

**Age-related changes in selection, recognition, updating and maintenance  
information in WM. An ERP study in children and adolescents**

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### Acknowledgments

This study was supported by two grants from the Spanish Ministry of Economy, Industry and Competitiveness (PSI2016-80416-P and PID2019-105618RB-I00, funded by FEDER). We are grateful to the children and adolescents who participated in the study, and to the San Felipe Neri and Hermanos Carvajales schools of Martos (Jaén).

Declaration of interests: none

PREPRINT

### Abstract

Possible age-related changes in different working memory (WM) subcomponents were assessed by analyzing the event-related-potentials associated with the *n*-back task. Two versions of the task (0- and 1-back) were administered to 168 subjects between 6 and 20 years of age. In both *n*-back tasks, lists of symbol-letter pairs were presented. Participants had to select the letter and decide whether it matched the target in memory. Selection-matching of the relevant item, as indexed by an N2pc component, was evident in all age groups, indicating early maturation of this ability. The decreasing amplitude of the P300 with age, coupled with the longer duration of the load effect in young children, suggests that WM updating requires greater processing resources at younger ages. The slow wave, present during the maintenance period, showed an inversion of polarity with age in anterior sites that could reflect age-related changes in the active maintenance of information in WM.

*Keywords:* Working memory, *n*-back, N2pc, P300, slow wave, development

## Introduction

Working memory allows us to keep the information needed for solving a given task active (Baddeley, 2012). WM is a limited capacity system that holds information temporarily. WM operation supports complex cognitive processes, and is essential for numerous daily cognitive activities, including those related to the school curriculum.

WM performance gradually improves during childhood and adolescence, up until adulthood (Gathercole, Pickering, Ambridge, & Wearing, 2004). The neural substrates of WM are established in infancy, although maturation of core regions such as the prefrontal cortex and its integration with other areas continue throughout childhood and adolescence into adulthood (Luna, Padmanabhan, & Hearn, 2010). A substantial body of research has shown that WM plays an important role in complex cognitive skills and school-related measures, such as reading comprehension (Carretti, Borella, Cornoldi, & De Beni, 2009; Peng et al., 2018), math achievement (Lee & Bull, 2016; Passolunghi & Costa, 2019; Raghubar, Barnes, & Hecht, 2010), academic achievement (Swanson & Alloway, 2012) and intelligence (Swanson, 2008; Tourva, Spanouidis, & Demetriou, 2016). Therefore, understanding how WM develops has clear theoretical and educational implications.

WM tasks engage different component processes that contribute to performance. We focus on the three core processes of selection, updating and maintenance. Selection of the information to be encoded may serve as the initial step in WM tasks in which relevant information is presented among distracters. Some studies using visual WM tasks have reported that 7-8 year-old children show efficiency in selecting target information comparable to adults (e.g., Cowan, Morey, AuBuchon, Zwilling, & Gilchrist, 2010), although Plebanek and Sloutsky (2019) recently demonstrated age-related improvements in filtering efficiency between 4 and 7 years of age, and in

adulthood. A second core process involved in WM tasks is updating. The limited capacity of WM requires a mechanism to continuously replace outdated content with new information. The ability to update information develops rapidly throughout childhood until adulthood (e.g., Linares, Bajo, & Pelegrina, 2016), and contributes to age-related differences in WM performance. Finally, a maintenance mechanism is required to keep the relevant information active in WM. Children as young as 7 years are able to maintain items in WM through strategic processing (refreshing and rehearsal), but improvements in maintenance are observed with increasing age (Barrouillet, Gavens, Vargauwe, Gaillard, & Camos, 2009; Tam, Jarrold, Baddeley, & Sabatos-DeVito, 2010). The age-related enhancement in the persistence of content in WM may be still apparent even when the contribution of strategic factors is minimized (Cowan, Nugent, Elliot, & Saults, 2000).

Despite ample evidence of rapid development of WM during childhood and adolescence, up to now, scant attention has been paid to the electrophysiological correlates of the different phases of WM processing development during childhood and adolescence. The current study aimed to examine possible age-related differences in ERP activity in relation to the critical processes of selection, updating and maintenance. The excellent temporal resolution of the ERP method makes it possible to isolate activity in different periods during the same WM task, in turn allowing study of the different processes that occur in such periods. To this end, we adapted an *n*-back task to tap the different process under study, and selected well-known ERP markers of each process: the N2pc for selection, P300 for updating, and slow wave for maintenance.

### **The *n*-back task**

The *n*-back task (Kirchner, 1958, see Kane & Conway, 2016 for a brief history of the task) is a widely used paradigm employed for investigating the cognitive

processes underpinning WM, and also as a tool for assessing WM. The  $n$ -back task can be considered as a continuous recognition task, in which a series of items (e.g., letters, digits, words) are sequentially presented. Participants are asked to decide whether or not the current item matches the item previously presented ( $n$  trials back). In the 0-back task, participants must decide whether the just-presented item matches a target presented during instructions given at the beginning of the task. In the 1-back, participants have to indicate whether the current item matches the immediately preceding item. At higher levels of load, the current item must be compared with the one presented  $n$  trials ago, with  $n$  varying with the load level.

The  $n$ -back is a complex task that involves a number of WM components, among which four are examined in the present study using the 0- and 1-back versions of the task: selection, recognition, updating, and maintenance (Chen, Mitra, & Schlaghecken, 2008; Yapel, Stevens, & Arsalidou, 2019). Selection and recognition (matching), whereby the presented item is compared to the item maintained in memory, is required in both versions of the task. Updating or replacing the information is involved in the 1-back version of the task, but not in the 0-back version. Active maintenance of the target in WM, for future comparison with upcoming items, is necessary in both task versions. Only one item has to be maintained in 0- and 1-back tasks; however, in the 0-back version the same item is repeatedly used as the target, while in the 1-back version the target changes continuously throughout the task. In the present study, only the 0- and 1-back levels have been included, since more complex levels make it more difficult to isolate the processes of interest, and also render the task more difficult for young children.

Performance on WM tasks improves rapidly throughout childhood and adolescence. A number of studies of the  $n$ -back task showed remarkable age-related

improvement in performance during this period (Brahmbhatt, White, & Barch, 2010; Kwon, Reiss, & Menon, 2002; Pelegrina et al., 2015; Schleepe & Jonkman, 2009; Vuontela et al., 2003). Age-related performance differences are more pronounced during childhood than adolescence; in addition, performance matures earlier for less demanding compared to more complex versions of the task (e.g., López-Vicente et al., 2016; Pelegrina et al., 2015; Schelepen & Jonkman, 2009). The asynchronous improvement in performance among the different versions of the *n*-back has been attributed to differential changes with age in various cognitive functions, such as the ability to maintain information and executive functioning. This is consistent with the early development of brain areas that support the maintenance of information in WM, in comparison to the areas involved in the manipulation of information or, more generally, in executive functioning (Bunge & Wright, 2007; Luciana, Conklin, Hooper, & Yarger, 2005).

### **Selection and recognition processes in WM tasks (N2pc)**

The visual selection of a relevant stimulus for further processing is a WM process that has been studied in the context of the N2pc component. This component, first described by Luck and Hillyard (1994), appears between 200-300 ms after display presentation, with a parietal distribution contralateral to the target, and indexes rapid shifts of attention during a serial search (Woodman & Luck, 1999). The presence of an N2pc (Luck & Hillyard, 1994) related to the attentional selection mechanism was demonstrated in the Delayed Match-To-Sample (DMTS) task during the target selection-recognition phase (Barriga-Paulino et al. 2015a). The DMTS task represents a particular type of WM task, in which sensory stimuli to be stored in WM (encoding phase) and the recognition phase are separated by a short period of a few seconds, during which the encoded item is stored in an internal representation (maintenance or

retention phase) to permit correct identification during the recognition phase (Fuster & Jervey, 1981). During the recognition phase, several stimuli can be presented in the visual field, and the subject must recognize the stored item in WM; it is this characteristic of selection of a particular item in a visual hemifield that permits comparison of the visual search task and recognition phase in the DMTS task. The relationship of N2pc with WM has been stressed in experiments in which delayed recall of information in memory was required (Dell'Acqua, Sessa, Toffanin, Luria, & Jolicœur, 2010; Kuo, Rao, Lepsien, & Nobre, 2009). In these experiments subjects have to indicate if a centrally presented item appeared in a memorized display. An N2pc-like component, located at P7-P8 and T3-T4, appeared in contralateral sites to the location of the stored item in the memorized display. Similarly, N2pc is also obtained when a single stimulus is memorized, followed by the presentation of a stimulus array in which the subject has to recognize the stored item (Kuo et al., 2009). These results suggest that, in WM tasks, shifts of attention must occur for a presented item to be recognized among a stored display of items (Dell'Acqua et al., 2010), or to attend to the hemifield in which the previously stored item is presented (Kuo, Rao, Lepsien & Nobre, 2009). Both types of experiments demonstrate how shifts of attention are needed for the recognition or matching of sensory and stored representations.

The attentional N2pc is operational, although with a delayed peak latency, at 9-12 years (Couperus & Quirk, 2015). During WM tasks, and by using cues and retrocues, Shimi et al. (2014, 2015) showed that N2pc latency was longer in children than in adults. In a DMTS task, Barriga-Paulino et al. (2015a) with a cross-sectional sample (6-26 years old), also showed the presence of an N2pc-like component during the recognition phase that was already present in the 6-8-year-old group, although with a longer duration than in adults. Those results suggest that an increase in the efficacy of

the visual selection processes occurs with increasing age (van der Stelt, Kok, Sumlders, Snel, & Gunning, 1998). The localization technique applied to the N2pc component suggests dorsal and ventral posterior sources (Hopf et al., 2000). An earlier maturation of the N2pc dorsal component is plausible, given the earlier cortical thinning and intranetwork connectivity maturation for dorsal pathways relative to ventral pathways (Ciesilski et al., 2019). However, there is currently no information to confirm this proposition, although it is suggested that maturation of N2pc during childhood and adolescence would likely be rooted in the delayed maturation of the ventral pathway.

