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Selective contributions of executive function ability to the P3

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ABSTRACT

The P3 component (P300, P3b) is considered to be an effective index of attention and categorization processes when elicited in a visual oddball task, specifically reflecting the selection of a rare target item among frequent non-targets. Researchers have proposed that target categorization is guided by representations of target features held in working memory (WM), thus guiding attention and categorization processes to distinguish targets from non-targets. Although WM is theorized to have visuospatial, verbal and executive function components, most studies do not investigate how these WM components contribute to the P3. This study uses an individual differences approach to determine whether correlations between WM capabilities and P3 amplitudes indicate a common underlying cognitive construct. Participants ($n = 140$) completed an 80/20 visual oddball task to elicit the P3 as well as independent visual working memory (VWM), spatial working memory (SPWM), and executive function (task switching (TS) and digit symbol substitution (DSS)) tests. Results indicated that measures of executive function, DSS and TS, but not VWM or SPWM ability, correlated with and predicted faster task response times and greater P3 amplitudes. RT and WM measures were not correlated with P3 fractional area latencies. These results support context updating theory. Executive function WM availability, whether as a property of the participant's processing system or based on task demands, plays a functional role in the P3 and an important role in efficient visual categorization and goal-directed learning.

1. Introduction[1]

Do individual differences in working memory (WM) predict neural responses associated with attention and working memory processes? In this study we use an individual differences approach to investigate the relations between the centroparietal P3 (or P300 or P3b) event-related potential (ERP) and several working memory operations. Specifically, we focus on the contributions of visual WM, spatial WM and executive function components that are involved in performing the visual oddball task. WM refers to a multi-component, limited-capacity information processing system comprised of interrelated attention and memory subsystems that actively maintain and transform information in the brain for goal-relevant behavior over short periods of time (Baddeley, 2003; Baddeley and Hitch, 1974; Fuster, 1973). The P3 is thought to reflect attention and memory mechanisms as part of an information processing cascade (Polich, 2007, 2012). It is a large, positive ERP that is observed 200–500 ms following stimulus onset (Polich, 2012; Gray et al., 2004; Squires et al., 1977). Often the P3 is elicited with an oddball paradigm in which a relatively rare target occurs within a series of relatively frequent non-targets (Duncan-Johnson and Donchin, 1977; Squires et al., 1976). Larger P3 amplitudes are observed for targets compared to non-targets (Donchin and Coles, 1988; Ritter et al., 1999; Polich and Criado, 2006; Snyder and Hillyard, 1976). The P3 to rare targets, or P3b, peaks around 300 ms at centroparietal electrodes. Thus, the P3 is an index of processing relevant but unexpected information.

A number of studies have associated the P3 with WM and the

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[1] WM = working memory, VWM = visual working memory; SPWM = spatial working memory, TS = Task Switching, DSS = Digit Symbol Substitution

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activation of attentional resources that promote memory operations in a distributed frontoparietal network (Brázdil et al., 2001, 2003; Gevins and Cutillo, 1993; Linden, 2005; Knight, 1996; Polich, 2007, 2012; Squire and Kandel, 1999). This network may include the anterior cingulate cortex which has also been associated with attention and memory processing resources (Lenartowicz and McIntosh, 2005). The P3-eliciting visual oddball paradigm involves many of these processes. For this task, top-down frontal attention mechanisms maintain visually processed target items in WM, compare the goal target with the current incoming stimulus, evaluate them, and organize appropriate responses (Conroy and Polich, 2007; Nieuwenhuis et al., 2005; Verleger et al., 2005). Several manipulations have been shown to affect P3 amplitude, including WM load, stimulus probability, target-to-target intervals, and interstimulus intervals (Gevins and Cutillo, 1993; Donchin et al., 1986; Gonsalvez and Polich, 2002). For example, in a task switching paradigm, P3 amplitudes increase with cues indicating that the task is changing, especially for switch trials (Kieffaber and Hetrick, 2005). Further, P3 amplitudes are also larger for stimuli that are subsequently recalled, suggesting that better WM should be associated with larger P3 amplitudes.

Several theories relate the P3 to WM processes (Donchin, 1981; Kok, 2001; Nieuwenhuis et al., 2005; Polich, 2007; Verleger et al., 2005). One prominent theory is the context updating theory (Donchin, 1981; Polich, 2007, 2012) which emphasizes the biological importance of attending to low probability, or rare, stimuli. It proposes that the P3 results from the detection of a change, or mismatch, between the task-relevant stimulus and its immediate context, which is defined by the frequent non-target stimuli and "updating" of the neural stimulus representation in WM. Frequent stimuli establish the mental model of the task environment. Each new stimulus is compared as a match or mismatch to the target or category held in WM. When a mismatch is detected, the mental model is updated in WM and elicits the P3. The probability of incoming stimuli creates task or context expectations such that rare stimuli require an adjustment of task expectations and related responses (Cavanagh, 2015; Eppinger et al., 2017; Frömer et al., 2019; Nassar et al., 2019). These processes are thought to be supported by frontal-parietal networks reflected by modulations of the P3 and are associated with WM functions (Polich, 2012; Friedman et al., 2001; Knight and Nakada, 1998; Nieuwenhuis et al., 2005; Ranganath and Rainer, 2003).

