Published in final edited form as:

Int J Psychophysiol. 2010 June ; 76(3): 148–157. doi:10.1016/j.ijpsycho.2010.03.005.

Behavioural correlates of the P3b event-related potential in school-age children

O. Boucher^{1,2}, C. H. Bastien^{1,3,*}, G. Muckle^{1,2}, D. Saint-Amour^{4,5}, S. W. Jacobson⁶, and J. L. Jacobson⁶

¹ École de psychologie, Université Laval, Québec, Canada

² Unité de recherche en santé publique, Centre de recherche du CHUQ-CHUL, Québec, Canada

³ Laboratoire de neurosciences comportementales humaines, Centre de recherche Université Laval-Robert Giffard, Québec, Canada

⁴ Département d'ophtalmologie, Université de Montréal, Montréal, Canada

⁵ Centre de recherche du CHU Sainte-Justine, Montréal, Canada

⁶ Department of Psychiatry and Behavioral Neurosciences, Wayne State University School of Medicine, Detroit (MI), U.S.A

Abstract

The latency and amplitude of the P3b component of event-related potentials (ERPs) have been related to behavioural performance on several attention and memory tasks in adult populations. However, the extent to which these results apply to children is unknown. This study examined the neurobehavioral correlates of the P3b component in a longitudinal sample of school-age children from Arctic Québec. Children ($N = 110$; mean age = 11.3 years) were assessed on an ERP auditory oddball paradigm and a neurobehavioral evaluation targeting several aspects of cognition, including the Stewart Extended Continuous Performance Test (E-CPT), California Verbal Learning Test (CVLT), Stroop Color-Word Interference Test, and five subtests from the Wechsler Intelligence Scale for Children–Fourth edition (WISC-IV). P3b latency was positively related to reaction time measures and negatively associated with performance on the WISC-IV Digit Span Forward subtest. Amplitude of the P3b was associated with shorter completion time on the Stroop test and better delayed recognition memory performance among children who did not use semantic strategies on the CVLT. Profile analyses revealed no difference in scalp distribution of the P3b according to performance on these tests. The results are consistent with previous studies with older participants and suggest that, despite age-related differences in waveform and scalp distribution, the P3b component relates to similar neurocognitive processes in children and adults.

Keywords

attention; auditory oddball; children; cognitive correlates; event-related potentials; memory; neuropsychology; P3b

Reprint requests should be sent to Célyne H. Bastien, École de psychologie, FAS-Local 1012, 2325, rue des Bibliothèques, Université Laval, Québec (Qc.), Canada, G1V 0A6. Phone: (418) 656-2131 ext. 8344. Fax: (418) 656-3646. Celyne.Bastien@psy.ulaval.ca.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Introduction

The P3b is one of the most extensively studied event-related potential (ERP) components, although its function in cognitive processing continues to be debated. One general assumption is that it reflects central cognitive processes occurring with the active detection of an attended stimulus (Hansenne, 2000). Its latency is commonly used as a neurophysiologic marker of processing speed. According to the stimulus evaluation hypothesis (Kutas et al., 1977; McCarthy & Donchin, 1981), P3b latency provides an index of the duration of stimulus categorisation that is independent from response-associated processes. This hypothesis suggests that the onset of the P3b occurs after the stimulus has been accurately evaluated, but it does not specify the exact nature of the process reflected by the P3b itself or its functional role in cognitive processing.

Among the most influential theories of P3b is the context-updating theory, which suggests that the P3b is involved in memory processing. According to this theory, P3b is a manifestation of activity occurring when one's model of the environment must be revised; that is, it represents the adaptation of working memory to the changing data in the environment (Donchin, 1981; Donchin & Coles, 1988). An alternative explanation is provided by the context-closure hypothesis, which suggests the P3b represents post-decision processes occurring when expectancies about the occurrence of a target stimulus are fulfilled (Desmedt, 1980; Verleger, 1988). The latter theory does not support any role of the P3b in memory processing. Since their formulation, these models have evolved separately and there is still no consensus on whether or not P3b is directly involved in mnemonic activities (Polich, 2007; Verleger, 2008).

The function of the P3b component has been examined in an impressive number of studies conducted with adults, several of which were aimed at identifying the relation of its parameters (latency and amplitude) to behavioural performance on cognitive tasks. Table 1 summarises the results from studies using this approach with healthy adults.

In support of the stimulus evaluation hypothesis (Kutas et al., 1977; McGarry-Roberts et al., 1992; Ritter et al., 1972), P3b latency was positively associated with simple reaction time and completion time on speeded tasks in most studies (Emmerson et al., 1989; Gurrera et al., 2005; Portin et al., 2000). Shorter latency also predicted better digit span performance in most studies (Egan et al., 1994; Gurrera et al., 2005; O'Donnell et al., 1992; Polich et al., 1983; Stige et al., 2007; Walhovd & Fjell, 2001; 2002) providing indirect support for the context-updating theory linking the P3b to working memory.

P3b amplitude has been related to performance on attention tasks, with larger amplitude associated with shorter completion time (Gurrera et al., 2005) and fewer errors (Portin et al., 2000). These findings are consistent with the view that P3b amplitude is influenced by the magnitude of attentional resources allocated to the task (Johnson, 1986; Kok, 1997). By contrast, the association between P3b amplitude and memory is less clear. In word-detection paradigms, studies have reported that words that elicit larger P3b amplitudes are better recalled in delayed recall trials than words eliciting smaller P3b amplitudes when participants use simple mnemonic strategies (Fabiani et al., 1986; Karis et al., 1984). These results were not supported by studies examining offline associations between P3b amplitude generated during an oddball task and performance on episodic memory tasks (Egan et al., 1994; Portin et al., 2000) although these studies did not control for the mnemonic strategies employed during the tasks.

In accordance with the theories relating to P3b function, P3b parameters tend not to be related to higher-level cognitive function. No association between P3b and performance on tasks requiring visuo-spatial perceptual reasoning was found by four different research groups (Egan et al., 1994; Polich & Martin, 1992; Portin et al., 2000; Walhovd & Fjell, 2002), and tests

assessing verbal abilities are only weakly correlated with P3b parameters (Gurrera et al., 2005; Portin et al., 2000; Walhovd & Fjell, 2002).