In order to examine the selection process in the present study, items in the  $n$ -back task consisted of letter-symbol pairs (e.g., # J). Participants were asked to determine whether or not the letter in the pair (e.g., J) matched the item maintained in memory. When targets are presented in a lateralized manner, a visual search would be needed to distinguish the target item (a letter) from a distractor (symbol), although with some differences between the 0- and 1-back tasks. In the 0-back condition, the characteristics of the item to be recognized are fixed (always the letter X), while in the 1-back condition the stimulus to be recognized (the target) is changed in non-target trials. In any case, selection of the visual hemifield in which a letter is presented is expected in the present experiment, and this imbalance in processing between hemispheres is expected to be reflected in an N2pc component, indexing the target selection process, which must somehow relate to the matching between the item stored in WM and the lateralized target.

### Updating information in *n*-back tasks (P300)

Numerous studies have related the P300<sup>1</sup> to the updating mechanism. The P300 is a positive-going deflection that typically appears around 300 ms after stimulus onset (Gómez et al., 2018; Polich, 2007, 2012). The P300 amplitude may reflect allocation of attentional resources, the intensity of processing, and context-updating (Donchin & Coles, 1988, Polich, 2007), whereas P300 latency may be considered as an index of processing speed (Kok, 2001).

P3 is a complex waveform with two subcomponents, P3a and P3b, having a topographical distribution in fronto-central and parieto-occipital locations, respectively. Neuropsychological studies comparing amplitude decreases of P3a and P3b associated with brain lesions suggest that P3b has a posterior origin, while P3a would have a predominantly frontal source (Lovstad et al., 2012). In particular, a reduction in P3a amplitude occurs due to damage of the lateral prefrontal cortex, orbitofrontal cortex and temporo-parietal junction (Lovstad et al., 2012). The temporo-parietal junction, but not frontal lesions, reduces the P3b amplitude. Additional sources can be added by

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<sup>1</sup> It should be noted that P300 is the term used most commonly in WM and *n*-back ERP studies to refer to posterior positive voltages around 300 ms and later. However, in the context of *n*-back WM, P300 does not correspond to the high amount of work related to P300 in oddball studies; thus, it would be more appropriate in *n*-back WM experiments to refer to this late positive voltage as the late positive component (LPC) rather than P300. However, we use P300 in the present report, because of its widespread application in literature studies of *n*-back to the late and posterior positive voltages that appear in this task, and because the classic P300 has also been related to the WM updating process (Donchin & Coles, 1988, Polich, 2007).

analyzing forward dipole modelling in fMRI seeded positions (Bledowski et al., 2004). The precentral sulcus and anterior insula were proposed as neural sources for P3a. P3b would have sources distributed in posterior regions, including the posterior parietal cortex (PPC) and inferior temporal cortex (Bledowski et al., 2004). Most of these areas undergo marked cortical thinning during childhood (Gerber et al. 2009), which would explain the reduction in visual P3a and P3b amplitude and latency with age (Courchesne et al. 1978, Flores, Gómez, & Meneres, 2010, Rojas-Benjumea, Sauqué-Poggio, Barriga-Paulino, Rodríguez-Martínez, & Gómez, 2015). There are also a few studies addressing the neural source of the so-called LPC in WM tasks. Using low-resolution electromagnetic tomography (LORETA), Imperatori et al. (2013) found an increase of delta activity in the left perirhinal and entorhinal cortices in the 3-back compared to 1-back condition. Although the study was not conducted on LPC, but rather on the delta rhythm, the slow positive waves are in this frequency range. In a delayed match-to-sample test, a similar task for assessing WM, Barriga-Paulino et al. (2015b) noted greater involvement of posterior areas in the generation of LPC, in the occipital, parietal and temporal cortex including the parahippocampal gyrus, in children than adults; meanwhile, adults showed greater activity in more anterior areas, including parietal, temporal frontal, cingulate and insular brain areas.

The P300 amplitude typically decreases in amplitude with increasing WM demands in the *n*-back task (e.g., Gevins et al., 1996; Rughnau, Wetzel, Widmann, & Schröger, 2010; Shen, Liu, & Chen, 2018; but see Vilà-Balló et al., 2018). This reduction has been attributed to a redistribution of attentional resources with higher loads, and to the greater effort expended during maintenance of the information (Daffner et al., 2011; Gevins et al., 1996; Watter, Geffen, & Geffen, 2001). However, this pattern may be different for the lowest levels of load. A number of studies have

reported that the 1-back level induces a higher P300 amplitude than the 0-back level (Chen et al., 2008; López Zunini et al., 2016; Morrison, Kamal, & Taler, 2019; Saliasi, Geerligs, Lorist, & Maurits, 2013; but see Watter et al., 2001). Saliasi et al. (2013) interpreted this finding in terms of differences in the attentional demands between the two levels. In addition, it may be worth considering that the levels also differ in updating requirements.

Although some researchers have examined ERPs using *n*-back tasks in children (e.g., Shen et al., 2018), few studies have addressed age-related differences in ERPs using these tasks. To our knowledge, only Myatchin and Lagae (2013) compared ERPs components between children of different ages using the *n*-back. These authors administered a 1- and 2-back task to children aged from 6 to 16 years, and observed a reduction in P450 amplitude with age in the 1-back task.

#### **Maintenance of encoded items (negative slow waves)**

A negative slow wave (SW) has been described during the retention period of DMTS tasks (Ruchkin, Johnson, Canoune, & Ritter, 1990; Ruchkin, Johnson, Grafman, Canoune, & Ritter, 1992). The topography of this wave seems to be dependent on the information memorized. A SW in frontal and temporal areas is found during auditory stimuli retention, while a more posterior distribution is observed in response to visual stimuli (Ruchkin et al., 1992; Barceló, Martín-Loeches, & Rubia, 1997). Also using a DMTS task, the SW has been described in children and adolescents (Barriga-Paulino, Rodríguez-Martínez, Rojas-Benjumea, & Gómez, 2014, 2015a; Barriga-Paulino, Rojas-Benjumea, Rodríguez-Martínez, & Gómez, 2015b; and Barriga-Paulino, Rodríguez-Martínez, Arjona, Morales, & Gómez, 2017). While in adults the negative SW spreads along the whole scalp, in children there is an inversion of polarity between anterior (positive) and negative (posterior) sites. On analyzing the SW with LORETA, a higher

contribution of anterior sites to the generation of the SW with older age was found, suggesting that young adults recruit anterior sites more intensively than children to retain items in WM (Barriga-Paulino et al., 2014, 2015b). The different topographies and neural sources between children and young adults with respect to the SW reflect an immaturity of the frontal cortex in the former group, accounting for the poorer WM performance of children compared to adults (Gerber et al., 2009).

In *n*-back tasks, between the response in a trial and presentation of stimuli in the next trial, the selected item must be retained in WM. Bailey, Mlynarczyk, and West (2016) observed an SW related to maintenance of the stored items in WM. This SW showed fronto-polar positivity and a centro-parietal spread of negativity. Additionally, during the retention phase, this negative SW has been demonstrated to be modulated by WM training (Salmi et al., 2019).

### **The present study**

Our objective was to investigate possible age-related changes in different subcomponents of WM by analyzing the ERPs associated with the *n*-back task. Specifically, we aimed to address the selection mechanism that determines the information to be processed to permit recognition, the updating mechanism that replaces the no-longer-relevant information, and the maintenance process that keeps the relevant information activated. To this end, we administered 0- and 1-back tasks. In the 0-back task, the target letter to be identified remained the same (the letter X), whereas in the 1-back the target changed continuously, thus requiring updating.

In both versions of the task, we sought to analyze possible age-related differences in the amplitude of different electrophysiological markers related to the components under study. Specifically, we focused on activity occurring during the following intervals: a) the N2pc-like activity over posterior scalp locations contralateral

to the item to-be-selected for further processing, b) the positive voltage deflection related to the P300 amplitude, and c) the SW activity taking place during the interval between the item offset and presentation of the following item.

The participants in this study were selected to cover a wide range of ages (6 to 20 years) throughout childhood and adolescence. We anticipated age-related improvements in performance, in terms of both accuracy and speed, in both versions of the task, with a more pronounced effect of age expected in the 1- versus 0-back task. Given that N2pc indexes a selection process necessary for performing these *n*-back tasks and based on previous research with other tasks (Barriga-Paulino, 2015b; Coperus & Quirk, 2015; Shimi et al., 2014), we predicted that, similarly to adults, children of different ages would show contralateral negativity when selecting an item for further processing in WM. This would indicate that a selection mechanism required to perform the task is in operation in young children. Regarding the P300, consistent with previous studies we expected a greater P300 amplitude in the 1-back compared to the 0-back task, given the requirement for updating in the 1-back condition. Moreover, as suggested by studies using tasks that elicit the P3b (Gómez et al., 2018; Polich, 2012), we anticipated age-related changes in the P300 amplitude and, more specifically, a reduction with age that could differ by load. This outcome implies that the processing demands to update information decrease with age. Finally, building on previous findings (Barriga-Paulino et al., 2017), we expected a SW in all child and adolescent age groups, to the extent that they are able to hold the relevant information activated in WM, although an inversion of polarity between anterior and posterior sites should only be observed in children. Such a pattern would indicate age-related changes in how the information is maintained in WM, and in the recruited regions.

## Methods

### Participants

One-hundred and sixty-eight subjects between 6 and 20 years of age participated in this study. However, 24 subjects were excluded due to excessive EEG artifacts, and 1 further participant (18.1 years old) due to their misunderstanding of the experimental task. The final sample was composed of 143 subjects: 61 males ( $M = 13.2$  years,  $SD = 3.9$ ) and 82 females ( $M = 14.9$  years,  $SD = 4.2$ ; see Table 1). The participants were divided into five age groups corresponding to middle childhood (6-8 years), late childhood (9-11 years), early adolescence (12-14 years), middle adolescence (15-17 years) and late adolescence (18-20 years).