WM has long been theorized to be a limited-capacity, multicomponent system comprised of interacting component processes that are specific to modality (visual, auditory) or content (spatial, verbal). They interact via an executive function component that acts as a supervisory control of goals, attention, mental manipulation and response selection (Baddeley, 2003; Baddeley and Hitch, 1974; Cowan, 2008; Engle, 2002). Behavioral and neuropsychological studies support separable subsystems for storing non-spatial and spatial visual representations, as well as executive functions and phonological representations (Farah et al., 1988; Baddeley and Logie, 1999; Carlesimo et al., 2001; McCabe et al., 2010; Vallar and Baddeley, 1984). However, many studies associating the P3 with WM processes do not distinguish contributions from different WM components. Donchin and Coles (1988), for example, did not commit to a specific memory system or subcomponent of WM for their context updating theory. However, Polich (2007, 2012) has associated the P3 with specific executive function components.

Previous research has examined changes in the P3 electrophysiological response as a function of WM demands within the EEG/ERP task (Daffner et al., 2011; Jaeggi et al., 2010; McEvoy et al., 1998; Watter et al., 2001; Isreal et al., 1980; Kramer et al., 1985; Wickens et al., 1983), but less research has focused on whether these changes vary across individuals with different WM capacities. An individual difference approach can demonstrate that WM has a functional role in the P3. Lefebvre et al. (2005) proposed that the P3 is a potential neurophysiological marker for WM capacity. Typically, increased cognitive demands reduce P3 component size (Kok, 2001; Wijers et al., 1989), suggesting that P3 amplitudes may be modulated by individual differences in WM capacity. If P3 amplitudes reflect limits on cognitive resources available for current mental operations, then smaller P3 amplitudes may indicate fewer available WM resources (McEvoy et al., 1998; Watter et al., 2001). Gevins and Smith (2000) found P3 amplitudes positively correlated with WM capacities and general cognitive abilities.

Several studies have used separate measures of WM capacity from the ERP task to obtain an independent estimate from the neural measure. Dong et al. (2015) measured WM capacity using a modified digit span task completed prior to an EEG/ERP n-back task that varied in difficulty. They found that P3 amplitudes correlated with individual WM capacities independent of ERP task difficulty, such that higher WM capacities produced larger P3 amplitudes. Similarly, Nittono et al. (1999) assessed WM capacity using a reading span test (Daneman and Carpenter, 1980) and elicited the P3 using a multiple-choice reaction time task. They too found larger P3 amplitudes for high-span compared to low-span individuals, but only in the more demanding task conditions. Consistent with Polich (2007) who proposed that the P3 plays a role in attentional resource allocation among concurrent operations, these findings suggest that those with greater WM capacity make more efficient use of neural resources that keep attention focused on task relevant information.

P3 latency can also be sensitive to task processing demands and vary with individual differences in cognitive capability (e.g., Emmerson et al., 1989; Johnson et al., 1985; Pelosi et al., 1992a; Polich et al., 1983). Shorter P3 latencies have been correlated with higher levels of cognitive performance (Houlihan et al., 1998; Pelosi et al., 1992b; Reinvang, 1999). For example, O'Donnell et al. (1992) used an auditory oddball task with and without task demands to determine if P3 amplitudes and latencies were related to psychometric performance. After deriving four factors from a factor analysis of a variety of WAIS-R, Wechsler Memory and word list learning tasks, they found that P3 latencies at Cz in active processing conditions correlated with factors reflecting general intelligence and concentration. Performance on psychometric WM tests (i.e., digit span) also negatively correlate with the P3 latency from auditory oddball tasks (Polich et al., 1983).

