The development of non-spatial working memory capacity during childhood and adolescence and the role of interference control: an N-Back task study.

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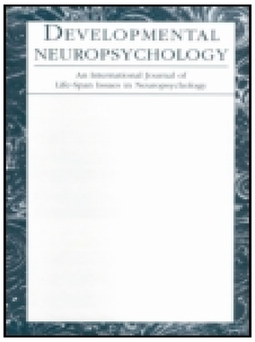

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The Development of Non-Spatial Working Memory Capacity During Childhood and Adolescence and the Role of Interference Control: An N-Back Task Study

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To investigate the role of interference control on the development of working memory (WM) capacity, 6–12-year-old children and adults performed an N-Back task with differing WM-load and interference control demands. Correlation analyses between flanker interference scores and WM-load levels showed that interference control was only required in the 2-back condition. While WM maintenance (1-back task) reached adult accuracy levels at age 10–12, the ability to maintain information in WM during distraction (2-back-task) displayed protracted maturation into adolescence. This is suggested to reflect yet immature connections between prefrontal and posterior association areas, respectively involved in interference control and WM storage.

The ability to maintain and manipulate information in working memory (WM) allows us to perform well in a variety of cognitive tasks and to function effectively in everyday life. In children as well, effective use of this capability is important for successful cognitive development and academic achievement, since WM capacity plays an important role in learning of complex cognitive skills, like language, mathematics, or reasoning (Pickering, 2006).

According to the influential WM model of Baddeley and Hitch (1974), WM consists of a central executive that acts as a supervisory system and is closely linked to two domain-specific buffers, respectively involved in the processing and short-term storage of nonspatial (verbal) or spatial information (Baddeley, 1992). Research has consistently shown that maintenance and manipulation of information in these respective systems is more difficult for children than for adults (Gathercole 1998, 1999). However, there is inconsistency in the ages at which mature WM function is reported in different studies. Such inconsistencies might be explained by the large differences in experimental tasks that are used to determine WM ability. For instance, different developmental trajectories have been reported for spatial or non-spatial WM (Isaacs & Vargha-Khadem, 1989; Nichelli, Bulgheroni, & Riva, 2001; Pickering, Gathercole, Hall, & Loyd, 2001; Van Leijenhorst, Crone, & Van der Molen, 2007). Furthermore, in many WM tasks used in the developmental literature, participants are required to perform activities that depend upon abilities (e.g., reading or arithmetic skills) that also undergo important development during childhood, and

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thus might confound WM results (Towse, Hitch, & Hutton, 2002). Reliance on such higher-order skills also complicates inclusion of younger children that do not yet master them. Finally, different developmental trajectories have been reported for performance in simple span (Riggs, McTaggert, Simpson, & Freeman, 2006) and more complex WM tasks that, besides maintenance, also require manipulation of to-be- stored information.

More specifically, while performance in simple span tasks has been shown to reach maturity during childhood, complex WM skills show protracted development into adolescence (for review see Bunge & Wright, 2007). Recent developmental neuro-imaging studies have shown that such delayed development goes along with immaturity in frontal-parietal networks that underlie mature complex WM skills. Crone, Wendelken, Donohue, Van Leijenhorst, and Bunge (2006) showed that only in a complex WM task requiring manipulation, 8–12-year-old children showed immature performance and failed to activate the same WM-related brain areas as adults (e.g., the Dorsolateral Prefrontal Cortex (DLPFC) and superior parietal cortex). In a study by Scherf, Sweeney, and Luna (2006) this reliance of children (10–13 years) on ventromedial prefrontal cortex, instead of on core WM regions such as DLPFC and parietal cortex, was confirmed in a visuospatial WM task. Interestingly, comparable fronto-parietal networks have been implicated in late development of executive control processes, such as response inhibition or interference control, that also continues into adolescence (Bunge & Wright, 2007; Casey et al., 1995; Diamond, 2002; Huizinga, Dolan, & Van der Molen, 2006; Luna & Sweeney, 2004; Kanemura, Aihara, Aoki, Araki, & Nakawaza, 2003; Sowell et al., 1999). This raises the important question of how much the development of complex WM skills depend on immaturity of executive control processes. Surprisingly, to our knowledge, the development of such specific WM-executive control interactions has not yet been directly studied. The aim of the present study is to investigate the role of one specific executive control process, namely interference control, on the development of WM capacity.

The present study focuses specifically on interference control because several lines of research have shown that the ability to suppress or ignore distracting information while holding information in memory plays an important role in the determination of one's WM capacity or the success of recall in WM tasks (De Fockert, Rees, Frith, & Lavie, 2001; Lavie, Hirst, De Fockert, & Viding, 2004; McNab & Klingberg, 2008; Sakai, Rowe, & Passingham, 2002). Furthermore, multiple studies have shown that individuals with low WM-capacity are more prone to distraction in attention tasks or display more attention problems. This has been demonstrated for adults (Kane & Engle, 2003) as well as children . These results all demonstrate that interference control and WM capacity are highly dependent on each other, as is supported by their reliance on overlapping brain circuitry, including lateral prefrontal cortex (PFC) (Chao & Knight, 1995; D'Esposito, Postle, Jonides, & Smith, 1999; Postle, 2005).