Major changes in P3b characteristics occur during development. Compared with adults, children typically show much longer P3b latencies (Courchesne, 1978; Goodin et al., 1978; Picton, 1992; Taylor, 1988). Adults show a modest but constant increase in P3b latency with age (Goodin et al., 1978; Mueller et al., 2008; Picton, 1992). By contrast, P3b latency decreases intensively from preschool age through late adolescence/early adulthood, when it reaches its minimum values (Johnstone et al., 1996; Polich et al., 1990). Children also show considerable differences in P3b distribution over the scalp when compared to adults (Friedman et al., 1997). Before adolescence, P3b is more posterior and is rarely identifiable at anterior scalp locations (Johnstone et al., 1996; Taylor, 1988). Through adolescence, its distribution becomes more equipotential, as observed with adults.

Age-related differences in P3b characteristics might reflect differences in the very nature of the cognitive processes indexed by this ERP component during development. Yet, few studies have attempted to identify the behavioural correlates of P3b parameters in children to attempt to replicate the findings from studies with adults. In one of the few studies to examine the behavioural correlates of P3b in children, Howard and Polich (1985) found that the association between P3b latency and digit span performance was stronger among 5- to 14-year olds than adults. This stronger correlation may be a spurious consequence of the fact that children show both a strong decrease in P3b latency and an increase in behavioural performance with age on most cognitive tasks. The age range in studies designed to identify the behavioural correlates of the P3b in children should be restricted to preclude confounding with age.

This study examines the relation of P3b latency and amplitude to performance on tasks assessing attention, memory and visuo-spatial reasoning in a sample of children with a narrow age range. Based on the studies with adults, we hypothesize that P3b latency will be related to performance on speeded attention measures and to short-term memory retention capacity. P3b amplitude should be related to performance on tasks assessing selective attention and learning. In addition, we hypothesize that the relation between P3b amplitude and rote verbal learning will be moderated by the mnemonic strategy employed during the task, with stronger associations in participants using less complex learning strategies. Topographic differences in P3b amplitude according to test performance are also explored.

Methods

Participants

The sample consists of school-aged Inuit children residing in Arctic Québec, Canada, who were recruited to participate in a study on the effects of exposure to environmental contaminants on neuropsychological function (Boucher et al., 2009). The data reported here come from a larger comprehensive neurodevelopmental evaluation, in which each child was administered a battery of neurophysiological and neurobehavioral assessments (see Muckle et al., 2001; Jacobson et al., 2008). Half of the children completed the neurophysiological protocol in the morning and the neuropsychological protocol in the afternoon; the others completed the two protocols in the reverse order. Written informed consent was obtained from a parent of each participant; oral assent, from each child. The research was approved by Laval University and Wayne State University ethics committees and has, therefore, been performed in accordance with ethical standards of the 1964 Declaration of Helsinki.

All participants were between 10.0 and 13.0 years of age. To be included in this study, the following criteria were used: birth weight ≥ 2500 g, gestation duration ≥ 36 weeks, no known neurological or developmental disorder. Children with a medical condition that could affect

ERP recording (e.g., history of epilepsy), and those on medication, such as methylphenidate, were also excluded. Pure-tone audiometry (1000 and 2000 Hz) was performed to document hearing impairment. One child with a hearing threshold ≥ 35 dB in his best ear was excluded. Of 201 children invited to participate, 15 refused to perform the ERP task and an additional 9 children could not complete it due to technical problems.

Neurobehavioral assessment battery

Stewart Extended Continuous Performance Test (E-CPT; Stewart et al., 2005)—

In this computer task, the child is instructed to press a button when the target (the numeral 9) appears on the screen but not when any other numeral appears. The target presentation rate is varied systemically across five conditions (10%, 30%, 50%, 70%, 90%), which are presented in a random order. Each condition consists of 300 trials, and each stimulus appears on screen for 200 ms followed by a 600-ms interstimulus interval. Mean hit reaction time, omission errors and commission errors are recorded.

California Verbal Learning Test for Children (CVLT; Delis et al., 1994)—

This task assesses the child's ability to encode into declarative memory a 15-item list of words drawn from three semantic categories (furniture, toys, and clothes). Short-delay free recall is tested after the child learns a second 15-item list of words (desserts, fruits and clothes). Long-delay free recall is tested after a 20-minute delay, followed by a word-recognition trial. The 15-item word list from the original version of the CVLT was translated into Inuktitut, the local language, and adapted to replace items that do not exist in that language with items from similar categories (e.g., "ice cream" was replaced with "jello", "brownies" with "chocolate", and "desk" with "bookshelf"). In each case we substituted words that the native Inuit teachers and learning specialists with whom we consulted considered equivalent in terms of familiarity and difficulty.

Stroop Color-Word Interference Test from the Delis-Kaplan Executive Function System (D-KEFS; Delis, et al., 2001)—

The child is first asked to name the ink color of small rectangles presented on a sheet as quickly as possible. Next, words denoting colors are presented and the child is asked to read them aloud as fast as he or she can. In the third condition, color words are presented with dissonant ink color, and the child is asked to name the ink color as quickly as possible. This requires the inhibition of an automated behaviour (word reading). In the last condition, the child has to switch between reading the conflicting color word when it is surrounded by a box in the visual display and naming the dissonant ink color when no box surrounds the word. This switching condition requires cognitive flexibility. Completion time is recorded for each condition.

Wechsler Intelligence Scale for Children, 4th Edition (WISC-IV; Wechsler, 2003)

Data from five WISC-IV subtests were examined in this paper, three of which—Digit Span, Coding, and Symbol Search, are assigned to measure attention and working memory. In Digit Span Forward, the examiner first reads sequences of numbers to the child, who is asked to repeat them in the order presented. Sequences lengthen until the child fails two consecutive trials of the same length. In Digit Span Backward, the child is asked to recall new sequences in reverse order. The former condition requires attention allocation and reflects the amount of information the child can hold in working memory, while the latter condition additionally involves central-executive processes. In the digit-symbol Coding test, digit-symbol associations are illustrated on top of the page. Under each digit, the child must write the matching symbol within a limited period of time. This task requires the efficient production of multiple motor responses and is thought to reflect cognitive processing speed. In Symbol Search, the child views two isolated symbols adjacent to series of five symbols and has to check if one of the isolated symbols is or is not illustrated in the series within a limited time period. This subtest assesses visual scanning and processing speed.

Two WISC-IV subtests—Block Design and Matrix Reasoning—were administered to represent domains not found to relate to the P3b in studies with adults. In Block Design the child is asked to reproduce illustrated designs using cube-shaped blocks within a given time period. This subtest assesses visuo-constructive abilities and perceptual reasoning. In Matrix Reasoning, the child is asked to choose the appropriate image to complete the missing part of a visual matrix. This subtest assesses reasoning with visually presented material and reflects fluid intelligence.