Although the above studies have shown P3 differences among individuals with different WM capacities, they typically assessed WM as a single cognitive operation. In this study, we built on this work and used a large sample of young adults to evaluate whether individual differences in task-relevant WM components were differentially predictive of P3 amplitudes and latencies. If the current representation in WM needs to be updated or revised to select the appropriate response, the P3 amplitudes and latencies should be related to individual differences in WM ability. Independent of the visual oddball task, we assessed four measures of WM that are potentially important to visual oddball task performance: two tasks assessing visuospatial WM and two assessing executive function. Visuospatial WM ability and executive function ability may influence task performance and the P3 because incoming visual information must be maintained for comparison with target representations and subsequent response selection. To assess visuospatial WM, we used validated measures based on visual WM paradigms (Luck and Vogel, 1997) and spatial WM paradigms (Awh et al., 1998) that require maintaining visual information in WM. To assess executive function, we used a task switching measure that requires the changing of task rules or goals in WM and response selection (Monsell, 2003) and a digit symbol substitution measure that requires attention, visual perceptual processing, comparisons in WM, processing speed, and motor speed (Hoyer et al., 2004). By assessing WM abilities separate from the P3-eliciting task, we can investigate whether visuospatial WM and executive function abilities are predictive of P3 amplitudes and latencies.

2. Methods

2.1. Participants

Event-related potential and behavioral data were collected as part of

a larger research project (for more information on this project see https://pursue.richmond.edu/). Participants were recruited from Hampshire College, University of Richmond, and Claremont McKenna College and the surrounding Amherst MA, Richmond VA, and Claremont, CA communities, receiving either partial course credit or financial compensation. This study was approved by the participating institutions' Institutional Review Boards and all participants provided informed consent. All participants reported corrected-to-normal vision with no history of severe psychological disorders (e.g., schizophrenia), neurological injury or disease, loss of consciousness for more than two minutes, or stroke. We included all participants who had data on all the reported measures (i.e., complete data sets) and who met data quality and task performance criteria. Data from 165 adults (ages 18–31 years) were included in the current study. Prior to statistical analyses, participants were excluded if there were less than 50% of trials remaining after artifact rejection and correction or significant noise remained in the data following artifact correction (i.e. the signalto-noise ratio was low due to poor recording quality) ($n = 8$). In addition, participants were excluded if their behavioral data on the visual oddball task was below the criterion of 78% accuracy in both task conditions to ensure a sufficient number of correct target trials for analysis ($n = 10$) or if their scores on the WM measures were 2.5 SDs from the sample mean ($n = 7$). In total, data from 140 participants ($M_{age} = 19.65$, SD = 1.82; 93 female) were included in data analysis.

2.2. Procedure

Participants provided demographic data and completed three computer-based measures of visual working memory, spatial working memory, and executive function. Working memory task order was counterbalanced across participants. Participants performed a visual oddball task while EEG was measured (Kappenman et al., 2021).

2.3. Tasks

2.3.1. Visual oddball task

Participants were seated 75 cm from the monitor, with their feet flat on the floor and torso centered with the monitor. Stimuli were presented on a 35.5 cm × 28 cm ViewPixx monitor (43.5 cm diagonal) using Presentation v 19.0 11.02.16 software (Neurobehavioral Systems). A Logitech Precision Game Pad recorded responses. Participants performed an active, visual oddball task to measure P3 activity (modified from Kappenman et al., 2021). For each trial (Fig. 1), an uppercase letter was presented for 200 ms in the center of the screen (A, B, C, D, E; Geneva font, subtending 2.5 × 2.5° of visual angle; probability of 20% for each letter) over a continuously visible central white fixation point (0.15° visual angle), with a jittered SOA of 1400 ms to 1600 ms (rectangular distribution, average of 1500 ms). Participants classified each letter stimulus as a target or non-target by pressing a button with either the index or middle finger of their dominant hand. The stimulus-response mapping was counterbalanced between participants (50% used index finger for target stimuli; 50% used index finger for non-target stimuli). The target letter was indicated before each block. The stimuli were presented in random order. Block order was randomized between participants. There were eight target trials (probability = 20%) and 32 non-target trials (probability = 80%). A total of 200 trials were completed in five, 40-trial blocks. Participants took breaks between blocks.

2.3.2. Working memory tasks

Working memory tasks were part of the validated BrainBaseline Cognitive Test Battery (https://www.brainbaseline.com/; Lee et al., 2012) and were performed on an iPad held approximately 50 cm away on a desk in front of the participant.

2.3.2.1. Visual working memory (VWM). VWM was assessed via a delayed match-to-sample task of four colored objects and the spatial location of the encoded objects was not relevant for task performance (modified from Luck and Vogel, 1997). A display of four colored squares, randomly selected from a set of seven, appeared for 1000 ms (red RGB (1,0,0), green RGB(0,1,0), blue RGB(0,0,1), yellow RGB(1,1,0), purple RGB(0.88,0.01,0.89), black RGB(0,0,0), cyan RGB(0.02,0.99,0.78)). Squares were 120 × 120 pixels and appeared at a center-to-center distance of 210 pixels. Squares were presented in a row above the fixation cross, in the same four locations. The squares were held in WM during a 1500 ms delay while a fixation appeared on the screen. A probe square appeared at screen center below fixation and participants determined if the square color matched one in the memory set. Following 10 practice trials, 68 test trials followed (50% were "match" trials where the probe square was in the memory set).