Age Group	Included				Excluded			
	<i>n</i>	Gender (male/female)	Handedness (left/right)	Age Mean ( <i>SD</i> )	<i>n</i>	Gender (male/female)	Handedness (left/right)	Age Mean ( <i>SD</i> )
6-8	23	12/11	1/22	7.7 (0.90)	10	7/3	0/10	7.4 (0.89)
9-11	23	12/11	1/22	10.5 (0.78)	9	5/4	0/9	10.1 (0.95)
12-14	32	15/17	4/28	13.6 (0.88)	2	0/2	1/1	12.9 (0.15)
15-17	32	16/16	6/26	16.5 (0.90)	1	0/1	1/0	16.3 (-)
18-20	33	6/27	1/32	19.5 (0.86)	2	0/2	0/2	18.5 (0.70)

*Table 1.* Characteristics of participants that were included and excluded from analyses due to excessive EEG artifacts

Subjects did not report any neurological diseases or psychological impairments, and children were recruited from public schools in middle-class areas of the city. According to the teachers' reports, the children had records that did not reflect academic failure or difficulties. College students were recruited from the University of Jaén

campus. Informed consent was obtained from experimental subjects (in the case of children, parents or legal guardians signed the consent forms), following the Helsinki protocol. Assent was obtained from all children. The present study was approved by the Ethical Committee of the University of Jaén.

### **Behavioral methods**

Two different versions of a visual *n*-back task (0- and 1-back) were administered to the experimental subjects. The stimuli were letters of the alphabet (B, C, D, F, G, H, J, K, L, M, N, P, Q, R, S, T, V, W, X, Y, Z) and symbols (!, #, \$, %, (, /, ?, @, }, ¡, ¿, ¢, <, =, >, ±, §, ©, ¶, æ) (Figure 1). In each trial, a symbol and a letter were presented simultaneously on opposite sides of the computer screen, with an eccentricity of 4.8 degrees in the horizontal plane (Figure 1), and with subjects situated at 60-70 cm from the screen. The position in which the letter and symbol appeared on the screen was pseudorandomized (left/right) in each trial. A fixation point “+” was presented in the centre of the screen.

Letters and symbols were presented during a 2000 ms interval that corresponded to the response window. The interstimulus interval (ISI) was 1500 ms. The 2000 ms period allowed evaluation of the ERPs related to the processes of stimulus selection, matching and updating, while the 1500 ms ISI allowed assessment of the ERPs associated with the maintenance phase. In the 0-back task, the subjects were required to press a response button (“yes”) if they saw an “X”, and to push the “no” button if they saw any other letter. In the 1-back task, the subjects were required to press “yes” if the letter was the same as that presented in the previous trial, and to press “no” if the letter was not the same. Responses were made using two fingers of the dominant hand, and were recorded via the response box. There were eight lists (four 0-back and four 1-back), which were arranged into four blocks each having the same load. Blocks of

different loads were presented in an alternating sequence, beginning with a 0-back block. Each list included 60 trials with 20 (33.3%) target stimuli and 40 (66.7%) non-target stimuli. There were 480 trials in total. Participants were permitted to have a short break after completing each block.

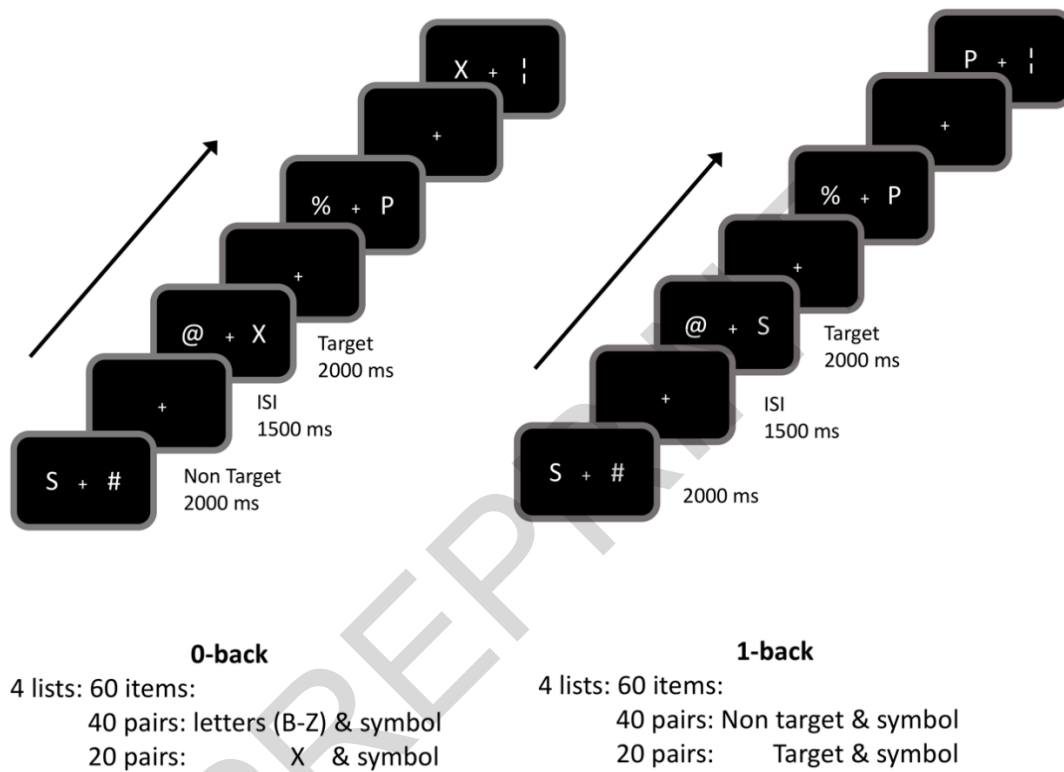


Figure 1. Graphical example of trials in the 0- and 1-back trials.

Children and adolescents aged from 6 to 17 years were tested in a quiet room at their school or high school. The young adult or late adolescence group (18-20 years old) was tested in the laboratory at the university campus. The experimenter remained with the participant throughout the task. Parents of younger children were allowed to remain in the room during the task, and some of them chose to do so, in silence and out of the sight of the child. All of the recordings were obtained by the same experimenter.

### **Recording and preprocessing of the EEG data**

To record the EEG data during the experimental task, an electrocap, with 32 electrodes placed according to the 10/20 system, was connected to a Brain Vision ActiChamp amplifier (Brain Products GmbH, Gilching, Germany). Four electrodes were placed on the midline (Fz, Cz, Pz y Oz); twelve electrodes in the right hemisphere (Fp2, F4, F8, Fc2, Fc6, C4, Cp2, Cp6, Tp10, P4, P8 y O2); and twelve electrodes in the left hemisphere (Fp1, F7, F3, Ft9, Fc5, Fc1, C3, Cp5, Cp1, P7, P3, O1). Three electrodes were placed around the eyes to record blinks and ocular movements. An electrode situated in the left mastoid (Tp9) was used as an on-line reference of the EEG signal, and an electrode located in front of the midline was used as the ground electrode. Impedance was below 10 k $\Omega$ . The BrainVision Recorder (BrainProducts GmbH, Gilching, Germany) was used for acquisition of the EEG data, which were sampled at a frequency of 500 Hz. EEG data pre-processing was performed with BrainVision Analyzer 2 (version 2.1, BrainProducts GmbH, Munich, Germany) and EEGLAB (v14.0.0) (Delorme & Makeig, 2004) using the 2016 version of Matlab (MathWorks Inc., Natick, MA, USA).

The first step consisted of filtering the recordings by means of a zero phase shift Butterworth filter (low cutoff: 0.1 Hz, high cutoff: 40 Hz, time constant: 0.3, order 2).

The second step involved elimination of the independent components (ICAs) related to blink and ocular artifacts by means of an algorithm implemented in Brain Vision Analyzer 2. Once the artifactual ICAs had been eliminated, the EEG was reconstructed.

The third step involved elimination of the codes of trials in which omission or commission errors occurred, and then obtaining the epochs. Two different epochs were obtained: one for assessing the stimuli selection and updating (-200 to 0 ms for baseline,

and 1500 ms post-stimulus), and another for assessing the maintenance phase (1800 to 2000 ms post-stimulus for baseline, and from 2000 to 3500 ms post-S1 for the maintenance phase).

Then, an artifact rejection protocol was differentially applied according to age. The use of distinct voltage thresholds according to age was based on the previously observed difference in EEG spectral power between the children and adults: children show higher spectral power than adults (see Barriga-Paulino, Flores, & Gómez, 2011). The artifact rejection threshold was  $\pm 100 \mu\text{V}$  for subjects aged 12 years or older, and  $\pm 150 \mu\text{V}$  for subjects up to 11 years old. For adults, the criterion of  $\pm 100 \mu\text{V}$  is very common in the literature. Applying this criterion in children would produce a high number of rejections by voltage with respect to adults, given the high spectral power differences in EEG voltages between children, adolescents and young adults (see Rodríguez-Martínez, Barriga-Paulino, Rojas-Benjumea, & Gómez, 2015). Therefore, considering the differences on spectral power with age, we used a high artifact rejection cutoff in children younger than 12 years.

### **Event-related potentials (ERPs)**

Analysis of the ERPs was performed with Matlab and the EEGLAB (v14.0.0) (Delorme & Makeig, 2004) and ERPLAB (v7.0.0) (Lopez-Calderon & Luck, 2014) toolboxes. Only trials with correct responses for targets and non-targets were included in the analyses. Averaging was computed independently for the targets in the 0- and 1-back conditions, and for non-targets in the 0- and 1-back conditions for each individual subject. Participants with fewer than 15 trials per condition were discarded from further analyses. ERPs were grouped to obtain the grand average and statistical analysis was performed on the data of five age groups: 6-8, 9-11, 12-14, 15-17 and 18-20 years. The

number of trials included in each experimental condition for each age group is presented in Table 2.

The components assessed were the N2pc and P300 during the period in which the stimulus was present (0-2000 ms post stimulus); and the SW during the maintenance period (2000-3500 ms post-stimulus). The time windows and electrodes analyzed for each of these components were in accordance with previous data on these components (Luck & Hillyard, 1994; Polich, 2012), and with the time windows and electrodes in which the component showed its maximum amplitude; however, it should be noted that these analysis parameters were not selected based on the experimental conditions, which would have produced a sampling bias, but rather based on the time window in which the peak amplitude was detected independent from the experimental condition. This procedure was particularly important for analyzing the P300 component, which exhibited delayed latencies for the youngest subjects.

