Old	Set Size 1 New	Set Size 4 Old	Set Size 4 New
Accuracy				
Single Task				
Controls	98.0 \pm 0.6	95.6 \pm 1.3	97.4 \pm 1.0	94.5 \pm 1.1
PTSD	93.9 \pm 1.8	92.7 \pm 2.8	97.1 \pm 1.3	91.1 \pm 1.9
Dual Task				
Controls	96.6 \pm 1.3	93.4 \pm 2.0	95.0 \pm 1.4	90.6 \pm 1.4
PTSD	90.2 \pm 3.7	86.1 \pm 3.3	89.3 \pm 2.5	81.3 \pm 3.8
Reaction Time				
Single Task				
Controls	769 \pm 46	882 \pm 60	1,049 \pm 60	1,135 \pm 95
PTSD	978 \pm 82	1,102 \pm 91	1,216 \pm 84	1,210 \pm 85
Dual Task				
Controls	1,027 \pm 79	1,119 \pm 73	1,279 \pm 72	1,360 \pm 92
PTSD	1,141 \pm 91	1,206 \pm 110	1,391 \pm 87	1,394 \pm 115

[$F(1, 29) = 3.616, p = .067$]. The adjusted mean accuracy scores suggest that the PTSD patients performed worse (87.5 %) than controls (93.4 %). In addition, the correlation between years of education and accuracy in the dual-task condition was not significant ($r = .27, p = .14$).

In contrast, the two groups did not differ in their RTs to the memory probe [$F(1, 31) = 1.44, p = .24$], nor did group interact with task ($p = .19$), set size ($p = .16$), or probe ($p = .45$). Only significant main effects of task [$F(1, 31) = 42.69, p < .0001$], set size [$F(1, 31) = 120.80, p < .0001$], and probe [$F(1, 31) = 5.90, p = .02$] were observed (Table 2). Responses were faster in the single than in the dual task, faster for set size 1 than for set size 4, and faster for old than for new probes.

Flanker Table 3 illustrates that the two groups showed highly similar performance. For RTs, the significant main effect of congruence reflected the classic flanker interference effect: All participants were faster to respond to congruent than to incongruent flankers [$F(1, 26) = 241.89, p < .0001$]. Neither a main effect of load ($p = .81$) nor an interaction between congruence and load [$F(2, 52) = 2.23, p = .12$] emerged, the latter result suggesting that the addition of the WM task did not significantly alter the flanker interference effect. Importantly, we found no differences between the PTSD patients and controls for RTs: Group main effect ($p = .99$), Load \times Group ($p = .94$), and Congruence \times Group ($p = .80$).

The flanker interference effect was also seen for accuracy, with a main effect of congruence [$F(1, 26) = 88.59, p < .0001$]. In addition, a main effect of load was apparent [$F(2, 52) = 7.39, p = .002$]. However, this did not reflect a decline in performance for the dual task, but a decline in performance in the single task. Although it was slightly unexpected, this could be explained by the greater number of flanker trials presented in the single task (each block consisting of 60 flanker trials) than in the dual task (with nine consecutive flanker trials between probe and set presentation). Load did not interact with congruence [$F(2, 52) = 2.23, p = .23$]. Once again, the PTSD patients did not differ from controls: group main effect ($p = .84$), Load \times Group ($p = .36$), and Congruence \times Group ($p = .80$).

ERP results

Beginning with the 300- to 400-ms window, large effects of task began to emerge. ERPs were more positive in the dual-task than in the single-task condition across all participants [$F(1, 31) = 37.6, p < .001$]. This task effect interacted with electrode [$F(5, 155) = 32.4, p < .001$], being largest at Cz and FCz. Furthermore, ERPs to old probes were more positive in amplitude than those to new probes [$F(1, 31) = 9.6, p = .004$]. This probe effect interacted with task and electrode [$F(5, 155) = 2.8, p = .05$], such that probe effects were larger at Cz and FCz

Table 3 Accuracy (percent correct \pm SEM) and response times (mean \pm SEM, in milliseconds) for the controls ($n = 14$) and the participants with PTSD ($n = 14$) in the arrow flanker task