2.3.2.2. Spatial working memory (SPWM). SPWM was assessed via a delayed match-to-sample task of four spatial locations (modified from Awh et al., 1998). A central fixation appeared for 1500 ms. Then, a display with 2 or 3 black dots (each 11 pixels radius) surrounding the fixation appeared for 500 ms. Locations were pseudo-randomly determined for each trial. Dot locations were held in WM for 1000 ms while the fixation appeared on the screen. A red dot probe appeared and participants determined if its location matched one of the dot locations held in memory. Following eight practice trials, 60 test trials followed (50% of which were "match" trials where the probe location was in the memory set).

2.3.2.3. Digit symbol substitution (DSS). Executive function was assessed via the digit symbol substitution task (modified from Hoyer et al., 2004). Nine, digit-symbol pairs were presented at the top of the screen; a table with nine, randomly ordered numbers and blank boxes below them was presented in the center of the screen; and a set of nine symbols was presented at the bottom of the screen. Participants used their index finger to drag as many symbols as they could into the boxes beneath the corresponding numbers within the 90s time limit.

2.3.2.4. Task switching (TS). Executive function was also assessed via TS (modified from Monsell, 2003). Each trial began with two response

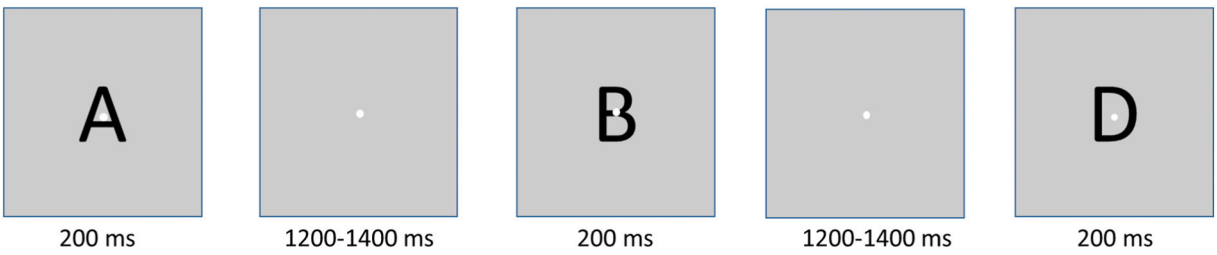

Fig. 1. For the visual oddball task, single letters (A, B, C, D, E) were presented in random order with probability 20% for each letter. At the beginning of each block of trials, one letter designated as the target; stimuli that were targets in one block were non-targets in other blocks. Participants pressed one button for the target stimulus and another button for non-target stimuli. Thus, target probability in a block was 20% and non-target probability was 80%.

boxes on either side screen: high/low on the left and odd/even on the right. Next, in the center of the screen, a number (1–9) was presented within either a blue or a pink square. If the background was blue, participants indicated whether the number was high (above 5) or low (below 5) using the left hand. If the background was pink, then participants indicated whether the number was odd or even using the right hand. The color of the square switched randomly from trial to trial.

2.4. Electrophysiological methods

Scalp electroencephalograms (EEGs) were recorded from 32 active Ag/AgCl electrodes (actiCAP, Brain Products GmbH, Gilching, Germany) using the BrainVision actiCHamp systems (Brain Products GmbH, Gilching, Germany). Electrode impedances were set below 25 kΩ at the start of the experiment and were kept below 50 kΩ during the experiment. Electrodes were placed at Fp1, Fp2, F3, Fz, F4, F7, F8, FC3, FC4, C3, Cz, C4, C5, C6, TP9, CPz, TP10, P3, Pz, P4, P7, P8, P03, P04, P07, P08, 01, Oz, and O2, according to the international 10/20 system. The horizontal electrooculogram (HEOG) was recorded from electrodes placed lateral to the external canthi. The vertical electrooculogram (VEOG) was recorded from an electrode placed below the right eye (Fp2 was used in combination with this electrode to create a VEOG for analysis as a difference in voltage between upper and lower eye locations) to identify trials in which participants blinked during stimulus presentation.