An experimental task that seems suitable to investigate the role of interference control ability on the development of WM capacity in simple and complex WM tasks, is the N-Back task. In this task, WM load is parametrically varied such that the effect of load on reaction time (RT) and accuracy rates can be parceled out. In a typical N-Back task, sequences of items (either spatial or non-spatial) are shown and participants are instructed to respond to items that are identical to the item presented one, two or more trials back in the sequence. Because this task requires to keep in mind the *n*th-item back in the sequence, a greater information load has to be stored in WM with increasing N-Back load. Furthermore, previous work suggests that with increasing *n* in the N-Back task, increased demands are posed on executive control processes. Smith and Jonides (1997) compared positron emission tomography (PET) activations in 0, 1, 2, and 3-back conditions in a verbal task and showed that the number of activated brain areas increased with *n*, but DLPFC only became involved in the task starting from the 2-back condition. Because of reported links between DLPFC activation and executive control processes (e.g., D'Esposito et al., 1995; Diamond, 2002), this finding implies that executive control is particularly involved, or at least more involved, in 2-(or higher) back conditions, when compared to 1-back. Supportive evidence for the involvement of interference control processes in 2-back tasks comes from a developmental functional magnetic resonance imaging (fMRI) study of Ciesielski, Lesnik, Savoy, Grant, and Ahlfors (2006). In this study, a correlation of $r = .50$ between performance in a categorical 2-back task and a Stroop task was reported. However, no comparison was made between 0, 1, and 2-back levels, so that it was not demonstrated that this correlation was specific for the 2-back condition.

Thus, the N-Back task seems very well suited to on the one hand study the development of WM capacity by parametrically varying load, while on the other hand determining how demands on executive control functions influence such patterns. Nevertheless, to our knowledge, there are only a few studies that have used the N-Back task to study the development of working memory (Vuontela et al., 2003; Kwon, Reiss, & Menon, 2002). These studies only used visuospatial tasks and did not report on developmental differences between 1 and 2-back tasks that both require maintenance but differ in executive control demands (see Smith & Jonides, 1997). Furthermore, Vuontela et al. (2003) did not include an adult age group, missing potential continued development during adolescence, an important period for executive control development (Luna & Sweeney, 2004). One recent developmental study by Conklin, Luciana, Hooper, and Yarger (2007), did examine the role of distinct executive processing requirements on WM development in children and adolescents (9–17 years). Delayed development of verbal and nonverbal WM performance was reported when the tasks required high-executive control. However, in this study WM tasks mutually varied in nature and type of required executive control. Parametric manipulation of WM-capacity (Load) and interference control within one task is important to exclude the influence of other (perceptual or motor) task demands on developmental patterns.

THE PRESENT STUDY

In sum, developmental studies of non-spatial WM employing the N-Back task are scarce and only one study included children, adolescents and adults (but starting from age 9). Furthermore, no study so far directly investigated the impact of differences in required executive control on the development of WM performance in tasks in which WM-capacity (load) is parametrically varied. The present study aims to fill this void by investigating the development of WM-capacity and interference control interactions from young childhood to adulthood, by comparing performance across N-Back load levels that differ in executive control. The current study will use a verbal version of the N-Back task (consisting of 0, 1 and 2 back conditions) because, besides that relatively little is known about age-related changes in verbal N-Back task performance, proof for the involvement of executive control in 2-back and higher came from a similar verbal task (Smith & Jonides, 1997).

It is hypothesized that performance in the 2-back condition (demanding high levels of executive control) will show protracted maturation into adolescence, since the development of executive control is known to depend heavily on the development of prefrontal cortex which is not anatomically and functionally mature until late adolescence (Giedd et al., 1999; Gogtay et al., 2004;

Pandya & Barnes, 1987). In contrast, performance in the 1-back task, requiring mainly maintenance of information in WM, is hypothesized to reach maturity before adolescence. To confirm the (enhanced) involvement of executive control processes particularly in the 2-back task, all subjects also performed a flanker task (Eriksen & Eriksen, 1974) that measures the executive process of interference control. Interference control is thought to be involved in the 2-back task since, at each trial, subjects have to update WM with a new letter while in the mean time suppressing the influence of this letter on the current response decision. It is hypothesized that in case of (higher) involvement of interference control processes in the 2-back task, there will be a positive correlation between the size of RT-interference effects in the flanker task and the size of performance decrements in the 2-back (vs. the 1-back) task.