	Single Task		Dual Task			
	Congruent	Incongruent	Set Size 1		Set Size 4	
			Congruent	Incongruent	Congruent	Incongruent
Accuracy						
Controls	95.5 \pm 0.7	83.6 \pm 2.1	97.6 \pm 0.5	89.3 \pm 1.6	97.6 \pm 0.5	89.4 \pm 1.6
PTSD	96.1 \pm 0.8	83.0 \pm 3.6	98.4 \pm 0.4	86.4 \pm 3.1	98.8 \pm 0.5	88.5 \pm 1.8
Reaction Time						
Controls	453 \pm 14	508 \pm 14	456 \pm 19	511 \pm 21	457 \pm 18	510 \pm 20
PTSD	455 \pm 18	504 \pm 18	450 \pm 16	512 \pm 19	454 \pm 16	516 \pm 19

in the single task, but were more uniform in the dual task. Finally, the analysis including the factor Set Size confirmed that ERPs to set size 1 were more positive than those to set size 4 [$F(1, 31) = 6.2, p = .02$]. This set size effect interacted with electrode [$F(5, 155) = 3.5, p = .03$], being largest at Fz.

The major finding was that the PTSD patients did not show any differences between ERPs to old and new probes in the dual-task condition. This was supported by a three-way interaction between task, probe, and group [$F(1, 31) = 12.3, p = .001$]. This interaction was explored in follow-up analyses conducted separately on the single- and dual-task conditions. For the single task alone, a strong effect of probe was observed [$F(1, 31) = 12.5, p = .001$], with more positive measurements for old probes. This effect did not interact with group for the single task ($p = .36$) (Figs. 2 and 3). For the dual task alone, a main effect of probe [$F(1, 31) = 4.0, p = .05$] interacted with group [$F(1, 31) = 5.3, p = .03$]. This interaction was in turn followed up in separate analyses for each group, which showed that, in the dual-task condition, controls demonstrated a significant effect of probe [$F(1, 15) = 7.6, p = .02$], consistent with single-task performance in which old probes produced a more positive shift in the waveform (Fig. 2). However, individuals with PTSD did not show any distinction between old and new probes in the dual-task condition ($p = .81$) (Fig. 3).

Largely similar effects and interactions were observed for the 400- to 500-ms, 500- to 600-ms, and 600- to 700-ms windows, shown in Tables 4 and 5. The main effect of task and its interaction with electrode remained significant across all of the later time windows. The critical interaction between task, probe, and group remained significant through 600 ms, after which it reduced to a trend (Table 4). Follow-up analyses demonstrated a consistent pattern from 300 to 500 ms, such that the interaction was driven by the ERPs of the PTSD group, who demonstrated a statistically flat effect of probe during the dual-task condition.

This was also followed up with a covariance analysis to account for group differences in education. After adjusting for education, a significant difference remained between groups in the magnitude of the old/new effect from 300 to 400 ms in the dual-task condition [$F(1, 29) = 9.959, p = .004$]. Additionally, we found no significant correlation between years of education and the ERP old/new effect in the dual-task condition ($r = -.112, p = .506$).

Discussion

PTSD patients performed similarly to controls and showed comparable electrophysiological differences between old and new probes in the single-task WM condition. However, in the dual-task condition, the patients showed declines in both recognition accuracy and in the ERP old/new effect. This finding suggests that limitations in central executive resources contributed to the PTSD patients' impaired performance in the dual-task condition. The ERP results indicate that the electrophysiological activity underlying WM retrieval was intact in the patients, but the addition of a secondary task interfered with the neural processes that support probe recognition. In contrast, the patients were not impaired on either the single-task or dual-task versions of the flanker interference task. Interestingly, this intact performance on the flanker task suggests that some forms of inhibitory control were spared in the veterans with PTSD. Furthermore, these results provide evidence for a dissociation between interference resolution processes and dual-task performance during WM.