2.4.1. Data analysis and reduction

Data were exported into MATLAB and analyzed using the EEGLAB (Delorme and Makeig, 2004; Delorme et al., 2011; https://sccn.ucsd.edu/eeglab/index.php) and ERPLAB (http://www.erpinfo.org/erplab) toolboxes. EEGs were adjusted for DC offset by removing the mean value across the EEG and then filtered using an IIR Butterworth bandpass filter from 0.1 to 30 Hz (half amplitude cut off, 12 db/oct and 40db/dec roll-off). Data were re-referenced off-line to linked mastoids (TP9/TP10). Continuous data were segmented into epochs (200 ms pre-stimulus to 800 ms post-stimulus) for rare target and frequent non-target conditions. Only data from correct trials were analyzed. Epochs were baseline-corrected using the mean of the 200 ms pre-stimulus period. Artifacts in the data were addressed in two ways. First, we removed trials if they contained significant ocular artifacts (+/− 100 μvolts at bipolar VEOG channels) during stimulus presentation (+/− 150 ms surrounding stimulus presentation). Second, we identified artifactual signals (e.g., eye blinks, eye movements, noisy channels, line noise, muscle movement) using independent component analysis via second-order blind identification, which "unmixes" the EEG signal into independent components that can be classified as task-related or artifactual. Initial artifact classification was performed using automated routines from the SASICA (Chaumon et al., 2015) and ICLabel (Pion-Tonachini et al., 2019) toolboxes, but all classifications underwent follow-up visual inspection to ensure that meaningful cognitive components were not mistakenly flagged for removal. For each participant's cleaned EEG data set, the trials were averaged for each condition.

For Rare (target) and Frequent (non-target) conditions, we selected a 300 ms to 600 ms time window to calculate mean amplitude, based on the examination of the combined-condition grand average data and Kappenman et al. (2021) who used the same paradigm. We used the 50% fractional area latency to quantify P3 latency. We measured from the Cz electrode, consistent with prior literature showing it demonstrates a clear P3 effect (Fig. 2: Rare-Frequent condition differences) and importantly, is sensitive to frontoparietal-based working memory modulations (e.g., Barcelo et al., 2008; Gevins and Cutillo, 1993; Luo and Zhou, 2020; Nittono et al., 1999; O'Donnell et al., 1992). The P3 Difference Wave, or "P3", was calculated by subtracting Frequent from Rare waveforms. To provide additional information regarding data quality, we calculated the analytic standard measurement error (aSME) for the baseline and selected time window at Cz following the procedures specified in Luck et al. (2019) and implemented via ERPlab (Table 1). We report the root mean square (RMS) of the individual-participant values. This measure reflects extent to which noise, or trial-to-trial variations, in the EEG recording, has an impact on the P3 measures.

Pearson correlation and multivariate regression analyses were used in all analyses to examine whether WM measures predicted correct response times (RTs), P3 amplitudes, and P3 50% fractional area latencies for the visual oddball task. In these regressions all assumptions of multiple linear regression were met, including measures of collinearity measured by VIF, which were all below 1.29.

3. Results

3.1. Behavioral performance and individual differences in working memory

Proportion accuracy and response times (RTs) for correct trials were

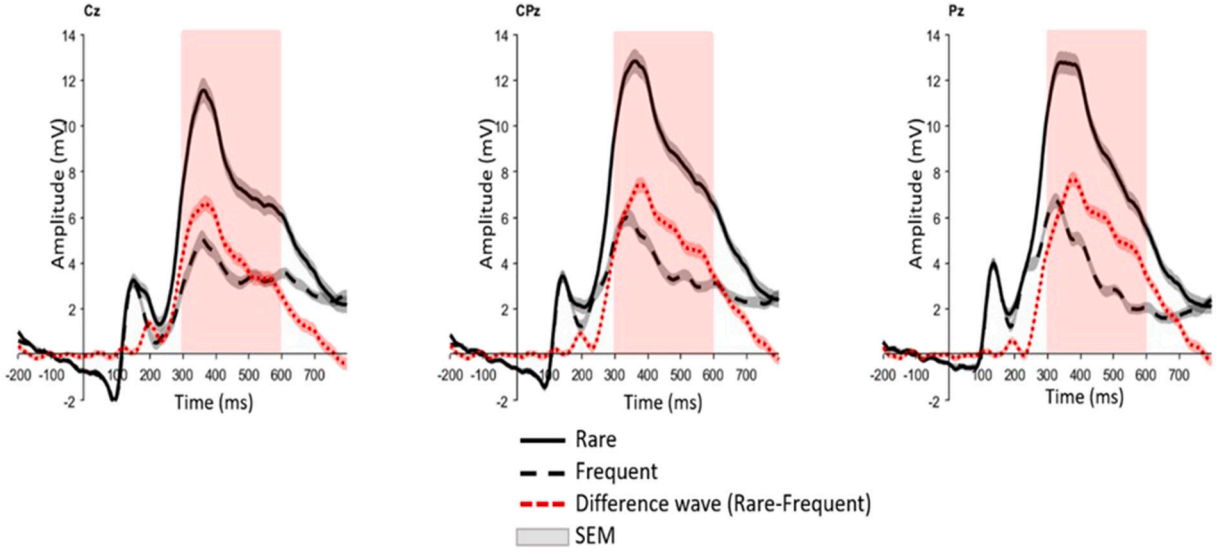

Fig. 2. P3 waveforms to rare (targets) and frequent (non-targets) and their difference wave at the Cz, CPz, and Pz electrodes. The shaded areas for each waveform indicate the standard error of the mean (SEM) and the highlighted box indicates the mean amplitude time window.