ERP protocol and recording

In order to be comparable with previous studies conducted with adults, a simple auditory oddball protocol was used to elicit the P3b wave. The children were asked to sit still in front of a computer screen, to fixate a small smiley face located at the center of the screen and to press the space key on the computer keyboard as quickly and accurately as possible to the deviant stimulus (2000 Hz tone), while not responding to the standard stimulus (1000 Hz tone). All stimuli were 70 dB tones, presented for 50 ms with a rise/fall time of 5 ms. Inter-stimulus interval was set at 2 s. Standard stimuli had a probability of 80%; target stimuli, a probability of 20%. Auditory tones were presented binaurally through « E-A-RTONE » audiometric insert earphones (Auditory Systems), and their generation was controlled by the Presentation Software (Neurobehavioral Systems). Stimuli were presented in a pseudo-randomized sequence: targets were always separated by a minimum of 2 standard tones. The total protocol included 4 trials of 100 stimuli, for a total of 13 minutes of stimulus presentation. Data acquisition was performed with InstEP® v5.17. The electro-oculogram (EOG) was recorded for both eyes with tin electrodes placed at the supra-orbital ridge of one eye and the infra-orbital ridge of the other. ERPs were recorded with 29 Ag-AgCl electrodes (Fz, F3, F4, F7, F8, AF3, AF4, AF7, AF8, FCz, FC1, FC2, Cz, C3, C4, T3, T4, T5, T6, Pz, P3, P4, Oz, O1, O2, M1, M2, A1, and A2 according to the international 10–20 system) referred to linked ear lobes, with forehead ground. The impedance was kept below 10 k Ω . EOG and EEG gain were amplified with a gain of 7500 and 15000, respectively, with Grass Model 15A54 amplifiers. The digitization rate was 512 Hz.

ERP analyses

ERP analyses were performed using Analyzer 1.05 (Brain Vision©) software. EOG correction was performed from the vertical EOG electrode using the algorithm described by Gratton and colleagues (1983). High and low pass filters were set at 0.16 and 30 Hz, respectively. Artifact rejection was performed with a ± 100 μ V criterion. ERPs were time locked to stimulus onset. Baseline correction was applied using a 100 ms pre-stimulus baseline. Trials with omission (false negative response) and commission (false positive response) errors as well as impulsive responses (<200 ms post-stimuli) were excluded from averaging. The P3b was identified at Pz and defined as the maximum positive deflection occurring between 250 and 500 ms. This scalp location was justified by the fact that P3b peaks at centro-parietal locations and that this ERP was more clearly distinguishable at this electrode site within our sample. Latency for each component was determined from stimulus onset to maximal peak, and peak amplitude was measured from baseline. Mean amplitude was also computed in the P3b latency time window (mean P3b latency $\pm$ 1 standard deviation). Semi-automatic peak detection was used, with co-validation from two different scorers. When discrepancies were found between scores, a decision was made by an expert neurophysiologist (CB). Interrater validity was high: Pearson correlations were 0.86 for P3b latency and 0.97 for amplitude.

Among the 177 children from whom data were obtained, the data were considered reliable for 110 (62.1% of the sample). Reasons for exclusion were: inability to identify a clear P3b wave ($n = 34$), noise in data due to alpha waves or eye movement resulting in unreliable ERP waveform ($n = 25$), too many errors during the task (commission errors $\geq 15\%$ of the standard

stimuli or omission errors on $\geq 50\%$ of the target stimuli; $n = 7$), and < 20 target stimuli in average wave (Cohen & Polich, 1997) ($n = 1$). A higher proportion of boys were rejected than girls (50% vs. 29.5%). Similar rejection rates have often been found in previous ERP studies with children (e.g. 52% of the 6-to-8-year-old children in Czernochowski et al., 2005, and 36% of 4-year-old children in Rueda et al., 2004).

Statistical analyses

Each variable was checked for skewness and kurtosis (normality range: -2.0 to 2.0) and visually inspected for normality of distribution. Log transformations were conducted for variables that followed a log-normal distribution (i.e. number of omission and commission errors during the auditory oddball task). Extreme values for normally distributed variables (>3 standard deviations below or over mean) were recoded to one point greater than the highest observed non-outlying value following the procedure recommended by Winer (1971). This procedure was employed to adjust the following variables: P3b latency, the E-CPT scores, Stroop Color-Naming, Interference and Shifting completion time and WISC-IV Digit Span Backward and Symbol Search raw scores.

The associations between the P3b parameters (latency and amplitude) and neurobehavioral performance were examined using Pearson correlation analyses. For behavioural variables found to be significantly associated with P3b amplitude, topographic differences according to test performance were assessed using post-hoc profile analyses in which the independent variables were the behavioural variables divided in two groups at the median of their distributions and the dependent variables were the mean amplitudes (target condition) at Fz, F3, F4, F7, F8, FCz, FC1, FC2, Cz, C3, C4, Pz, P3 and P4. The moderating role of mnemonic strategy in the relation between verbal learning and P3b amplitude was examined by performing the correlation analyses separately for two subgroups of participants, who differed in the use of semantic categorization strategies on the CVLT. Semantic categorization was assessed as the degree to which the child tended to list words from the same category together when learning or recalling the list. The group median value of the semantic categorization index was used to create the subgroups of semantic category users—low (< 11 semantic groupings; $n = 47$) and high (≥ 11 semantic groupings; $n = 62$). Associations were considered statistically significant at $p < 0.05$. Raw scores were used in all analyses because Inuit norms do not exist for these tests.

Results

Descriptive data

The demographic characteristics and test performance of the children who provided valid ERP data are summarized in Table 2. Participants were predominantly right-handed, and a majority of those whose data were retained in the final analyses were assessed on the ERP task during the morning. Peak and mean P3b amplitudes did not differ by age within the narrow age range assessed in this study (all p 's > 0.20), and the expected negative association between latency and age fell short of statistical significance ($r = -0.15$, $p = 0.11$). T -tests revealed no difference for time of ERP testing (morning or afternoon) for P3b latency or amplitude and no difference in relation to gender for P3b latency or amplitude (all p 's > 0.20). Few differences in task performance were found between participants who were excluded because they did not show a clear P3b wave in their ERP average and participants who were included in the study: the former group made less commission errors on the auditory oddball task ($p = 0.04$) while the latter group showed non-significant tendency to perform better on the CVLT short delay ($p = 0.06$) and long delay ($p = 0.09$) free recall, on Digit Span Backwards ($p = 0.07$) and on Stroop Word Reading ($p = 0.10$) (all other p 's > 0.20). The correlation between P3b peak and mean amplitudes at Pz was strong ($r = 0.88$, $p < 0.001$). The grand average waveform for retained

participants is illustrated in Figure 1. The P3b can be seen across centro-parietal electrode sites approximately 350 ms after target stimulus. The waveform, ERP parameters and scalp distribution are similar to those reported in previous studies using auditory oddball protocols with children of this age (Johnstone et al., 1996; Mueller et al., 2008).