Baddeley (1996) found that patients with Alzheimer's disease performed similarly to controls on WM alone, but showed a significant decline in accuracy with a concurrent attention task. This finding signified that the disruption of performance was related to executive control dysfunction

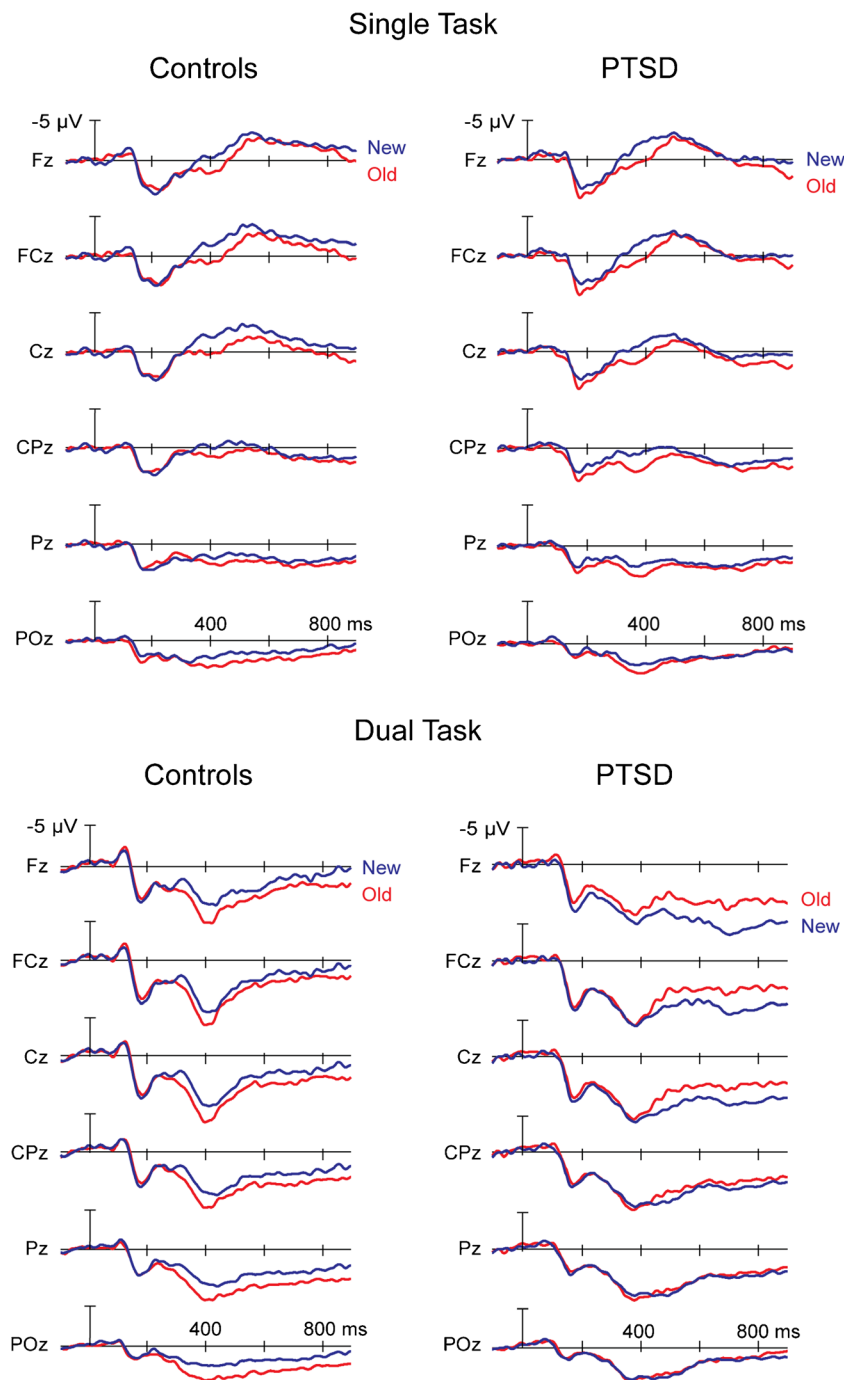


Fig. 2 Event-related potentials (ERPs) time-locked to the onset of the Sternberg probe item, as a function of task (single, dual), electrode (six midline electrodes), probe (old, new), and group (controls, PTSD). The ERP old/new effect—the positive shift for previously presented (old)