Table 1
Root mean square (RMS) values of individual-participant analytic standard measurement error (aSME) values for Rare and Frequent conditions during baseline and P3 time windows.

	Baseline measure (−200 to 0 ms)	P3 time window (300 to 600 ms)
Rare condition	1.54	1.98
Frequent condition	0.79	1.98

calculated for each participant and condition for the visual oddball task. For all tasks, trials in which RTs were less than 200 ms or greater than 1000 ms were excluded from analyses because they were attributed to anticipatory or inattention responses (greater than 3 SD's from the grand mean) resulting in a loss of less than 2% of the data. For the visual oddball task, overall accuracy was 91.71% (SD = 6.90). We analyzed correct RT data for each participant and condition, given that accuracy on the visual oddball task was part of the participant inclusion criteria.

For VWM and SPWM, proportion accuracy was calculated for each participant. For DSS, the number of correct digit-symbol matches was recorded. For TS, a switch trial efficiency score was calculated because switching cost measures have come under criticism in the literature and have been replaced with efficiency scores (e.g., Draheim et al., 2016). Further, the switch trials have been shown to be most closely related to the P3 (Barcelo et al., 2008; Kieffaber and Hetrick, 2005). Nine participants were removed from analyses for having outlier scores (i.e., scores exceeding 2.5 SD) in at least one of the individual difference measures. In all the reported analyses, data patterns and levels of significance did not differ with and without their inclusion. Table 2 provides descriptive measures and summarizes the correlations between WM and visual oddball task performance and P3 measures.

Correlation and multiple regression analyses were conducted to examine the relationship between WM ability and correct RTs on the oddball task. RTs positively correlated with TS: participants with faster RTs tended to have more digit symbol matches and more efficient task switches. VWM, SPWM, and DSS were not correlated with oddball task RT. The multiple linear regression model on oddball task RTs with VWM, SPWM, DSS and TS as predictors explains a small but significant proportion of the variance ($R^2 = 0.10$, adj. $R^2 = 0.07$, $F(4, 138) = 3.76$, $p = .006$). Only TS had significant positive regression weights, indicating participants with more efficient task switching ability are expected to have faster responses performing the oddball task, after controlling for the other variables in the model ($B = 0.05$; $\beta = 0.30$, $t = 3.44$, $p = .001$). DSS did not contribute to the model ($B = -0.19$, $\beta = -0.03$, $t = -0.29$, $p = .77$), nor did VWM ($B = -38.72$, $\beta = -0.06$, $t = -0.61$, $p = .55$) or SPWM ($B = 28.73$, $\beta = 0.04$, $t = 0.38$, $p = .71$).

3.2. ERP analyses

3.2.1. P3 amplitude

The presence of the P3 was confirmed by a significant repeated-measures analysis of variance (ANOVA) with the within-subject factor of Condition (rare, frequent). As expected, larger P3 amplitudes were found for rare (M = 8.34, SE = 0.42) compared to frequent conditions ($M = 3.79$, $SE = 0.27$) (Fig. 2; $F(1, 148) = 332.57$, $p < .0001$, $\eta_p^2 = 0.69$).

3.2.2. P3 amplitude and task performance

Correlation and multiple regression analyses were conducted to examine the relationship between P3 (rare-frequent difference wave) amplitude and oddball task correct RTs (Table 2). RTs were significantly and negatively correlated to the P3 amplitude. Multiple linear regression on P3 amplitude with RT as a predictor explained a small but significant proportion of the variance ($R^2 = 0.17$, adj. $R^2 = 0.02$, $F(1,139) = 4.16$, $p = .04$). RTs had significant negative regression weights (B = −0.01, $\beta = -0.17$, $t = -2.04$, $p = .04$), confirming prior findings that faster task performance produces larger P3 amplitudes (Ramchurn et al., 2014).

3.2.3. P3 amplitude and individual differences in working memory

Correlation and multiple regression analyeses were conducted to examine potentially differential contributions of VWM, SPWM, and executive function (DSS, TS) to P3 amplitudes (Table 2). DSS and TS showed significant correlations with P3 amplitude (Fig. 3), but VWM and SPWM did not. The multiple linear regression on P3 amplitude with VWM, SPWM, DSS and TS as predictors explained a significant proportion of the variance ($R^2 = 0.12$, adj. $R^2 = 0.10$, $F(4,138) = 4.73$, $p = .001$). TS had significant negative regression weights (B = −0.002, $\beta = -0.24$, $t = -2.77$, $p = .01$), indicating that better task switching is predictive of larger P3 amplitudes (Fig. 3). DSS had significant positive regression weights (B = 0.08, $\beta = 0.24$, $t = 2.49$, $p = .01$), suggesting that more digit-symbol matches were predictive of larger P3 amplitudes. Neither VWM (B = −0.1.52, $\beta = -0.05$, $t = -0.49$, $p = .63$) nor SPWM (B = −5.15, $\beta = -0.14$, $t = -1.39$, $p = .17$) had significant regression weights.