Age Group	0-back		1-back	
	Target	NonTarget	Target	NonTarget
6-8	47.3 [17, 77]	89.3 [36, 145]	31.5 [15, 67]	73.6 [34, 144]
9-11	53.3 [20, 78]	105.6 [38, 150]	42.3 [15, 73]	95.1 [38, 153]
12-14	56.9 [21, 78]	111.3 [41, 157]	49.3 [18, 75]	103.9 [37, 155]
15-17	63.0 [31, 80]	123.5 [58, 158]	59.3 [23, 76]	126.4 [56, 160]
18-20	60.7 [19, 79]	120.1 [45, 156]	61.1 [29, 80]	120.5 [54, 157]

*Table 2.* Mean number and range of trials included for each experimental condition and age group

To analyze the N2pc (time window: 150-300 ms), the voltage differences between electrodes P8 and P7 (when the letter stimulus letter appears on the left side and for P7 minus P8 (when the letter appeared on the right side) were collapsed (Luck & Hillyard, 1994). For P300, the time window was set around the positive peak (from 50 ms before to 150 ms posterior to the P300 peak) of each age group in posterior electrodes Pz and Oz. This strategy was based on an initial inspection, which showed that the posterior P300 peak was delayed in the younger subjects. A delayed P300 in the youngest children has been observed previously (Rojas-Benjumea et al., 2015). The positive peaks occurred at 800, 616, 512, 404, and 408 ms for the Pz electrode, and at 614, 498, 378, 360, and 406 ms for the Oz electrode, for the 6-8, 9-11, 12-14, 15-17, and 18-20 years age groups, respectively. This time window was considered as an early P300. A second time window was selected for a late P300 with mean voltage from 1000 ms to 1500 ms in the Pz and Oz electrodes. For the SW, the time window from 3000 to 3500 ms post-stimulus (equivalent to 1000 to 1500 ms after stimulus offset) in the central electrodes were used (Fz, Cz, Pz and Oz). These electrodes were chosen to allow observation of a possible inversion of polarity between anterior and posterior sites in young children.

### Statistical analysis

**Behavioral.** To assess *n*-back performance, response time (RT) and *d*'-prime (*d*') were used as outcome measures. RTs were calculated separately for the 0- and the 1-back levels. RTs for incorrect trials and practice lists were excluded from the analyses. Data were also trimmed to exclude RTs under 200 ms and beyond 3.5 *SDs* of the individual participants' mean times in each condition. On this basis, 0.72% of the RTs were excluded. The *d*' parameter, which reflects the ability of participants to discriminate targets from non-targets, was estimated as  $d' = Z_{\text{Hits}} - Z_{\text{FalseAlarms}}$ . The fourth

method proposed by Stanislaw and Todorov (1999) was used to avoid indeterminate values of  $d'$  when the hit or the false-alarm rate was equal to 0 or 1.

A mixed-model ANOVA was conducted on the RTs with load (0-back, 1-back) as the within-subject variable and age group as the between-subjects variable. A mixed-model ANOVA was also performed on  $d'$  with load (0-back, 1-back) as the within-subject variable and age group as the between-subjects variable. Follow-up ANOVAs were conducted when interactions occurred. Differences among age groups were analyzed using post-hoc pairwise tests, with Bonferroni correction applied for multiple comparisons. Alpha was set at .05 for all tests.

**ERPs.** For ERPs, the dependent variables were the mean amplitudes of the early and late P300, and the SW, as well as the mean voltage amplitude difference (contralateral minus ipsilateral) for the N2pc. All of the ANOVAs included load (0-back, 1-back) and trial type (target, non-target) as within-subject variables, and age group as the between-subject variable. In addition, electrode (Pz, Oz) was added as a within-subject variable for the early and late P300 amplitudes. The same was done for the analysis of SW amplitude, although the electrode variable had four levels (Fz, Cz, Pz, Oz). A qualitative description of the data is given below; follow-up ANOVAs were performed to analyze interactions that are of theoretical relevance to the objectives of the present study. Age group differences were determined via post-hoc comparisons, with Bonferroni's correction applied for multiple comparisons.

## Results

### Behavioral results

**Response Times.** We conducted a 5x2 repeated measures analysis of variance (ANOVA) with age group (6-8, 9-11, 12-14, 15-17, 18-20 years) and load level (0-back, 1-back) as independent variables and reaction time as the dependent variable. The

results showed significant effects of age,  $F(4,138) = 70.44, p < .001; \eta_p^2 = 0.67$ , and load level (0-back, 1-back),  $F(1, 138) = 201.72, p < .001; \eta_p^2 = 0.59$  (Figure 2), but there was no Age x Load interaction effect ( $F < 1$ ). The load effect was due to longer RTs in the 1-back condition ( $M = 873, SD = 206$ ) compared to the 0-back condition ( $M = 768, SD = 192$ ). With respect to the age effect, there was a progressive reduction of RT with age until the age of 15-17 years, at which the RTs stopped decreasing (all age group comparisons  $ps < .01$ , except groups age 15-17 and 18-20 years, in which no differences were found; Bonferroni correction for multiple comparisons; Supplementary Table 1 also see Figure 2 (panel A).

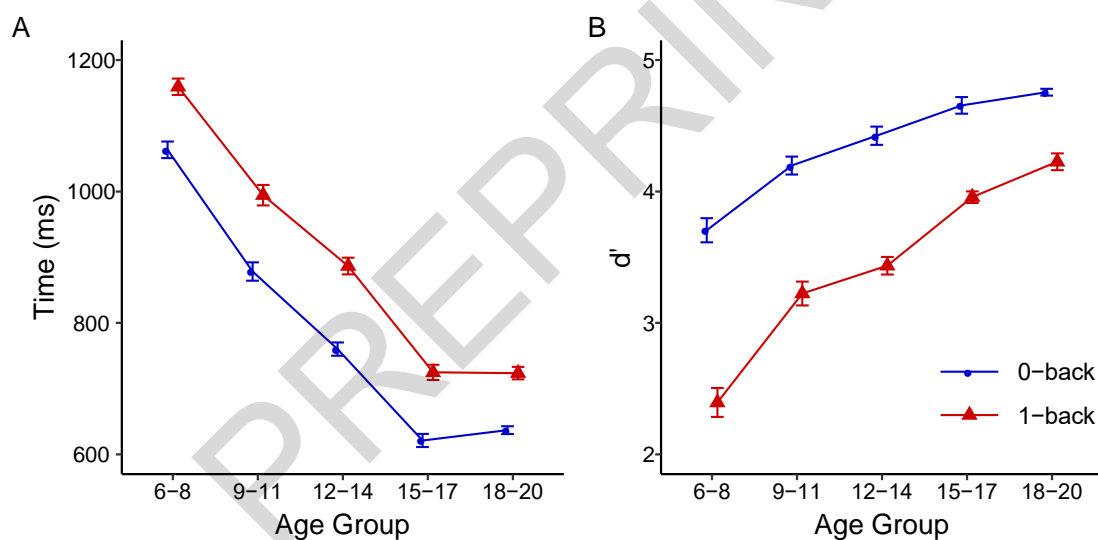


Figure 2. Panel A shows the decrease in RT with age for the two levels of load (0- and 1-back). Error bars represent one standard error of the mean. Panel B shows the decrease in  $d'$  with age for the two levels of load (0- and 1-back). Error bars represent one standard error of the mean.

**D-Prime ( $d'$ ).** We conducted a 5x2 (ANOVA) with age group (6-8, 9-11, 12-14, 15-17 and 18-20 years) and load level (0-back and 1-back) as independent variables and

$d'$  as the dependent variable. The analysis showed an effect of age group,  $F(4, 138) = 21.63, p < .001; \eta_p^2 = 0.38$ , and load level,  $F(1, 138) = 189.36, p < .001; \eta_p^2 = 0.58$ . The load level effect was due to a higher  $d'$  in the 1-back task compared to the 0-back task, and the age effect was due to an increase of  $d'$  with age. Both simple effects were qualified by the interaction between them,  $F(4, 138) = 4.17, p = .003; \eta_p^2 = 0.11$ .