probes that are correctly recognized, relative to new probes that are correctly rejected—was observed beginning at 300 ms for both groups in the single-task condition, but only for the controls in the dual-task condition

and not necessarily impairment in verbal WM capacity (Baddeley, 1996; Baddeley, Logie, Bressi, Della Sala, & Spinnler, 1986). Our present findings show similar intact performance when WM was tested in isolation, yet significant decreases in accuracy when a dual-task condition was performed. This pattern of impaired multitasking performance,

as compared to relatively preserved performance on the single task and flanker interference task, therefore suggests that individuals with PTSD show disruption to some subset of executive control processes.

Given the intact performance in the flanker interference task in patients with PTSD, the results do not support the

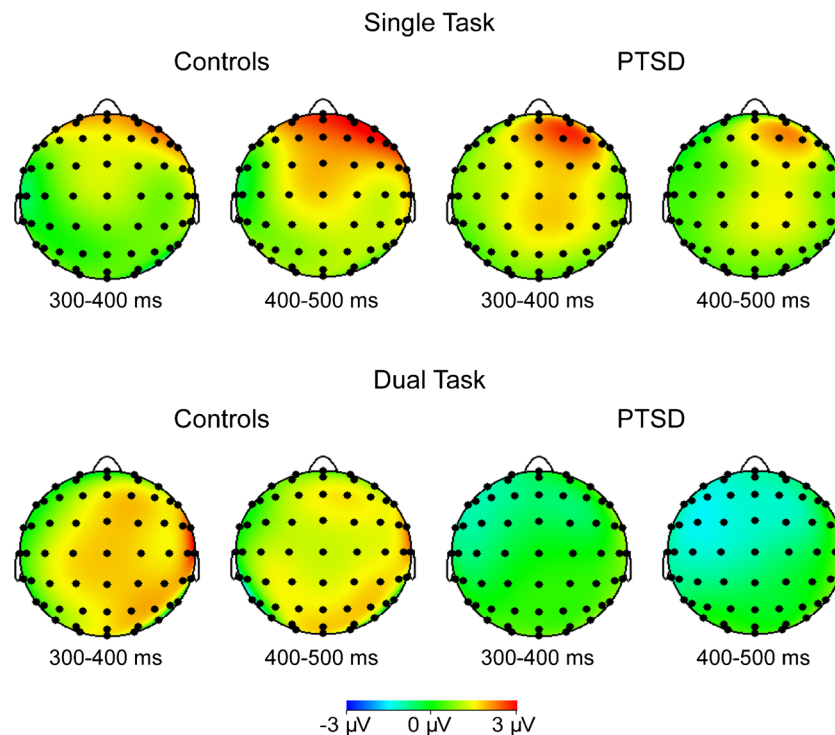


Fig. 3 Topographic plots illustrating the old/new difference wave as a function of task (single, dual) and group (controls, PTSD). More positive measurements for previously presented (old) probes, relative to new probes, are indicated by warmer colors

concept of a unitary central executive, which is not endorsed by Baddeley (2000). Indeed, another conception of executive control is that the different functions are fractionated and anatomically dissociable as evidenced by neuroimaging and neuropsychological studies (Stuss, 2011). A recent meta-

analysis of the neuroimaging literature identified four different executive component processes within WM (Nee et al., 2013). As we previously mentioned, latent variable analysis has differentiated WM updating from task switching and response inhibition, which are considered separate executive functions

Table 4 Event-related potential time window analysis: Task, Probe, Electrode \times Group