The relation of P3b to neurobehavioral performance

P3b latency—Shorter P3b latency was associated with faster reaction time and greater accuracy (fewer omission errors) in performance on the auditory oddball task (Table 3) and with faster reaction time on E-CPT. Shorter P3b latency was also associated with longer auditory memory span on Digit Span Forward from the WISC-IV. These associations are illustrated on Figure 2.

P3b amplitude—The associations between peak P3b amplitude and performance on behavioural assessments are presented in Table 3. Significant correlations are illustrated in Figure 3. Peak P3b amplitude was related to shorter completion time on the Color Naming and Interference conditions of the Stroop test, suggesting a relation of this ERP measure to better performance on tasks involving faster processing and better selective attention, respectively. Greater peak P3b amplitude was also associated with better long-delay recognition memory on the CVLT. Pearson correlations using mean amplitude [309–387 ms] instead of peak amplitude values yielded similar results, revealing significant associations with mean reaction time ($r = -0.21, p = 0.03$) and the number of omission errors ($r = -0.20, p = 0.04$) on the auditory oddball task, with completion time on the Color Naming ($r = -0.19, p = 0.05$) and the Interference ($r = -0.23, p = 0.02$) conditions of the Stroop test, and with the number of correct responses on the long-delay recognition trial of the CVLT ($r = 0.21, p = 0.03$).

Profile analyses were conducted in order to examine topographic differences between high and poor performers on the three behavioural measures that were found to be associated with P3b amplitude (Stroop Color Naming, Stroop Interference, and CVLT Recognition). Results revealed significant level differences for overall P3b mean amplitude between high and poor performers on the Stroop Interference ($F_{(1,103)} = 7.38, p = 0.01$) and the CVLT Recognition ($F_{(1,102)} = 4.73, p = 0.03$) measures, but not for the Stroop Color Naming measure ($F_{(1,104)} = 1.91, p = 0.17$). Tests for flatness indicated marked differences in P3b amplitude between electrode locations ($p < 0.001$), mean amplitude being maximal at Pz. Finally, the results from the Wilks' tests for parallelism revealed no significant difference in profile (P3b scalp distribution) between high and poor performers on either the Stroop Color Naming ($F_{(13,92)} = 1.32, p = 0.22$), the Stroop Interference ($F_{(13,91)} = 0.64, p = 0.81$) or the CVLT Recognition ($F_{(13,90)} = 0.44, p = 0.95$) measures, indicating the absence of topographic difference according to test performance. Figure 4 depicts the ERP grand average waveform in relation to three levels of recognition memory performance—perfect score ($n = 45$), one error ($n = 34$), more than one error ($n = 29$). As can be seen, amplitude differences in the P3b latency range are present across the scalp. This figure also shows that topographical patterns in P3b amplitude do not differ as a function of behavioural performance. Larger amplitudes of the P3b are seen in children with perfect performance at left, central and right frontal, central and parietal locations, somewhat smaller amplitudes are seen in the poorest performing children in these regions, and the amplitudes of the children who made one error are generally intermediate.

Pearson correlations between peak P3b amplitude and memory encoding performance on the CVLT for each group of semantic strategy users are presented in Table 4. Within the subgroup of children making fewer semantic groupings, greater P3b amplitude is significantly associated with better recognition memory performance. By contrast, no association is found between P3b amplitude and memory performance within the subgroup making more frequent semantic groupings. The same pattern was observed when using mean amplitude instead of peak values

(not shown). These data suggest that greater P3b amplitude is related to better encoding and recall of verbal information in children who do not rely strongly on semantic strategies, but not in children who rely more strongly on this type of high-order cognitive strategy.

In order to insure that the associations reported above were not due to confounding by exposure to environmental contaminants, partial correlations were performed to control for contaminants known to affect cognitive development; namely, mercury and polychlorinated biphenyls measured at birth (cord blood samples, log values) and lead levels measured at time of testing time (blood samples, log values). Statistical control for these exposures did not alter any of the significant association between P3b and neurobehavioral outcome by more than $r = 0.014$.

Discussion

The aim of this study was to identify the cognitive correlates of the P3b ERP in a sample of school age children who were assessed with a battery of neuropsychological tests. As in studies with adults, the tasks most clearly associated with the P3b parameters related to speeded attention and memory. More specifically, shorter P3b latency was associated with faster reaction time on continuous performance tasks and with longer auditory digit span, and P3b amplitude was associated with better verbal recognition memory and shorter completion time on the Stroop color naming condition, which reflects cognitive processing speed, and the Stroop interference condition, which indexes attention.

The relation found between shorter P3b latency and mean hit reaction time on both the auditory oddball task and the E-CPT replicates earlier findings with adults (Kutas et al., 1977; McGarry-Roberts et al., 1992; Portin et al., 2000; Ritter et al., 1972) and provides support for the stimulus evaluation hypothesis (McCarthy & Donchin, 1981). However, P3b latency was not related to the other behavioural measures of processing speed—Coding and Symbol Search—even though similar measures were related to P3b latency in studies with adults (Emmerson et al., 1989; Gurrera et al., 2005; Portin et al., 2000). It is possible that fine motor abilities and visual scanning skills may have a stronger influence on performance on these tasks in children; whereas they may provide a purer measure of information processing speed in adults.

The relation between shorter P3b latency and better digit span forward performance is consistent with findings from previous studies (Egan et al., 1994; Gurrera et al., 2005; Polich et al., 1983; Stige et al., 2007; Walhovd & Fjell, 2001; 2002) and suggests that the faster the information is processed, the more items can be processed at a time. This finding reflects the importance of processing speed in working memory loading capacity (Lezak et al., 2004). As in previous studies, there was no association with digit span backward performance, which depends on executive processes to coordinate and perform a mental operation (reversing the order of the numbers) in the content of working memory. Similarly, there was no association with Stroop shifting completion time, which assesses the ability to use executive processes to flexibly modify one's response as contingencies (task requirements) change. The P3b appears to be independent of such higher-order cognitive processes. As also predicted from the adult studies, neither P3b measure was related to visual-spatial information processing, as assessed on the WISC-IV Block Design and Matrix Reasoning subtests.