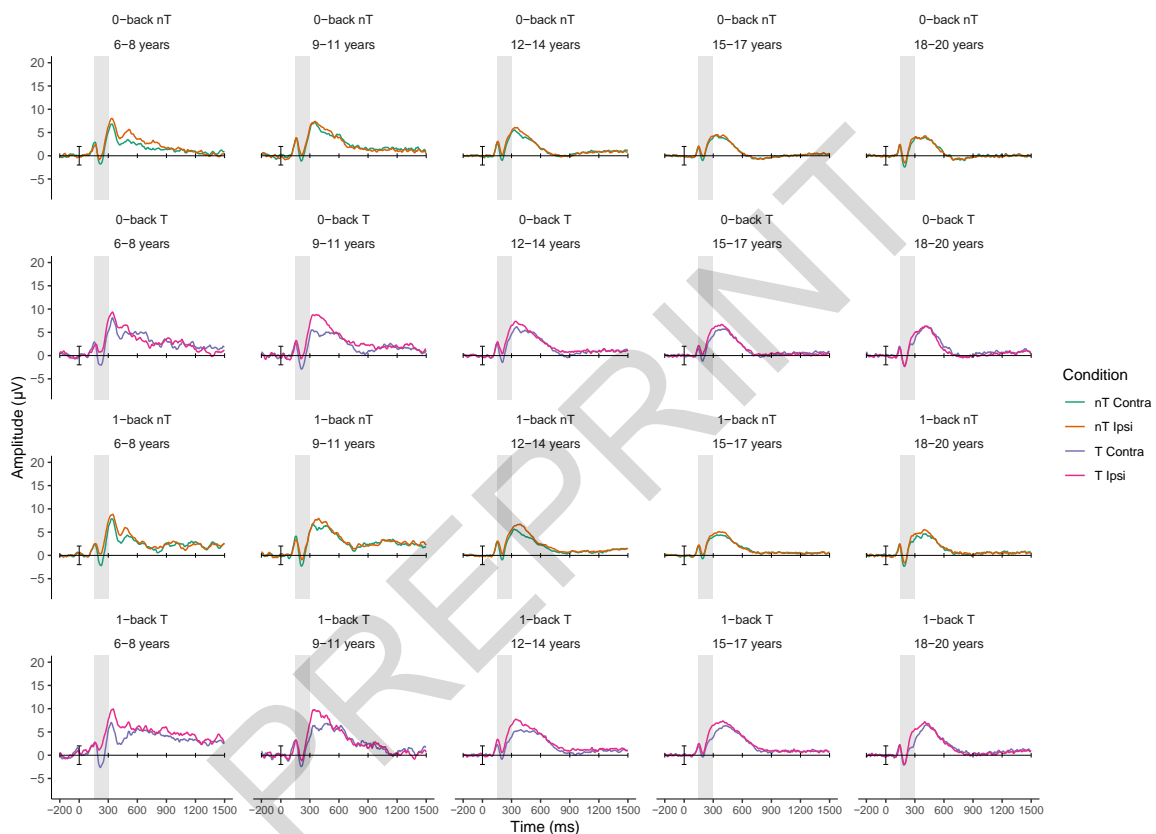
Post-hoc analyses showed that the values of  $d'$  increased with age in both load conditions, although with a different pattern. In the 0-back task, the  $d'$  values of the 6-8 years age group were significantly different to those of the age 12-14, 15-17 and 18-20 years age groups; the 9-11 years age group was different to the 18-20 years age group ( $p < .05$ ; Bonferroni corrected for multiple comparisons; see Supplementary Table 2). For the 1-back task, there were significantly different  $d'$  values between the 6-8 years age group and all other age groups. The 9-11 years age group exhibited different  $d'$  values compared to the 15-17 and 18-20 years age groups. The 12-14 years age group showed different  $d'$  values compared to the 18-20 years age group ( $p < .05$ , Bonferroni corrected for multiple comparisons; see Supplementary Table 2). Globally, the results indicate a more pronounced age-related change of  $d'$  in the 1-back task (see Figure 2, panel B).

### **Event-related potentials (ERPs)**

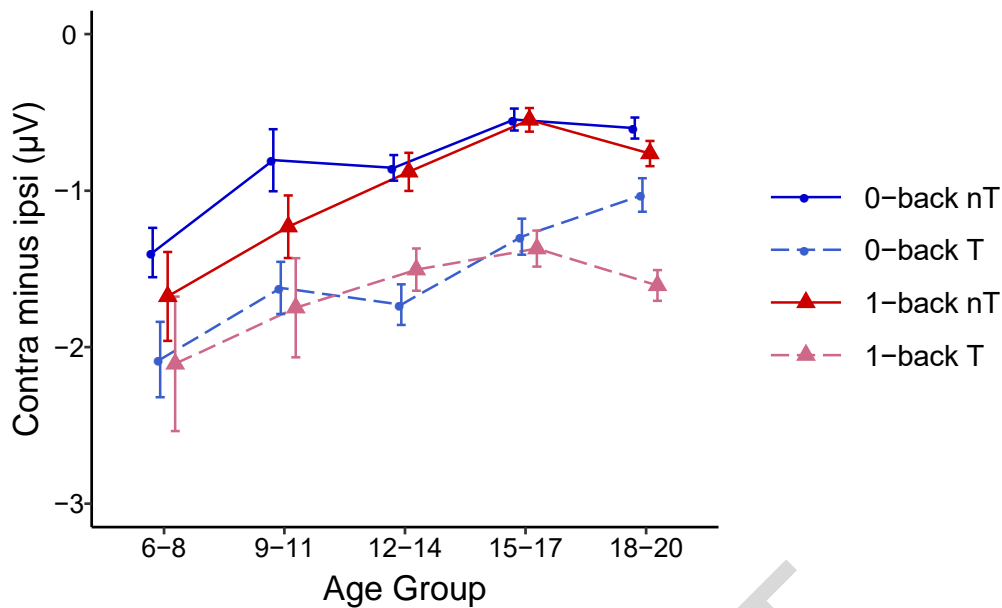
**Selection-matching Process (N2pc).** Figure 3 shows the presence of increased negativity in the ERPs, as induced by stimulus presentation in the contralateral site in the four conditions and in the different age groups. This increased early negativity to stimuli in the contralateral site can be interpreted as an N2pc component due to its polarity, time window and location (electrodes P7 and P8).

There were effects of target type and age. The effect of target type,  $F(1,138) = 26.35; p < .001, \eta_p^2 = 0.16$ , was due to a higher amplitude of the N2pc component in the

target condition compared to the non-target condition (see Figure 4). The effect of age was due to a reduction in the N2pc component with increasing age,  $F(4,138) = 2.7$ ;  $p = .03$ ;  $\eta_p^2 = 0.07$ . Post-hoc analysis showed that the 6-8 years age group differed significantly compared to the 15-17 years age group ( $p < .05$ , see Supplementary Table 3, Bonferroni-corrected for multiple comparisons).

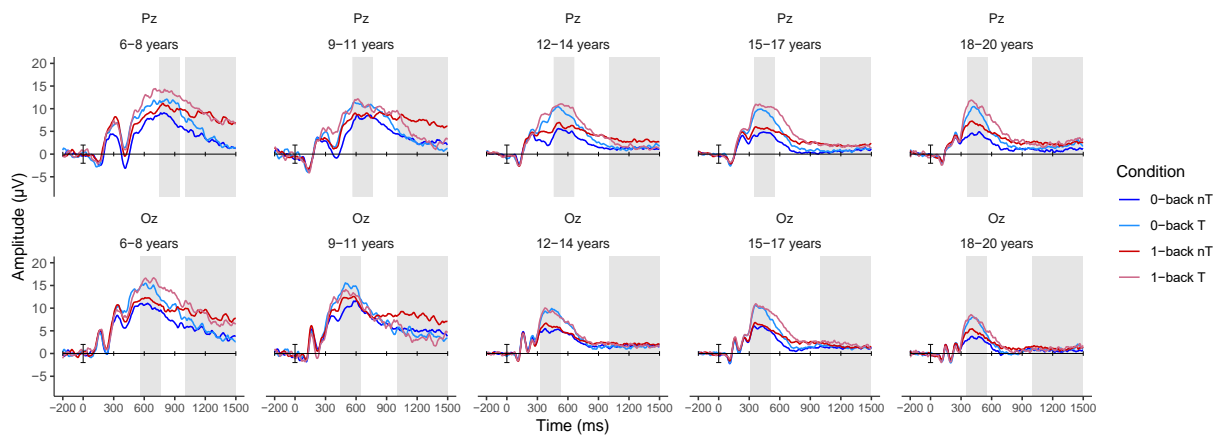


*Figure 3.* Visual ERPs of contralateral and ipsilateral targets. The visual ERPs induced by the contralateral and ipsilateral targets, P8-P7, when the letter stimulus appears in the left side, collapsed with P7-P8 when the letter stimulus appears in the right side, are presented for the five age groups and four experimental conditions (0-back non-target, 0-back target, 1-back non-target, 1-back target). Note the higher negativity for targets presented on the contralateral site, which indicates an N2pc component.



*Figure 4.* Mean values of the N2pc component among the different ages and the four experimental conditions (0-back non-target, 0-back target, 1-back non-target, 1-back target). Note the higher amplitude of the N2pc component in the target conditions (T) compared to the non-target conditions (nT), and the decrease of amplitude with age. Error bars represent one standard error of the mean.

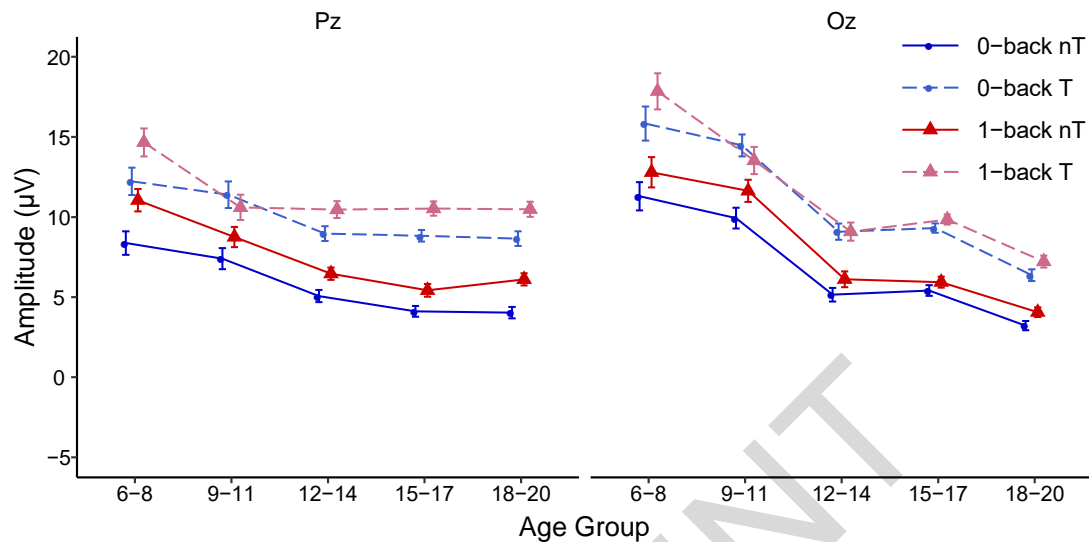
**P300.** For the early P300, the load factor was statistically significant,  $F(1,138) = 30.57$ ;  $p < .001$ ;  $\eta_p^2 = 0.18$ , due to a higher amplitude of the P300 in the 1-back than in the 0-back condition. The main effect of type of target was also significant,  $F(1,138) = 338.87$ ,  $p < .001$ ,  $\eta_p^2 = 0.71$ , owing to the higher amplitude of the target than the non-target condition. There was an age effect due to the decreased amplitude of the early P300 with age,  $F(1,138) = 9.0$ ;  $p < .001$ ;  $\eta_p^2 = 0.21$ . Post-hoc analysis showed that the P300 amplitude of the 6-8 years age group was higher compared to those of the 12-14 years age group and above. The 9-11 years age group differed from the 18-20 years age group ( $p < 0.05$ , Bonferroni corrected; Supplementary Table 4). Figure 5 show the ERPs for the four experimental conditions.