	300–400 ms	400–500 ms	500–600 ms	600–700 ms
Task	$F = 37.6, p < .001$	$F = 64.6, p < .001$	$F = 30.4, p < .001$	$F = 15.8, p < .001$
Task \times Electrode	$F = 32.4, p < .001$	$F = 38.0, p < .001$	$F = 14.6, p < .001$	$F = 11.6, p = .001$
Probe	$F = 9.6, p = .004$	$F = 5.2, p = .03$	n.s.	n.s.
Task \times Probe	n.s.	$F = 7.3, p = .01$	n.s.	n.s.
Task \times Probe \times Electrode	$F = 2.8, p = .05$	$F = 3.2, p = .03$	$F = 2.5, p = .08$	n.s.
Group	n.s.	n.s.	n.s.	n.s.
Probe \times Group	n.s.	$F = 3.2, p = .08$	$F = 4.0, p = .05$	$F = 5.2, p = .03$
Task \times Probe \times Group	$F = 12.3, p = .001$	$F = 6.0, p = .02$	$F = 5.0, p = .03$	$F = 3.2, p = .08$
Single Task				
Probe	$F = 12.5, p = .001$	$F = 13.4, p = .001$	n.s.	n.s.
Probe \times Group	n.s.	n.s.	n.s.	n.s.
Dual Task				
Probe	$F = 4.0, p = .05$	n.s.	n.s.	n.s.
Probe \times Group	$F = 5.3, p = .03$	$F = 6.3, p = .02$	$F = 7.9, p = .009$	$F = 8.6, p = .006$
Probe, controls	$F = 7.6, p = .02$	$F = 5.1, p = .04$	$F = 4.9, p = .04$	$F = 5.8, p = .03$
Probe, PTSD	n.s.	n.s.	$F = 3.2, p = .09$	$F = 3.4, p = .08$

Main effects of electrode are not reported. The remaining interactions not listed above were not significant (all p values $> .10$).

Table 5 Event-related potential time window analysis: Task, Set Size, Electrode \times Group

	300–400 ms	400–500 ms	500–600 ms	600–700 ms
Set Size	$F = 6.2, p = .02$	$F = 7.1, p = .01$	$F = 3.1, p = .09$	$F = 8.1, p = .008$
Set Size \times Electrode	$F = 3.5, p = .03$	$F = 4.1, p = .01$	n.s.	$F = 2.7, p = .07$

Main effects and interactions involving task, electrode, and group were comparable to those in the preceding analysis and are not repeated here. All remaining interactions were not significant (all p values $> .10$).

(Miyake et al., 2000). The limitations found in the PTSD patient population also support separate, but potentially overlapping, executive control functions. Findings from the present study revealed multitasking deficits, but only for the WM condition, and not the attention condition. This suggests that the emotional impairments commonly associated with PTSD deplete resources associated with WM when participants are required to complete a concurrent task.

One explanation for the present results is that the patients were better able to maintain the items in WM when no distraction was present, but had difficulties doing so when asked to divide their limited executive resources between the WM and flanker tasks. The single-task condition relies on only the storage component of WM, whereas the dual-task condition also invokes distractor resistance, an executive component of WM (Nee et al., 2013). Previous findings have suggested that patients with PTSD rely more strongly on repeating the last few items on a word list, as indicated by an increase in recency scores on memory tests relative to controls (Johnsen & Asbjørnsen, 2009). If patients with PTSD were more reliant on a rote encoding strategy in the current task, and less efficient at maintaining the stimuli in a longer-term store that would be less susceptible to interference, then the secondary task could have reduced their ability to explicitly rehearse the encoded information. This view is supported by theories suggesting that PTSD symptoms can cause deficits in learning and memory due to an inability to disengage from trauma-related memories, even on neutral, non-trauma related tasks (Vasterling et al., 1998). In other words, the traumatic memories occupy a central portion of WM, and an added cognitive task has to compete with the processing of emotionally charged material.

This interpretation suggests that the mechanisms required for maintaining items in WM during distraction can be compromised by ongoing symptoms of emotional stress or anxiety. The results extend the processing efficiency theory developed by Eysenck and Calvo (1992) to a clinical population. This theory states that trait anxiety reduces the processing and storage capacity of WM, especially when the central executive is required. In turn, greater effort is expended as a compensatory strategy to maintain performance (a reduction in processing efficiency). High-anxious individuals can typically maintain performance effectiveness, but are less efficient than controls. In contrast, the present results suggest

that the clinically significant anxiety of PTSD causes a reduction in performance effectiveness than cannot be overcome by increased effort, since WM updating was impaired when executive demands were high. Future studies in PTSD patients can examine the operation of top-down attentional-control mechanisms (Eysenck, Derakshan, Santos, & Calvo, 2007; Falies et al., 2008) in this light.