3.2.4. P3 latency, task performance, and individual differences in working memory

Correlation and multiple regression analyses were conducted to examine whether VWM, SPWM, DSS, TS, and oddball task RTs were predictive of the P3 50% fractional area latency (range: 352 ms to 522 ms, SD = 34.45). No significant correlations were found for task RTs or any WM measures with P3 latency (Table 2) nor were the multivariate linear regressions on P3 latency with VWM, SPWM, DSS and TS ($R^2 = 0.09$, adj. $R^2 = -0.02$, $F(4,138) = 0.27$, $p = .90$; coefficient regression

Table 2
Means, standard deviations (SD) and Pearson correlations for behavioral and ERP data

Variable	Mean (SD)	1	2	3	4	5	6
1. Oddball Task RT (ms)	275.07 (62.77)						
2. VWM accuracy (%)	90.39 (0.09)	−0.09					
3. SPWM accuracy (%)	90.87 (0.08)	−0.08	0.45#				
4. TS (Switching Efficiency)	1323.22 (381.36)	0.31#	−0.14	−0.27#			
5. DSS (Count)	43.84 (9.37)	−0.10	0.30#	0.45#	−0.38#		
6. ΔP3 amplitude (μV)	4.61 (3.10)	−0.17*	0.01	0.02	−0.24#	0.24^	
7. ΔP3 fractional area latency (ms)	390.68 (62.77)	0.004	−0.004	−0.07	−0.004	−0.03	0.10

* Two-tailed significance $p < .05$.
^ Two-tailed significance $p < .01$.
# Two-tailed significance $p < .001$.

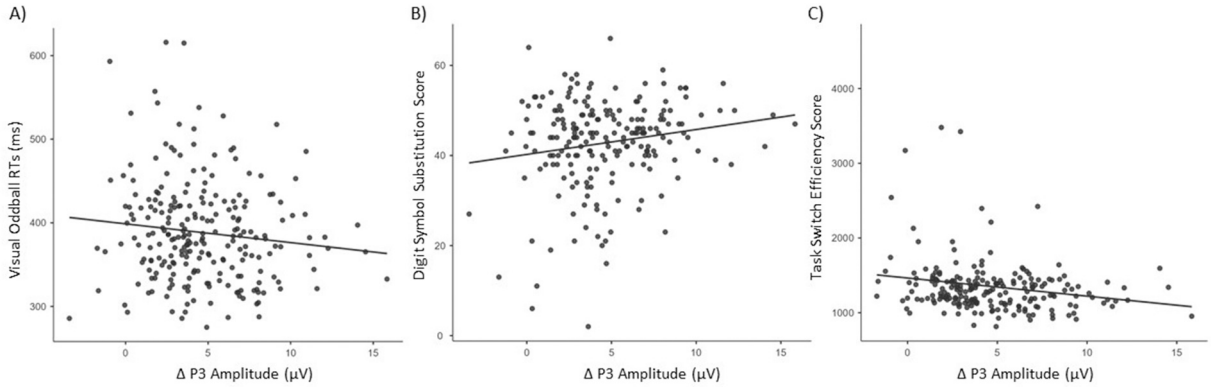

Fig. 3. Illustrative scatter plots to show relations between P3, correct RT, and executive function ability. (A) ΔP3 amplitude plotted by correct RT, (B) ΔP3 amplitude by digit symbol substitution scores, (C) ΔP3 amplitude plotted by task switch efficiency scores.

weights $p > .34$) or with oddball task RTs ($R^2 = 0.004$, adj. $R^2 = -0.01$, $F(1,139) = 0.002$, $p = .96$; coefficient regression weights $p > .96$) significant.