This study is the first to report a positive correlation between P3b amplitude obtained during an oddball task and performance on a verbal memory task (CVLT), a result predicted by the context-updating hypothesis. Previous studies with adults reported either no association or an inverse relation between these constructs (Egan et al., 1994; Portin et al., 2000). As noted above, P3b waves elicited during word-detection paradigms are thought to be larger for the words that are better recalled only when simple (e.g. rote) mnemonic strategies are used (Fabiani & Donchin, 1995; Fabiani et al., 1986; Karis et al., 1984). Consistent with these

studies, we found that associations between P3b amplitude and CVLT performance applied only to the subgroup of children who made little use of semantic categorization strategies during the task. Since semantic organization strategies to facilitate encoding are elicited increasingly spontaneously and improve with age (Delis et al., 1994), correlations between P3b amplitude and memory performance might be more readily observed in children than in adults.

This paper also explored the possibility that the topography of the P3b differs between high and poor performers on behavioural tasks. Fabiani et al. (1998) have shown that, in a subgroup of elderly participants, individuals showing frontally-maximal P3b scalp distributions had lower performance on behavioural assessments of frontal lobe function compared to those who showed posterior-maximal topographies. In our study, there was no difference in P3b scalp distribution according to test performance. The young age of our study participants may explain why no such topographic differences were detected, as Fabiani and colleagues did not find any clear individual differences in P3b scalp distribution among their younger participants.

Our results support the view that the processes indexed by the P3b wave play an active role in memory encoding (Polich, 2007). The context-updating theory suggests that P3b amplitude reflects the amount of resources allocated for revising the content of working memory (Donchin, 1981; Donchin & Coles, 1988). A greater ability to allocate resources for processing a stimulus in active memory (reflected by larger P3b amplitude) might contribute to better encoding of the stimulus in episodic memory (reflected by better CVLT recognition memory performance). Alternatively, the role of the P3b might not be exclusive to memory and could extend to broader attentional processes, as suggested by Nieuwenhuis and colleagues (2005a). The relations found with performance on both the Color Naming and Interference conditions of the Stroop test are consistent with this view.

This study has identified cognitive correlates of the P3b ERP in children using well-known behavioural measures of cognition. It should be noted that most of the reported correlations are not as strong as those previously reported for adults. Cultural factors and limited language skills may have influenced performance on these behavioural measures and had an impact on the observed correlations. Correlating auditory oddball P3b parameters with performance on visual neuropsychological tasks may have also reduced the magnitude of some of the correlations, but evidence of generality across sensory modalities strengthens the inference that these ERP components reflect basic cognitive processes. The use of a more challenging task to evoke the P3b might also have yielded stronger or different associations with test performance (Nittono et al., 1999; Polich & Martin, 1992), a possibility that should be tested in future studies.

The lack of specificity of standard neuropsychological tests may also be responsible for the relatively modest correlations with the P3b parameters. Most of these tests depend on and reflect a broad range of neuropsychological processes/functions. The use of more specific behavioural measures could lead to the identification of stronger correlates of this ERP component. For instance, attention blink paradigms, which are thought to index processes closely related to P3b generation at both the functional (e.g., Krancioch et al., 2003; Vogel et al., 1998) and neuroanatomical (Nieuwenhuis et al. 2005a; 2005b) levels, have the potential to fulfill this role. Another pertinent task is the Attention Network Test (Fan et al., 2002), which provides behavioural indexes of three different aspects of attention relying on separable brain networks (Fan et al., 2005; Posner & Rothbart, 2007).

Another limitation is that no diagnostic interviews were conducted to document attention-deficit/hyperactivity disorder, which is known to affect P3b parameters (Barry et al., 2003). It is thus possible that our sample included children with this disorder, which might have affected

our results. Whether the associations between P3b parameters and performance on cognitive tasks differ according to clinical presentation is uncertain, and future studies should address this issue.

In summary, this study found that the P3b wave obtained from school-age children during an auditory oddball task is correlated with performance on measures of attention and memory. Most of the neuropsychological endpoints found to be correlated with these ERP components are similar to those previously observed in adults. Where there are differences, they appear to be attributable to differences in the strategies and processes used by children to perform the behavioural tasks (e.g., memory encoding). These findings suggest that, despite differences in waveform and scalp distribution, the P3b relates to the same cognitive processes in children as in adults. These data also demonstrate that this ERP component constitutes an appropriate and useful neurophysiologic measure to study attentional and mnemonic processes in ethnically and culturally diverse populations.

Acknowledgments

We are grateful to the Nunavik population for their participation in this study and to the medical and health care professionals from the health centers and the nursing stations involved for their assistance. We acknowledge the long time support of the Nunavik Nutrition and Health Committee, the Public Health Director of the Nunavik Regional Board of Health and Social Services, the Municipal Councils of Puvirnituq, Inukjuak, Kuujjuak and Kuujjuarapik, Inuit Tapiriit Kanatami, Pauktuutit Inuit Women's Association, and Nunatuqait Ikaluqatigiit Association. We appreciate the contributions of Renee Sun, Alacie Puv, Line Roy and Brenda Tuttle, for their work on participant recruitment and data collection, and Jocelyne Gagnon and Neil Dodge, for assembling the data set. This research was supported by the National Institute of Environmental Health and Sciences/U.S. National Institutes of Health (J.L.J.), Indian and Northern Affairs Canada--Northern Contaminants Program (G.M.) and doctoral grants from the Canadian Institutes of Health Research and from the Nasivvik Centre for Inuit Health and Changing Environments (O. B.).