The resolution of response conflict is another major executive control function (Nee et al., 2007). We expected that the PTSD population would have difficulties with an interference resolution task, especially in light of their previously demonstrated deficit in motor response inhibition (Swick et al., 2012). Therefore, we predicted that the patients would show greater RT interference and decreased accuracy relative to controls in the flanker task. However, the patients performed as well as controls in both the single- and dual-task versions of the flanker task. New research has emerged that supports the idea that overlapping but distinct neural networks are associated with different aspects of inhibitory control (Swick, Ashley, & Turken, 2011). Sebastian et al. (2013) suggested that response inhibition processes can be divided into interference inhibition, withholding action response, and canceling current actions. It may be that patients with PTSD show difficulties withholding action responses in a Go/NoGo task (Swick et al., 2012), but not with interference inhibition, as demonstrated by the intact performance in the flanker task.

Our present results tend to support the view that separate cognitive systems are involved in implementing executive control. Deficits in only one aspect of executive control may contribute to the inconsistent neuropsychological testing results reported previously (Polak, Witteveen, Reitsma, & Olf, 2012). For example, patients with PTSD performed worse than trauma-exposed controls on the trail-making test and Wisconsin card-sorting task, but not on the Stroop or the digit-span backward task (Polak et al., 2012). However, the present findings could also reflect differential prioritization of common executive resources in the dual-task condition, in which performance in the flanker task was more important to the patients than accurate performance in the WM task. Comparing and contrasting performance in various attentional-control and inhibition tasks is a new and understudied area of PTSD and executive control research. One challenge to this approach is disentangling task-specific effects from common underlying cognitive processes.

Electrophysiological and hemodynamic imaging methods can be helpful in this regard.

We used ERPs to investigate the neural dynamics of WM. Accurate recognition of previously encoded items is generally reflected as a positive shift in the ERP waveform starting around 300 ms (Rugg & Curran, 2007). In the present study, both groups showed comparable ERP effects from 300 to 500 ms when distinguishing between old and new probes in the single-task condition, similar to previous reports on the ERP old/new effect (Danker et al., 2008; Tays et al., 2011). However, the PTSD group no longer produced ERP differences between old and new probes when taxed with an additional flanker task during the maintenance period. The early onset of the ERP deficit in the patients suggests that their decreased accuracy was a direct result of retrieval difficulties in the dual-task condition, as opposed to problems with later decision processes. This is generally consistent with Weber et al.'s (2005) study examining WM in PTSD patients using a variable target task. ERPs associated with WM updating showed a diminished positive wave in PTSD patients starting around 300 ms over frontal and parietal regions. Weber et al. suggested that diminished ERP responses from 300 to 900 ms reflected abnormal frontal and parietal activation in patients with PTSD. Specifically, the authors argued that reductions in both frontal and parietal activity suggest that patients with PTSD have difficulties integrating information into WM (Weber, et al., 2005).

In the present study, differences between the PTSD and control groups were found in the frontal–parietal network, but only for the ERPs associated with distinguishing old versus new items under the dual-task condition. The topographic maps indicated a more frontally distributed effect in the single-task condition in both groups. In controls, this effect shifts to central and posterior regions when distinguishing old and new probes in the dual-task condition. PTSD patients show similar frontal scalp distributions in the single-task condition, but fail to show a shift in scalp topography in the dual-task condition. This result may suggest that the frontal and parietal networks necessary to maintain information in WM during distraction, and to successfully retrieve information from WM, are functioning at a limited capacity in PTSD patients. Specifically, the lack of frontal and parietal activation during the ERP old/new waveform indicates an impairment in recognition when patients are taxed with an additional task. Our findings extend previous reports by Weber and colleagues and suggest that dual-task performance exacerbates WM difficulties often found in PTSD patients.