4. Discussion

In this study we attempt facilitate the theoretical integration of commonly used neuropsychological and electrophysiological measures of cognitive function. Despite decades of P3 research, there is a relative paucity of research linking it with established neuropsychological constructs. A number of studies have indicated that working memory (WM) plays a functional role in P3 (also known as the P3b) amplitudes and latencies (c.f. Polich, 2012). Others have assessed WM as a unitary construct or with a single capacity measure and have found that individual differences in WM capacity affect the P3. However, WM is a multifaceted system and few studies have examined directly differential contributions of *different types of WM* to the P3. Here we took an individual differences approach and examined a large sample of young adults to determine whether specific WM abilities were predictive of P3 amplitudes and latencies. Participants completed two measures of visuospatial WM (visual WM, spatial WM) and two measures of executive function (task switching, digit symbol substitution) prior to an EEG visual oddball task. Our results confirmed that not all components of WM are equally predictive of visual oddball task performance or P3 amplitudes. Although both visuospatial and executive function abilities were relevant to potential WM operations used in the visual oddball task, only the executive function measures were correlated with centroparietal P3 difference wave amplitudes. Specifically, greater task switch efficiency and more digit-symbol matches were predictive of greater P3 amplitudes, but not P3 latencies. Faster RTs were also correlated with greater P3 amplitudes. However, visual WM and spatial WM were not correlated with either P3 amplitudes or latencies.

Further, it is interesting to note that the two executive function measures were not equally predictive of visual oddball task performance and P3 amplitudes. The regressions indicated that task switching ability was more strongly predictive of P3 amplitudes than digit symbol substitution ability. This finding may be attributed to the cognitive mechanisms employed by the tasks. Task switching ability is associated with executive control because it requires the updating of task rules. Confirming these findings, several studies have also associated the task switch component with the modulation of P3 amplitudes (Barcelo et al., 2008; Kieffaber and Hetrick, 2005). Alternatively, the digit symbol substitution task requires the coordination of visual and spatial information as well as motor response selection and speed. Although Emmerson et al. (1989) found a relationship between P3 latency and DSS performance, our results did not. Our results are suggestive that it is the matching and evaluating of incoming information in executive WM that may be most important. Individuals who differ in executive function capacities may also differ in their ability to allocate attention to task relevant information as well as in their efficiency to use neural resources (Dong et al., 2015). Thus, it is important to assess different aspects of executive function. Future studies designed to isolate specific aspects of executive function might provide further insight into what specific cognitive functions the P3 indexes.

Our results are consistent with current theories of the neural substrates underlying the P3, such as the context updating theory (Polich, 2012). Important, cognitive processes eliciting the P3 point to the frontoparietal brain network and the executive function components of WM (Polich, 2012; Friedman et al., 2001; Knight and Nakada, 1998; Nieuwenhuis et al., 2005; Ranganath and Rainer, 2003). The context updating theory states that the centroparietal P3 reflects neural processes subserving the updating or revision of current mental representations in WM resulting from incoming stimuli, including neural inhibition occurring when those incoming stimuli engage additional attentional processes to facilitate memory (Polich, 2012). In WM, sensory input is evaluated in the context of the previous event and sequence of stimuli. Changes in incoming stimuli requiring the updating of the neural stimulus representation in WM are associated with P3 production (Polich, 2012). In the oddball paradigm, discrimination between the rare target and the frequent standard stimuli is said to engage attention in the frontal lobe and memory operations in temporal-parietal regions (Polich, 2007; Smith et al., 1990). These cognitive and neural operations relate most strongly to the executive function component of WM. They also are similar to the operations required for the executive function WM tasks.

Although we found reliable effects indicating that executive function ability is correlated with greater P3 amplitudes, our effect size is small. Instead of manipulating various types of WM load within the ERP-eliciting task, we measured individual ability in WM in independent tasks. Our question was whether different types of WM ability could be predictive of P3 neural responses. As a result, we would not expect the effect size to be as large in this type of study. Nonetheless, one of the strengths of this study is that our large sample size allowed us to detect the relatively small effects of executive function ability on the P3. No similar relationship was found between VWM or SPWM and P3 effect amplitudes in the same sample. These results suggest that the executive function component contributes differently from visuospatial WM components to the P3 effect.

In summary, executive function ability appears to be important for visual oddball P3 amplitudes (Polich, 2012). With a large sample of participants, we examined whether individual differences in different components of WM ability could predict the strength of the P3. When WM ability was assessed separately from the ERP-eliciting visual oddball task, our findings indicated the executive function– not just WM in general or visuospatial components of WM– aids attention and memory processes leading to subsequent actions. Specifically, P3 amplitudes are

larger for those with better executive function but not visuospatial WM abilities. This is true despite spatial WM abilities being predictive of other attention related processes such as the N2pc in tasks such as the visual search (Couperus et al., 2021). Our data do not support that executive function is a predictor of P3 latency using our version of the visual oddball task. Finally, our findings are consistent with the proposed cognitive and neural mechanisms posited by the context updating theory that emphasize the functional role of executive WM in eliciting the P3 in the visual oddball task. The current study's individual differences approach investigates the contributions of different WM components and demonstrates that some proportion of P3 amplitudes can be attributed to the executive function capabilities that participants bring to any study. This work has implications for the development of improved theoretical models of the cognitive processes indexed by the P3.

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Data availability

Data will be made available on request.

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