*Figure 5.* Visual ERPs for the four experimental conditions. The visual ERPs induced an early P300 component (first gray area in the ERP plot), followed by a late P300 component (second gray area in the ERP plot). Note the higher amplitude and delayed latency of the early P300 as age decreases; this motivated the use of different time windows for the statistical analysis of the early P300 component, as indicated in the method section. The ERP are presented for the five age groups and the four experimental conditions (0-back non-target, 0-back target, 1-back non-target, 1-back target).

Age-related changes in early P300 amplitude are depicted in Figure 6. There was an Age Group x Channel interaction,  $F(1,138) = 5.26, p = .001, \eta_p^2 = 0.13$ , which was qualified by the Age Group x Channel x Type of Target interaction,  $F(1,138) = 3.61, p = .008, \eta_p^2 = 0.09$ . This interaction was due to a change in focus of the P300 component from Oz to Pz with increasing age, which was somewhat more pronounced in older age groups in the target condition compared to the non-target condition. A comparison of the difference in amplitude between the Pz and Oz electrodes, for both types of targets in each age group, revealed a significant difference between targets and non-targets for the 15-17 years age group, ( $M_{diff} = 1.0$ ),  $F(1, 31) = 16.3, p < .001, \eta_p^2 = 0.34$ , as well as for the 18-20 years age group ( $M_{diff} = 1.3$ ),  $F(1, 32) = 31.23, p < .001, \eta_p^2 = 0.49$ . In

contrast, the difference in amplitude of both electrodes between targets and non-targets did not reach significance for any of the other three groups (all  $ps > .16$ ).

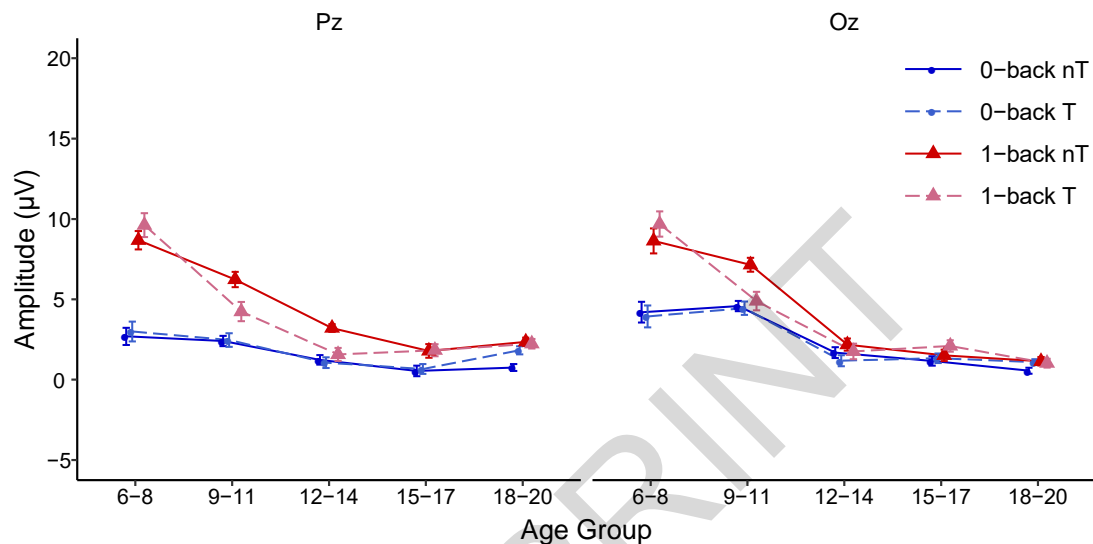


*Figure 6.* Early P300 amplitude for the different ages and the four experimental conditions (0-back non-target, 0-back target, 1-back non-target, 1-back). Notice the reduction of P300 amplitude with age, the higher amplitude in the target condition (T) compared to the non-target condition (nT), and the higher amplitude of the 1- versus 0-back level. Error bars represent 1 standard error of the mean.

For the late P300, the main effect of load was significant,  $F(1,138) = 93.26$ ;  $p < .001$ ;  $\eta_p^2 = 0.40$ , due to a higher amplitude of the P300 in the 1- versus 0-back condition (Figure 7). There was an age effect due to the decrease in amplitude of the P300 component with age. Bonferroni post-hoc comparison indicated that the 6-8 and 9-11 years age groups were different from all the other groups ( $p < .01$ ; see Supplementary Table 5 for details).

The interaction between load and age group,  $F(4,138) = 13.01$ ;  $p < .001$ ;  $\eta_p^2 = 0.27$  was due to a higher amplitude for the younger group children when processing the stimuli in the 1- versus 0-back condition relative to the adolescent and young adults

groups. Post-hoc analysis of the difference in amplitude of the late P300 between both load levels (collapsed across type of target and channel) revealed that the difference was greater for the younger group (6-8 years old) than for the other groups ( $p < .001$ , Bonferroni corrected; Supplementary Table 6).



*Figure 7.* Mean values of the late P300 component for the different ages and the four experimental conditions (0-back non-target, 0-back target, 1-back non-target, 1-back). Note the higher amplitude of the 1-back condition, and the general decrease of amplitude with age. Interactions are described in the text. Error bars represent 1 standard error of the mean.

**Slow wave (SW).** After switching off the target, an SW can be assessed (Figure 8). Notably, the SW of the youngest groups has a positive polarity in central electrodes, while it is negative across the scalp for the rest of electrodes. There was a broader distribution of negativity with older age. The main effect of load was qualified by the interactions with the other factors.

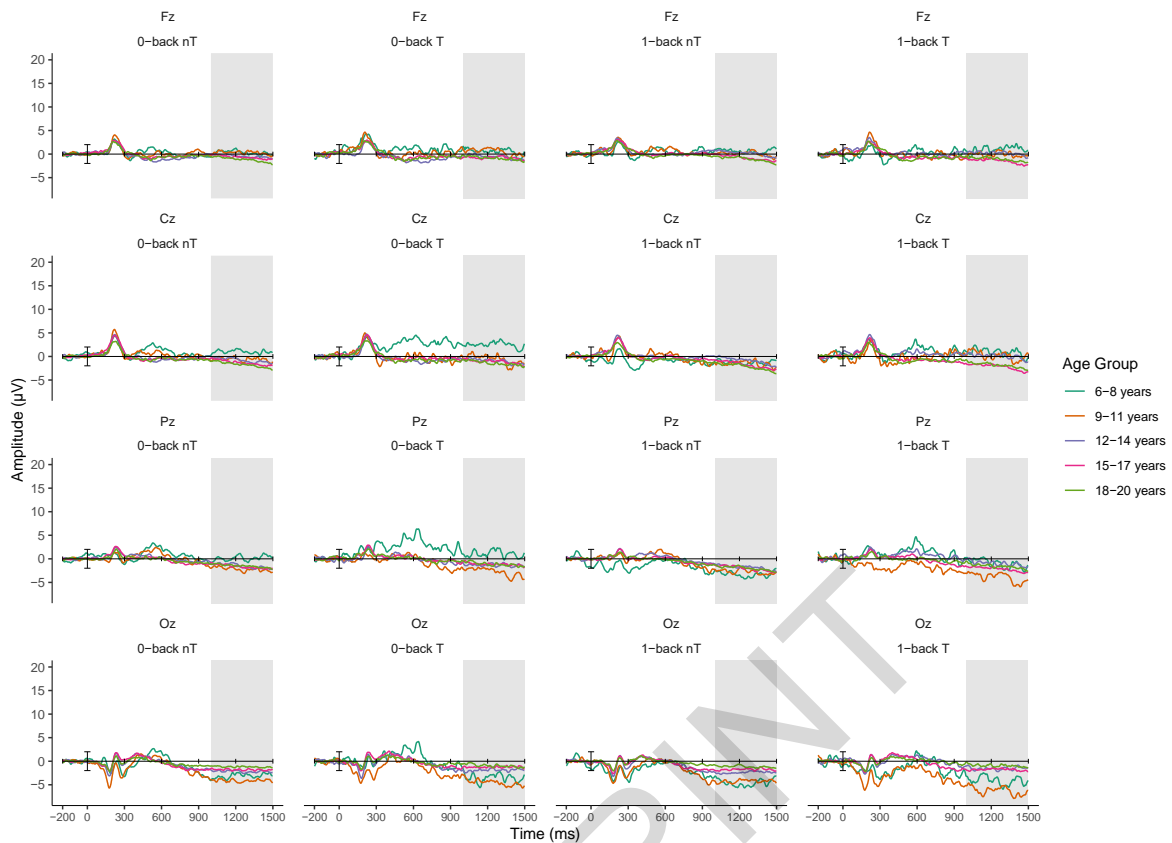


Figure 8. SW during the maintenance phase. After the switch of target, an SW developed. The ERP are presented for the five age groups and the four experimental conditions (0-back non-target, 0-back target, 1-back non-target, 1-back target).

There was an interaction between channel and age group,  $F(12,414) = 5.4$ ,  $p < .001$ ,  $\eta_p^2 = 0.14$ , due to the inversion of polarity that appears in young children between anterior and posterior electrodes: positive polarity in anterior electrodes and negative in posterior electrodes. This inversion of polarity disappeared with age and negativity was extended along the entire scalp (see Figure 9); it was also influenced by load, as indicated by the third order interaction of age group, channel and load,  $F(12,414) = 5.2$ ,  $p < .001$ ,  $\eta_p^2 = 0.13$ . To decompose the third order interaction of age group, channel and load, two separate ANOVAs were performed for each load level. For the 0-back task, the interaction between age group and channel was significant,  $F(12,414) = 6.08$ ,  $p <$

.001,  $\eta_p^2 = 0.15$ , due to the previously described relationship of central-parietal positivity with age, and the increase of negativity with age in posterior electrodes (Figure 10). For the 1-back level, there was also a significant interaction between age group and channel  $F(12,414) = 4.96$ ,  $p < .001$ ,  $\eta_p^2 = 0.13$ . The pattern of results was similar to those previously described for the 0-back level, except that the inversion of polarity in young children occurs in fronto-central electrodes for the 1-back level, rather than in centro-parietal electrodes.