Previous reports have specifically compared WM deficits in patients with PTSD to patients with frontal-lobe damage (Vasterling et al., 1998; Weber et al., 2005). Chao & Knight, 1998; Nielsen-Bohlman & Knight, 1999 have observed diminished ERPs in patients with dorsolateral PFC damage when updating events in WM (Chao & Knight, 1998; Nielsen-Bohlman & Knight, 1999). Our present findings also

suggest diminished cortical activation in both the frontal and parietal lobes in WM updating. However, these results were specific for the dual-task condition.

The deficits in the dual-task condition cannot be attributed solely to task difficulty because we observed no interaction with WM set size, nor were deficits found for the flanker task in the dual-task condition. All participants showed increased response times to probes when maintaining a larger as compared to a smaller set size. Although we expected set size to affect patient performance, our results instead suggest that significant WM impairment was observed only when coordinating more than one task, and was not caused by a general decline in WM capacity, at least for set sizes of one versus four items. Many previous studies have associated WM impairment with PTSD, but have usually used immediate free recall tests, such as the California Verbal Learning Test (CVLT), which are more difficult and typically require that more than four items be maintained in WM (for a review, see Johnsen & Asbjørnsen, 2008). Future studies using dual-task designs may consider increasing the set size to determine whether an interaction between set size and task exists.

One limitation of the present study is the lack of a distractor condition in which participants passively viewed arrow flanker stimuli during the maintenance period. The present findings are unclear as to whether the disruption in WM performance was due to performance of the secondary flanker task or to the presence of visual distractors. Nonetheless, resistance to external distraction is also considered an executive component of WM (Gazzaley, 2011; Nee et al., 2013). In accord with this view, patients with prefrontal lesions were impaired in a match-to-sample WM task only when distractors intervened between the study item and the probe (Chao & Knight, 1998). Future studies including passive presentations of visual distractor stimuli will be critical in evaluating the extent of cognitive impairments using a dual-task design.

Another limitation of the present study was the inability to determine whether the deficits in the WM dual-task condition were specific to PTSD or to the combination of PTSD and depression. The comorbidity rate of depression in patients with PTSD is extremely high (Seal et al., 2008), and that was also the case in our current population, according to self-report. The focus of this study was to recruit patients with PTSD. Future studies would greatly benefit from taking comorbidity into account, and even including a major depression group with no PTSD. Including a psychiatric control group would better increase our understanding of the deficits associated with PTSD versus the deficits that could be attributed to depression. In addition, it would be beneficial to also match groups on the basis of combat exposure. In the present study, we did not obtain information related to the severity of combat exposure. Future studies would benefit from incorporating this into the methods and analysis.

Conclusion

Patients with PTSD were able to perform a WM task in isolation, showing no significant difference from controls. However, when the maintenance period was filled with a distracting task, the PTSD patients declined significantly in WM accuracy, and the associated ERPs no longer differentiated old and new probes. The patients also showed no performance declines in the flanker interference task, either in isolation or in the dual-task condition. This supports research suggesting distinct and separable processes of executive control (Miyake et al., 2000). Deficits in WM dual-task performance may suggest that ongoing traumatic memories in PTSD patients are interfering with a portion of WM. Limitations in WM processes were found in PTSD patients when an added cognitive task was included and the required resources had to compete with the processing of emotionally charged material. Impairments in executive control have great clinical importance, because even subtle deficits can influence coping style and cognitive reappraisal strategies (Vasterling & Verfaellie, 2009). Previous results have indicated that dual-task performance is reflective of real-world functioning (McDowell, Whyte, & D'Esposito, 1997). Limitations in executive processing may contribute to the inability of individuals with PTSD to disengage from traumatic memories (reexperiencing) and to modulate emotional responses (hyperarousal). These, in turn, may lead to withdrawal from situations in which executive control is likely to fail (avoidance and numbing; Aupperle, Melrose, Stein, & Paulus, 2012). The dual-task design presented here is a useful experimental representation of real-world multitasking deficits and suggests that emotional impairments from an anxiety disorder like PTSD can produce distinct limitations in executive control.

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