References

- Barry RJ, Johnstone SJ, Clarke AR. A review of electrophysiology in attention-deficit/hyperactivity disorder: II. Event-related potentials Clin Neurophysiol 2003;114:184–198.
- Boucher O, Muckle G, Saint-Amour D, Dewailly É, Ayotte P, Jacobson SW, et al. The relation of lead neurotoxicity to the event-related potential P3b component in Inuit children from arctic Québec. NeuroToxicology 2009;30:1070–1077. [PubMed: 19576242]
- Cohen J, Polich J. On the number of trials needed for P300. Int J Psychophysiol 1997;25:249–255. [PubMed: 9105949]
- Courchesne E. Neurophysiological correlates of cognitive development: changes in long-latency event-related potentials from childhood to adulthood. Electroencephalogr Clin Neurophysiol 1978;45:468–482. [PubMed: 81749]
- Czernochowski D, Mecklinger A, Johansson M, Brinkmann M. Age-related differences in familiarity and recollection: ERP evidence from a recognition memory study in children and young adults. Cogn Affect Behav Neurosci 2005;5:417–433. [PubMed: 16541812]
- Delis, DC.; Kaplan, E.; Kramer, JH. Delis-Kaplan Executive Function System (D-KEFS). San Antonio, TX: The Psychological Corporation; 2001.
- Delis, DC.; Kramer, JH.; Kaplan, E.; Ober, BA. The California Verbal Learning Test for Children. The Psychological Corporation; San Antonio, TX: 1994.
- Desmedt JE. P300 in serial tasks: an essential post-decision closure mechanism. Prog Brain Res 1980;54:682–686. [PubMed: 7220985]
- Donchin E. Surprise!... Surprise? Psychophysiology 1981;18:493–513. [PubMed: 7280146]
- Donchin E, Coles MGH. Is the P300 component a manifestation of context updating? Behav Brain Sci 1988;11:357–374.
- Egan V, Chiswick A, Santosh C, Naidu K, Rimmington JE, Best JJK. Size isn't everything: a study of brain volume, intelligence and auditory evoked potentials. Pers Individ Diff 1994;17:357–367.

- Emmerson RY, Dustman RE, Shearer DE, Turner CW. P3 latency and symbol digit performance correlations in aging. *Exp Aging Res* 1989;15:151–159. [PubMed: 2638634]
- Fabiani M, Donchin E. Encoding processes and memory organization: a model of the von Restorff effect. *J Exp Psychol Learn Mem Cogn* 1995;21:224–240. [PubMed: 7876771]
- Fabiani M, Friedman D, Cheng JC. Individual differences in P3 scalp distribution in older adults, and their relationship to frontal lobe function. *Psychophysiology* 1998;35:698–708. [PubMed: 9844431]
- Fabiani M, Karis D, Donchin E. P300 and recall in an incidental memory paradigm. *Psychophysiology* 1986;23:298–308. [PubMed: 3749410]
- Fan J, McCandliss BD, Fossella J, Flombaum JI, Posner MI. The activation of attentional networks. *Neuroimage* 2005;26:471–479. [PubMed: 15907304]
- Fan J, McCandliss BD, Sommer T, Raz A, Posner MI. Testing the efficiency and independence of attentional networks. *J Cogn Neurosci* 2002;14:340–347. [PubMed: 11970796]
- Friedman D, Kazmerski V, Fabiani M. An overview of age-related changes in the scalp distribution of P3b. *Electroencephalogr Clin Neurophysiol* 1997;104:498–513. [PubMed: 9402892]
- Goodin DS, Squires KC, Henderson BH, Starr A. Age-related variations in evoked potentials to auditory stimuli in normal human subjects. *Electroencephalogr Clin Neurophysiol* 1978;44:447–458. [PubMed: 76553]
- Gratton G, Coles MGH, Donchin E. A new method for off-line removal of ocular artifact. *Electroencephalogr Clin Neurophysiol* 1983;55:468–484. [PubMed: 6187540]
- Gurrera RJ, Salisbury DF, O'Donnell BF, Nestor PG, McCarley RW. Auditory P3 indexes personality traits and cognitive function in healthy men and women. *Psychiatry Res* 2005;133:215–228. [PubMed: 15740997]
- Hansenne M. Le potentiel évoqué cognitif P300 (1): aspects théorique et psychobiologique. *Neurophysiol Clin* 2000;30:191–210. [PubMed: 11013894]
- Howard L, Polich J. P300 latency and memory span development. *Dev Psychol* 1985;21:283–289.
- Jacobson JL, Jacobson SW, Muckle G, Kaplan-Estrin M, Ayotte P, Dewailly E. Beneficial effects of a polyunsaturated fatty acid on infant development: evidence from the Inuit of Arctic Québec. *J Pediatr* 2008;152:356–364. [PubMed: 18280840]
- Johnson R. A triarchic model of P300 amplitude. *Psychophysiology* 1986;23:367–384. [PubMed: 3774922]
- Johnstone SJ, Barry RJ, Anderson JW, Coyle SF. Age-related changes in child and adolescent event-related potential component morphology, amplitude and latency to standard and target stimuli in an auditory oddball task. *Int J Psychophysiol* 1996;24:223–238. [PubMed: 8993997]
- Kaplan, E.; Goodglass, H.; Weintraub, S. *The Boston Naming Test*. 2. Philadelphia: Lippincott Williams & Wilkins; 2001.
- Karis D, Fabiani M, Donchin E. “P300” And memory: individual differences in the von Restorff effect. *Cogn Psychol* 1984;16:177–216.
- Kok A. Event-related-potential ERP reflections of mental resources: a review and synthesis. *Biol Psychol* 1997;45:19–56. [PubMed: 9083643]
- Krancioch C, Debener S, Engel AK. Event-related potential correlates of the attentional blink phenomenon. *Cogn Brain Res* 2003;17:177–187.
- Kutas M, McCarthy G, Donchin E. Augmenting mental chronometry: the P300 as a measure of stimulus evaluation time. *Science* 1977;197:792–795. [PubMed: 887923]
- Lezak, MD.; Howieson, DB.; Loring, DW. *Neuropsychological Assessment*. 4. Oxford: Oxford University Press; 2004.
- McCarthy G, Donchin E. A metric for thought: a comparison of P300 latency and reaction time. *Science* 1981;211:77–80. [PubMed: 7444452]
- McGarry-Roberts PA, Stelmack RM, Campbell KB. Intelligence, reaction time, and event-related potentials. *Intelligence* 1992;16:289–313.
- Muckle G, Ayotte P, Dewailly E, Jacobson SW, Jacobson JL. Prenatal exposure of the northern Québec Inuit infants to environmental contaminants. *Environ Health Perspect* 2001;109:1291–1299. [PubMed: 11748038]