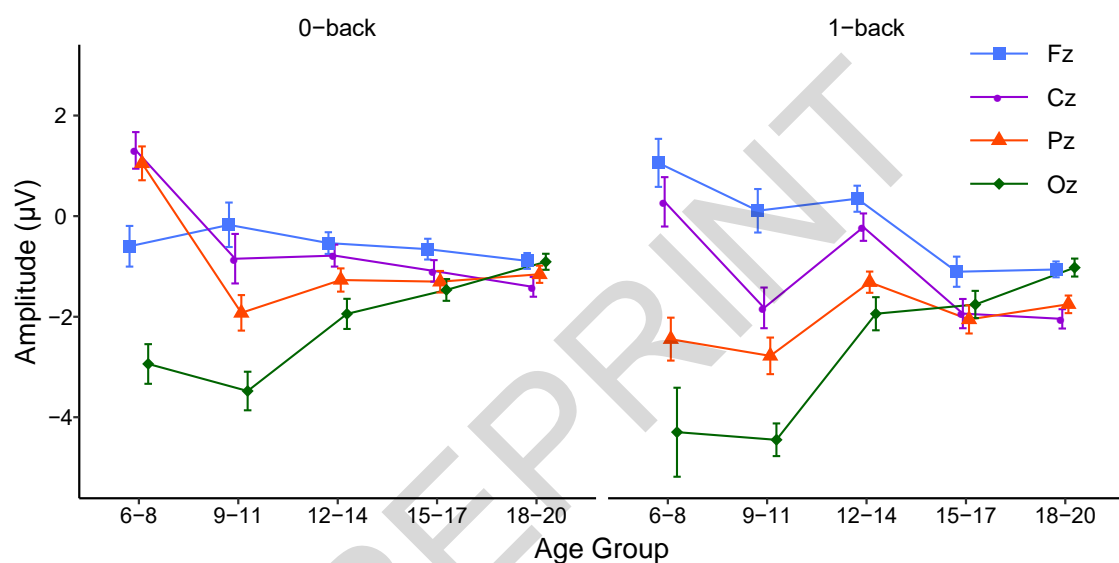


Figure 9. Interactions of age group, channel and load. Note the inversion of polarity of the SW in young children, from positive (in centro-parietal electrodes) to negative (in posterior electrodes) for the 0-back condition. In the 1-back condition, the positive-negative inversion of polarity with age occurs between the fronto-central and parieto-occipital electrode. Error bars represent 1 standard error of the mean.

## Discussion

The goal of the present study was to explore possible age-related differences in behavior and electrophysiological indices of the different phases of WM processing: selection and subsequent matching, updating and maintenance. To this end, we

examined performance and electrophysiological activity in children and adolescents during an  $n$ -back task with two loads (0- and 1-back). The major finding of this study can be summarized as follows: there was an improvement in WM performance with age. All of the groups of children and adolescents showed a negativity contralateral to the selected item that decreased with age. The early P300 amplitudes decreased with age to the same extent for both load conditions, whereas the effect of load on the late P300 amplitude was evident only in the youngest groups. The SW evidenced a decrement of voltage negativity with age in posterior channels, coupled with an opposite trend toward a reduction of positivity in fronto-central-parietal sites.

### **Behavioral results**

The behavioral results showed a decrease in response times and increase in accuracy with age, although these measures showed different trajectories. While response times reached the asymptotic level at about 15-17 years, accuracy increased until 18-20 years. We found that age differences in  $d'$  were more pronounced when updating was required. Thus, age was related to an improvement in accuracy in the updating condition (1-back) over and above the improvement observed in the non-updating condition (0-back). In contrast, response times decreased with age to the same extent in the updating and non-updating conditions. The different pattern for time and accuracy is in line with previous findings comparing 0- and 1-back tasks (e.g., Schleepen & Jonkman, 2009). Overall, these results suggest that factors related to updating speed and accuracy develop with a certain degree of independence. One possible interpretation of the present results for  $d'$ , based on signal detection theory, is that the representation of the target in the 0-back condition would be more precise (less variance) than in the 1-back condition; moreover, this representation would be less precise in younger than in older children, adolescents and young adults (Macmillan &

Creelman, 2004). Neural representations of particular objects have been confirmed through multivoxel pattern analysis and classification techniques (LaRocque, Lewis-Peacock, Drysdale, Oberauer, & Postle, 2013). In this view, the distance between the neural activity of the neural network representing the stored item and the background neural activity of the same neural network would be greater in the 0-back condition than in the 1-back condition; moreover, this distance would increase with age, and/or the variance of the neural representation would be lower (higher precision) in conditions and group of subjects with higher  $d'$ .

### **Recognition and selection processes (N2pc)**

The matching and selection processes were indexed by the N2pc, computed by subtracting the ERPs of contralateral and ipsilateral electrodes relative to the side on which the letter appeared (Luck & Hillyard, 1994). With respect to the type of target, the higher amplitude of the N2pc in the target condition could be related to the fact that, in this condition, there was matching between the template and the current stimulus, which permits continuation of the selection process, while in the non-target condition the non-matching between the template and the presented letter interrupts selection and further processing. In fact, a negative response when comparing two shapes can occur due to a disparity in any part of the images, while successfully matching two shapes requires an exhaustive comparison. Thus, the contralateral negativity in the non-targets could reflect that a letter has been detected, indicating sensitivity to the task-relevant stimulus category (i.e., letters). Letter processing would be enhanced for target stimuli, resulting in a larger N2pc (Kappenman & Luck, 2012).

With regard to age differences, one relevant result is that an N2pc was observed for all age groups, indicating that selection and matching processes are operational even in young children. Furthermore, a trend for decreasing contralateral negativity with age

was observed. This reduction in contralateral negativity may be driven by the same factors that determine the general decrease of ERP amplitude with age (Itier & Taylor, 2004; van Dinteren, Arns, Jongasma, & Kessels, 2014). However, it is also possible that children must exert more attentional effort to select the letter stimulus and match it with the item maintained in WM, as suggested by the lower  $d'$  seen in younger children, which indicates a lower precision (the inverse of variance) of the stored item representation.

The results indicate that the same selection mechanism present in young adults is already in place in children as young as 6-8 years. The present findings add to previous studies that demonstrated the presence of the N2pc in children using different WM tasks. Shimi et al. (2014, 2015) showed that 10-11 year-old children elicited contralateral negativity in a visual working memory task, and Barriga-Paulino et al., (2015a) observed a similar negativity in 6-7 year-old children using a DMTS task. In an attentional visual search task, Couperus and Quirk, (2015) reported the presence of the N2pc in children aged 9-12 years.

### **Updating (P300)**

In this study, the P300 amplitudes were larger for the 1- versus 0-back condition, possibly due to the higher difficulty of the 1-back task, including the updating process (which never occurs in the 0-back condition because the template is always the same; Chen et al., 2008; López Zunini et al., 2016; Morrison et al., 2019; Saliassi et al., 2013). This effect was of short duration; it was significant for the early P300, whereas for the late P300 it was only evident in the youngest groups.

The late P300 component presented the same topography and statistical results than the early P300 (except for load level), suggesting that the late P300 corresponds to the decay phase of the early P300. In the late P300, there was an interaction between

load and age group, indicative of a higher burden for children in the younger age group when processing the stimuli in the 1- versus 0-back condition, in comparison to the adolescent and young adult groups. This interaction could be also due to the greater allocation of resources required for young children to update information in WM. This latter effect can also be interpreted as a longer-duration load effect in the younger children that would give rise to the need for a longer-duration updating process, which in the 1-back is always required to render the “prioritized representation” of the item presented in the previous trial as the focus of attention, and to transfer the current stimulus (as a “prioritized representation”) for recovery at the end of the next trial (LaRocque et al., 2013).

A general decline in P300 amplitudes with age, across childhood and adolescence, was found for both the early and late P300 (Ruhnau et al. 2010). The decrease in P300 amplitude is consistent with the pattern reported for other tasks that elicit the P3b, such as visual oddball tasks (see Gómez et al., 2018; Polich, 2012; van Dinteren et al., 2014 for reviews), and also for the *n*-back task (Myatchin & Lagae, 2013).

Age effects were also evident in the spatial distribution of the P300. Specifically, the focus of the P300 component changed from Oz to Pz with age; moreover, this change was slightly more pronounced in the target than in the non-target condition, but only for the older groups. The change in P300 topography with age, from occipital to parietal sites, has been previously described (Flores, et al., 2010; Polich, Ladish & Bruns, 1990; Taylor, 1998).

### **Maintenance (SW)**

A SW appeared during the maintenance period, in line with previous results obtained in adults using *n*-back tasks (Bailey et al., 2016). According to Bailey, the SW

activity in the  $n$ -back task is related to the maintenance of information between trials in the 1-back task, a result that can be extended to the 0-back condition based on the present results, given that the signaled target (the X letter) must also be active in the focus of attention during the maintenance period. However, it is still possible that, in part, the SW represents the neural index of a more general activation (due to general arousal or general preparatory attention for the next trial); this cannot be ruled out in the context of the present experimental design. Vilà-Balló et al. (2018) demonstrated that SW amplitude is specifically related to response time in a 1-back, but not in a 3-back, task. Barriga-Paulino et al., (2014) also reported a relationship between the amplitude of the SW and WM performance (RTs and errors) in a DTMS task performed by children and adolescents. This leads us to suggest that the SW in this study is probably related to continuous neural activity that holds the stored item in WM. This concept would be applicable to both the 0- and 1-back tasks, given that the SW pattern is roughly similar between them.