- Mueller V, Brehmer Y, von Oertzen T, Li S-C, Lindenberger U. Electrophysiological correlates of selective attention: a lifespan comparison. *BMC Neurosci* 2008;9
- Nieuwenhuis S, Aston-Jones G, Cohen JD. Decision making, the P3, and the locus coeruleus-Norepinephrine system. *Psychol Bull* 2005a;131:510–532. [PubMed: 16060800]
- Nieuwenhuis S, Holmes BD, Gilzenrat MS, Cohen JD. The role of the locus coeruleus in mediating the attentional blink: A neurocomputational theory. *J Exp Psychol* 2005b;134:291–307.
- Nittono H, Nageishi Y, Nakajima Y, Ullsperger P. Event-related potentials correlates of individual differences in working memory capacity. *Psychophysiology* 1999;36:745–754. [PubMed: 10554588]
- O'Donnell BF, Friedman S, Swearer JM, Drachman DA. Active and passive P3 latency and psychometric performance: Influence of age and individual differences. *Int J Psychophysiol* 1992;12:187–195. [PubMed: 1592672]
- Picton TW. The P300 wave of the human event-related potential. *J Clin Neurophysiol* 1992;9:456–479. [PubMed: 1464675]
- Polich J. Updating P300: An integrative theory of P3a and P3b. *Clinical Neurophysiology* 2007;118:2128–2148. [PubMed: 17573239]
- Polich J, Howard L, Starr A. P300 latency correlates with digit span. *Psychophysiology* 1983;20:665–669. [PubMed: 6657855]
- Polich J, Ladish C, Burns T. Normal variation of P300 in children: Age, memory span, and head size. *Int J Psychophysiol* 1990;9:237–248. [PubMed: 2276942]
- Polich J, Martin S. P300, cognitive capability, and personality: a correlational study of university undergraduates. *Pers Individ Dif* 1992;13:533–543.
- Portin R, Kovala T, Polo-Kantola P, Revonsuo A, Müller K, Matikainen E. Does P3 reflect attentional or memory performances, or cognition more generally? *Scand J Psychol* 2000;41:31–40. [PubMed: 10731841]
- Posner MI, Rothbart MK. Research on attention networks as a model for the integration of psychological science. *Ann Rev Psychol* 2007;58:1–23. [PubMed: 17029565]
- Ritter W, Simson R, Vaughan HG Jr. Association cortex potentials and reaction time in auditory discrimination. *Electroencephalogr Clin Neurophysiol* 1972;33:547–555. [PubMed: 4117332]
- Rueda MR, Posner MI, Rothbart MK, Davis-Stober CP. Development of the time course for processing conflict: an event-related potentials study with 4 year olds and adults. *BMC Neurosci* 2004;5:39. [PubMed: 15500693]
- Stewart P, Reihman J, Gump B, Lonky E, Darvill T, Pagano J. Response inhibition at 8 and 9 1/2 years of age in children prenatally exposed to PCBs. *Neurotoxicol Teratol* 2005;27:771–780. [PubMed: 16198536]
- Stige S, Fjell A, Smith L, Lindgren M, Walhovd KB. The development of visual P3a and P3b. *Dev Neuropsychol* 2007;32:563–584. [PubMed: 17650994]
- Taylor MJ. Developmental changes in ERPs to visual language stimuli. *Biol Psychol* 1988;26:321–338. [PubMed: 3207790]
- Verleger R. Event-related potentials and cognition: a critique of the context updating hypothesis and an alternative interpretation of P3. *Behav Brain Sci* 1988;11:343–356.
- Verleger R. P3b: towards some decision about memory. *Clin Neurophysiol* 2008;119:2128–2148.
- Vogel EK, Luck SJ, Shapiro KL. Electrophysiological evidence for a postperceptual locus of suppression during the attentional blink. *J Exp Psychol* 1998;24:1656–1674.
- Walhovd KB, Fjell A. Two- and three-stimuli auditory oddball ERP tasks and neuropsychological measures in aging. *Cogn Neurosci Neuropsychol* 2001;12:3149–3153.
- Walhovd KB, Fjell A. The relationship between P3 and neuropsychological function in an adult life span sample. *Biol Psychol* 2002;62:65–87. [PubMed: 12505768]
- Wechsler, D. Wechsler Intelligence Scale for Children. 4. San Antonio, TX: The Psychological Corporation; 2003. (WISC-IV)
- Winer, BJ. Statistical principles in experimental design. 2. McGraw-Hill; New-York: 1971. p. 907

Figure 1. Grand average for auditory oddball task at midline scalp positions ($N = 110$). The P3b wave peaks around 350 ms post-stimulus and is maximal at Pz in the target condition.

Figure 2. Scatterplots illustrating the significant correlations between P3b latency (Pz) and behavioural performance.

Figure 3. Scatterplots illustrating the significant correlations between P3b peak amplitude (Pz) and behavioural performance.

Figure 4.

Grand averages for auditory oddball task according to CVLT recognition performance. The straight line represents 15 correct responses performance ($n = 45$), the dotted line, 14 correct responses ($n = 34$) and the dashed line, less than 14 correct responses ($n = 29$).

Table 1

Correlations between P3b parameters and behavioural performance reported in previous studies

Neuropsychological test	Correlation coefficient		Reference
	Latency	Amplitude	
Attention			
Simple reaction time	.16*	-.14	Portin et al. (2000)
Two-choice reaction time	.12	-.08	Portin et al. (2000)
Ten-choice reaction time	.15	-.21*	Portin et al. (2000)
Symbol Digit Modalities Test	-.45**a	N.A.	Emmerson et al. (1989)
Digit Symbol	-.13	.19	Polich and Martin (1992)
	.30*	-.18	Egan et al. (1994)
	-.19*	.24**	Portin et al. (2000)
	-.33*	.40**	Gurrera et al. (2005)
Digit Symbol total errors	-.05	-.02	Polich and Martin (1992)
Letter cancellation hit rate (%)	-.19*	.01	Portin et al. (2000)
Letter cancellation total r time	.32**	-.29**	Portin et al. (2000)
Letter cancellation total errors	.03	-.17*	Portin et al. (2000)
Trail Making Test A (time to complete)	.27*	.20	Egan et al. (1994)
Trail Making Test B (time to complete)	.41**	.28*	Egan et al. (1994)
Trail Making Test A (scaled score)	-.25	.31*	Gurrera et al. (2005)
Trail Making Test B (scaled score)	-.33*	.15	Gurrera et al. (2005)
Memory			
Digit Span (Total)	-.36**a		Polich et al. (1983)
	-.18	-.01	Polich and Martin (1992)
	-.29*	-.22	Egan et al. (1994)
	-.04	-.02	Portin et al. (2000)
	-.51*a	.29*	Walhovd and Fjell (2002)
	-.34*	.12	Gurrera et al. (2005)
Digit Span Forward	-.37**	N.A.	Polich et al. (1983)
	-.51*a	.26*	Walhovd and Fjell (2002)
Digit Span Backward	-.28**	N.A.	Polich et al. (1983)
	-.38*b	.26*b	Walhovd and Fjell (2002)
Logical memory – Immediate	.06	-.22	Egan et al. (1994)
AVLT Σ Trial 1–5	-.25*	-.41**	Egan et al. (1994)
Paired Words Immediate Recall	-.04	.13	Portin et al. (2000)
Logical memory – Delayed	.00	-.31*	Egan et al. (1994)
AVLT Delayed Recall	-.13	-.37*	Egan et al. (1994)
Paired Words Delayed Recall	-.04	.14	Portin et al. (2000)