The SW was observed in all age groups, which indicates that this neurophysiological signal is already present at the age of 6-8 years. We found an interaction between channel and age group due to the change from positivity to negativity in fronto-central-parietal electrodes with age, while in the posterior electrodes there was a reduction in negativity with age. These results fit well with the SW topographical changes described in children and adolescents using DMTS tasks (Barriga-Paulino et al., 2014, 2015a, 2015b and 2017), and extend the previous results on the SW from the DMTS to the  $n$ -back task. Barriga-Paulino et al. (2017) attributed the negative reduction in posterior areas mainly to the elimination of synaptic connections between neurons with age. In contrast, the reduction in positivity in fronto-central areas could be caused by different factors, such as synaptic pruning, but also to

the reorganization of cortical layers with development. As a functional interpretation of the fronto-central-parietal polarity inversion of the SW with maturation, in order to maintain the items in WM, younger children may rely on posterior brain areas to a greater extent due to the immaturity of their frontal lobes, whereas adolescents are more able to recruit the anterior regions (see Barriga-Paulino et al., 2014). The maturation of anterior areas, demonstrated by the polarity inversion of SW, would be coincident with the WM performance improvement. No load effects were observed for the SW, possibly because both the 1-back and 0-back signals during the retention period should be the focus of attention in WM (Cowan, 1999; Oberauer, 2009). Recently, based on results from multipattern voxel analysis and classification techniques, it has been suggested that WM retention is not necessarily linked to sustained activities, as suggested by the contralateral delay activity (CDA) and SW; however, this result seems to be more associated with the so-called “prioritized representations” rather than with the representations in the focus of attention, which can be identified through classification techniques (LaRocque et al., 2013; Lewis-Peacock, Drysdale, Oberauer, & Postle, 2012). Therefore, the SW reported here would possibly be related to the activation of the item necessary for the recognition process in next trial, in both the 1-back and 0-back conditions in the focus of attention during the intertrial period.

It is reasonable to assume that the processes involved in the  $n$ -back task are performed serially; for example, the letter has to be selected first, compared with the information held in memory, and then updated. Therefore, a cascading effect may occur, in which processing differences in the first stages influence subsequent processing. For instance, a less defined representation after the selection step would require the most neural resources in subsequent steps. Similarly, the need for more resources for updating may induce a higher-amplitude early P300, which may leak into

later time windows (e.g., the corresponding to the late P300). Therefore, the age-related differences observed in the ERP components considered in the present study are compatible with such a cascading effect, and may reflect the contribution of both the processing performed in previous stages and the actual processes engaged in.

### **Conclusions**

There was an improvement in WM performance with age. All ERP components decrease in amplitude with age, which could be related to synaptic pruning (Huttenlocher, 1990). The selection-matching process of the WM item presented on the screen was indexed by an N2pc component. N2pc was already present in the youngest group of children, suggesting a similar mechanism underlying the selection process for the youngest children and the young adults. The updating process was indexed by the P300, with young children allocating more resources to modify WM representations, as demonstrated by load differences in the late P300. The maintenance phase was indexed by an SW. This SW inverted polarity with age in the youngest children in fronto-central-parietal sites, suggesting an immaturity of anterior and central brain areas in these children. Interestingly, the SW seems to be homologous to the SW previously described in the DMTS task (Gómez et al., 2018), interpreted as the macroscopic counterpart of the sustained activity of single neurons in WM tasks (Fuster & Jervey, 1981).

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PREPRINT

**Supplementary material**

## Supplementary Table 1

Post-hoc contrasts with Bonferroni adjustment for multiple comparisons of mean RTs of the different age groups

Contrast	estimate	<i>SE</i>	<i>t</i> (138)	<i>p</i>	<i>d</i>
6-8 - 9-11	185.21	32.47	5.70	<.0001	1.68
6-8 - 12-14	303.30	30.10	10.08	<.0001	2.75
6-8 - 15-17	442.25	30.10	14.69	<.0001	4.02
6-8 - 18-20	426.45	29.91	14.26	<.0001	3.87
9-11 - 12-14	118.10	30.10	3.92	.001	1.07
9-11 - 15-17	257.04	30.10	8.54	<.0001	2.33
9-11 - 18-20	241.24	29.91	8.07	<.0001	2.19
12-14 - 15-17	138.95	27.53	5.05	<.0001	1.26
12-14 - 18-20	123.15	27.32	4.51	<.001	1.12
15-17 - 18-20	-15.80	27.32	-0.58	1.0	-0.14

Supplementary Table 2

Post-hoc contrasts with Bonferroni adjustment for multiple comparisons of 0- and 1-back  $d'$  means of each age group

Contrast	0-back					1-back				
	estimate	<i>SE</i>	<i>t</i> (138)	<i>p</i>	<i>d</i>	estimate	<i>SE</i>	<i>t</i> (138)	<i>p</i>	<i>d</i>
6-8 - 9-11	-0.49	0.20	-2.45	.155	-0.72	-0.83	0.23	-3.60	.004	-1.06
6-8 - 12-14	-0.72	0.19	-3.86	.002	-1.06	-1.04	0.21	-4.87	<.0001	-1.33
6-8 - 15-17	-0.95	0.19	-5.10	<.0001	-1.39	-1.56	0.21	-7.31	<.0001	-2.00
6-8 - 18-20	-1.05	0.19	-5.68	<.0001	-1.54	-1.83	0.21	-8.63	<.0001	-2.34
9-11 - 12-14	-0.23	0.19	-1.22	1.0	-0.33	-0.21	0.21	-0.99	1.0	-0.27
9-11 - 15-17	-0.46	0.19	-2.46	.153	-0.67	-0.73	0.21	-3.43	.008	-0.94
9-11 - 18-20	-0.56	0.19	-3.02	.031	-0.82	-1.00	0.21	-4.72	<.001	-1.28
12-14 - 15-17	-0.23	0.17	-1.35	1.0	-0.34	-0.52	0.20	-2.67	.085	-0.67
12-14 - 18-20	-0.33	0.17	-1.96	.525	-0.49	-0.79	0.19	-4.08	<.001	-1.01
15-17 - 18-20	-0.10	0.17	-0.59	1.0	-0.15	-0.27	0.19	-1.39	1.0	-0.34

## Supplementary Table 3

Post-hoc contrasts with Bonferroni adjustment for multiple comparisons of N2pc amplitude differences in P7/P8 for each age group

Contrast	estimate	SE	<i>t</i> (138)	<i>p</i>	<i>d</i>
6-8 - 9-11	-0.46	0.32	-1.46	1.0	-0.43
6-8 - 12-14	-0.57	0.29	-1.94	.542	-0.53
6-8 - 15-17	-0.87	0.29	-2.97	.035	-0.81
6-8 - 18-20	-0.81	0.29	-2.78	.062	-0.76
9-11 - 12-14	-0.11	0.29	-0.37	1.0	-0.10
9-11 - 15-17	-0.41	0.29	-1.40	1.0	-0.38
9-11 - 18-20	-0.35	0.29	-1.20	1.0	-0.33
12-14 - 15-17	-0.30	0.27	-1.12	1.0	-0.28
12-14 - 18-20	-0.24	0.27	-0.91	1.0	-0.22
15-17 - 18-20	0.06	0.27	0.22	1.0	0.06

## Supplementary Table 4

Post-hoc contrasts with Bonferroni adjustment for multiple comparisons of the early P300 amplitude for each age group

Contrast	estimate	<i>SE</i>	<i>t</i> (138)	<i>p</i>	<i>d</i>
6-8 - 9-11	2.05	1.42	1.44	1.0	0.42
6-8 - 12-14	5.46	1.32	4.15	.001	1.13
6-8 - 15-17	5.59	1.32	4.24	<.0001	1.16
6-8 - 18-20	6.74	1.31	5.16	<.0001	1.40
9-11 - 12-14	3.41	1.32	2.59	.105	0.71
9-11 - 15-17	3.54	1.32	2.69	.080	0.74
9-11 - 18-20	4.70	1.31	3.59	.005	0.98
12-14 - 15-17	0.13	1.20	0.11	1.0	0.03
12-14 - 18-20	1.28	1.19	1.07	1.0	0.27
15-17 - 18-20	1.16	1.19	0.97	1.0	0.24

## Supplementary Table 5

Post-hoc contrasts with Bonferroni adjustment for multiple comparisons of the late

P300 amplitude for each age group

Contrast	estimate	<i>SE</i>	<i>t</i> (138)	<i>p</i>	<i>d</i>
6-8 - 9-11	1.75	1.01	1.74	.846	0.51
6-8 - 12-14	4.57	0.94	4.88	<.0001	1.34
6-8 - 15-17	4.94	0.94	5.28	<.0001	1.44
6-8 - 18-20	4.93	0.93	5.30	<.0001	1.44
9-11 - 12-14	2.82	0.94	3.01	.031	0.82
9-11 - 15-17	3.18	0.94	3.40	.009	0.93
9-11 - 18-20	3.18	0.93	3.42	.008	0.93
12-14 - 15-17	0.37	0.86	0.43	1.0	0.11
12-14 - 18-20	0.36	0.85	0.42	1.0	0.11
15-17 - 18-20	-0.01	0.85	-0.01	1.0	0.00

## Supplementary Table 6

Post-hoc contrasts with Bonferroni adjustment for multiple comparisons of the difference in late P300 amplitude between both levels of load for each age group

Contrast	estimate	<i>SE</i>	<i>t</i> (138)	<i>p</i>	<i>d</i>
6-8 - 9-11	3.54	.732	4.84	<.0001	1.43
6-8 - 12-14	4.80	.679	7.08	<.0001	1.93
6-8 - 15-17	4.82	.679	7.09	<.0001	1.94
6-8 - 18-20	5.06	.675	7.51	<.0001	2.04
9-11 - 12-14	1.26	.679	1.86	.658	0.51
9-11 - 15-17	1.27	.679	1.87	.632	0.51
9-11 - 18-20	1.52	.675	2.25	.259	0.61
12-14 - 15-17	0.01	.621	0.02	1.0	0.01
12-14 - 18-20	0.26	.616	0.42	1.0	0.10
15-17 - 18-20	0.25	.616	0.40	1.0	0.10