Neuropsychological test	Correlation coefficient		Reference
	Latency	Amplitude	
Rey Figure Short-Delay Reproduction	.08	.09	Portin et al. (2000)
Digit Symbol incidental learning	.05	.00	Portin et al. (2000)
Visuospatial reasoning			
Raven Matrices	.00	-.01	Polich and Martin (1992)
Matrix Reasoning	-.48 ^{*b}	.33 ^{*b}	Walhovd and Fjell (2002)
Block Design	.02	-.17	Egan et al. (1994)
	-.14	.01	Portin et al. (2000)
	-.41 ^{*b}	.32 ^{*b}	Walhovd and Fjell (2002)
Object Assembly	-.09	-.23	Egan et al. (1994)
Verbal abilities			
Vocabulary	-.16	-.07	Walhovd and Fjell (2002)
Similarities	-.01	-.30 [*]	Egan et al. (1994)
	-.08	-.01	Portin et al. (2000)
	-.25 ^{*b}	.02	Walhovd and Fjell (2002)
Word fluency	-.29 [*]	.03	Egan et al. (1994)

Abbreviations: N.A., Not available information.

Note. Pearson correlation analyses are reported except for Portin et al. (2000) (Spearman's partial rank-order correlations adjusting for age and education) and Gurrera et al. (2005) (Partial Least Squares).

^aThe association remains significant after statistical control for age;

^bThe association is no more significant after statistical control for age.

**
 $p < 0.01$;

*
 $p < 0.05$

Table 2

Descriptive data for participants included in the data analysis

	N	Mean	Std. Dev.	Range	%
<i>Child and assessment characteristics</i>					
Age (years)	110	11.3	0.57	10.2 – 12.9	
Gender (% female)	110				67.3
Manual laterality (% right-handers)	110				90.0
Time of ERP assessment (% morning)	110				61.8
<i>P3b characteristics (Pz)</i>					
Peak latency (ms)	110	347.9	39.4	267.6 – 484.4	
Peak amplitude (µV)	110	10.8	3.77	4.3 – 21.1	
Mean amplitude [309–387 ms] (µV)	110	8.2	3.66	–1.5 – 18.0	
<i>Auditory oddball</i>					
Hit reaction time (ms)	110	542.0	77.2	327.6 – 745.4	
Omission errors rate (%)	110	9.3	8.2	0.0 – 42.5	
Commission errors rate (%)	110	0.8	0.9	0.0 – 5.0	
<i>E-CPT</i>					
Hit reaction time (ms)	106	455.7	37.8	357.1 – 540.5	
Omission errors rate (%)	106	20.9	8.4	4.6 – 42.8	
Commission errors rate (%)	106	14.7	5.0	6.2 – 31.8	
<i>CVLT</i>					
Short-delay free recall	109	8.3	2.6	1 – 13	
Long-delay free recall	109	8.6	2.5	1 – 14	
Long-delay recognition hits	108	13.9	1.3	11 – 15	
<i>Stroop</i>					
Color-naming completion time (s)	110	67.0	21.7	39.4 – 178.8	
Word-reading completion time (s)	109	56.8	16.0	30.8 – 102.7	
Interference completion time (s)	109	98.1	27.1	53.2 – 209.5	
Shifting completion time (s)	109	114.8	30.7	66.4 – 257.2	
<i>WISC-IV (raw scores)</i>					
Block Design	110	35.9	9.9	10 – 58	
Matrix Reasoning	110	16.6	3.8	8 – 28	

	N	Mean	Std. Dev.	Range	%
Digit Span Forward	110	9.1	2.3	4 – 16	
Digit Span Backward	110	6.8	1.6	2 – 13	
Coding	110	41.7	8.3	21 – 59	
Symbol Search	110	21.1	5.6	0 – 33	

Table 3

Pearson correlations (r) between P3b characteristics (Pz) and behavioural performance (N=110)

	Peak latency	Peak amplitude
Auditory oddball		
Mean hit reaction time	0.27**	-0.17 [†]
Omission errors (%) ^a	0.23*	-0.10
Commission errors (%) ^a	0.08	0.07
E-CPT		
Mean hit reaction time	0.23*	-0.07
Omission errors (%)	0.11	-0.01
Commission errors (%)	0.08	0.10
CVLT		
Short delay, free recall (# correct)	0.01	0.16
Long delay, free recall (# correct)	0.01	0.06
Recognition total hits	0.10	0.22*
Stroop		
Color naming completion time	0.15	-0.20*
Word reading completion time	0.02	-0.18 [†]
Interference completion time	-0.05	-0.20*
Shifting completion time	0.02	-0.09
WISC-IV Raw Scores		
Block Design	-0.09	-0.02
Matrix Reasoning	-0.07	0.04
Digit Span Forward	-0.19*	0.02
Digit Span Backward	-0.08	0.02
Coding	-0.11	0.01
Symbol Search	-0.09	0.06

^aVariable was log-transformed because its distribution followed a log-normal curve.**
 $p < 0.01$ *
 $p < 0.05$ [†]
 $p < 0.10$

Table 4

Pearson correlations (r) between P3b peak amplitude (Pz) and memory performance according to the number of semantic groupings made during learning and free recall trials

	Semantic groupings	
	< 11	≥ 11
Short delay, free recall (# correct)	0.26 [†]	0.03
Long delay, free recall (# correct)	0.11	-0.05
Recognition total hits	0.30 [*]	0.13

*
 $p < 0.05$

[†]
 $p < 0.10$