METHOD

Subjects

Three groups of children (*N* = 57) and one group of adults (*N* = 21) participated in the present study. Demographic information (age, gender, IQ scores, socioeconomic status (SES), attention

TABLE 1
Demographic Characteristics per Age Group

	Age Group			
Variable	*6–7*	*8–9*	*10–12*	*Adults (19–28) years*
N	19	21	17	21
Gender (% female)	47	48	65	52
Age (in years)				
M	7	9	11.2	21.7
SD	0.52	0.62	0.81	2.70
Attention score[a]				
M	52.8	55.8	53.8	52.2
SD	5.5	5.8	5.3	5.0
range	50–70	50–67	50–66	43–60
Estimated IQ[b]				
M	111.7	104.9	102.9	117.1
SD	10.2	12.2	12.4	10.4
range	91–132	88–132	80–123	100–143
SES[c]				
M	5.4	5.6	5.4	—
SD	1.7	1.5	1.4	—

[a] None of the participants scored within the clinical range of attention problems on the Child Behavior Checklist (children) or self report form of the ADD-H Comprehensive Teacher's Rating Scale (ACTeRS) (adults). [b] IQ scores differed significantly between the groups, $F(3,74) = 6.43, p < .01$. Bonferroni-corrected post hoc comparisons revealed that both 8–9 and 10–12-year-olds differed significantly from the group of adults ($p < .01$). Therefore, all analyses were performed with IQ as covariate, which revealed no altered significant levels and thus all further analyses were performed without IQ as covariate. [b] Socioeconomic status (SES) was determined by Hollingshead (1975) occupational scale for the parent holding the higher status job (1 or 2 = unskilled or unemployed positions, 3 or 4 = skilled or semiskilled laborers, 5 or 6 = managerial professions, 8 or 9 = major professions). Parental occupation data were not available for one child in the group of 6–7- and two children in the group of 8–9-year-olds. SES was not available for adults, but all adults were university students.

scores, and group size) for all groups is shown in Table 1. The choice of age groups is based on previous studies showing important developmental transitions in either inhibition or interference control during these age periods (Jongen & Jonkman, 2008; Jonkman, 2006).

Exclusion criteria for both children and adults were (1) presence of neurological or psychiatric disorders, (2) medication use, (3) a score in the clinical range on relevant attention rating scales (see measures paragraph below), and (4) an IQ below 80. One child in the 10–12-years-old group was excluded from the study because of scores more than 3 standard deviations from the mean for both hit and false alarm percentages. All children were recruited from two different local primary schools and received a present for participation. Adults were university students of Maastricht University and received either course credit or were paid for participation. Written informed consent was obtained from both the adult subjects and the parents of the children. The study was approved by a local ethical committee at the Faculty of Psychology and Neuroscience, Maastricht University.

Measures

Attention rating scales. Whereas one of the exclusion criteria was a clinical diagnosis of attention deficit hyperactivity disorder (ADHD), all children and adults were additionally screened for attention deficits. In the case of children parents were asked to fill out the Child Behavior Checklist (CBCL—4–18 years; Achenbach, 1991). Adults were screened for the presence of inattention symptoms by filling out the self-report form of the ADD-H Comprehensive Teacher's Rating Scale (ACTeRS) (Ullman, Sleator, & Sprague, 1991). This self-report form consists of 35 items, of which 10 items form the attention-subscale. For the CBCL, T-scores between 67–70 are considered as borderline-clinical and a T-score > 70 is considered a clinical score. Two children scored within the subclinical range (i.e., one in the 6–7 and one in the 8–9 group). However, these children were not excluded from the present study because their performance in the N-Back task was not deviating from that of the mean group. The ACTeRs raw scores are converted to gender neutral percentile ranks and T-scores, with a lower score indicating enhanced problem behavior; a T-score of 46 or higher on the Attention subscale indicates a score within the 70% range of the population scores (according to the manual, subjects diagnosed with ADHD scored in the top 10% of the population range, corresponding to a T-score below 41 on this scale).

Intelligence. In order to asses IQ, subjects were administered two subtests (i.e., vocabulary and block design) of the Wechsler Intelligence Scale for Children (WISC–III, Dutch version) and the Wechsler Adult Intelligence Scale (WAIS–III, Dutch version). The estimated IQ score on basis of these two subtests has a mean reliability and validity of .9 (Jeyakumar, Warriner, Raval, & Ahmad, 2004; Spreen & Strauss, 1998), when compared to the IQ derived after completion of the full test.

Experimental Computer Tasks

N-Back task. In the present study a letter version of the N-Back task was used in which semi-random sequences of letters (A, B, F, G, H, K, L, S, T, W, X, Z) appeared one at a time at the centre of the screen (see Figure 1). The letters (height: 1 cm, width: 0.5 cm) were green and presented between two white vertical bars (height: 1.5 cm) on a black background. Subjects were seated at a distance of approximately 50 cm in front of a 17 inch VGA monitor. Stimulus presenta-

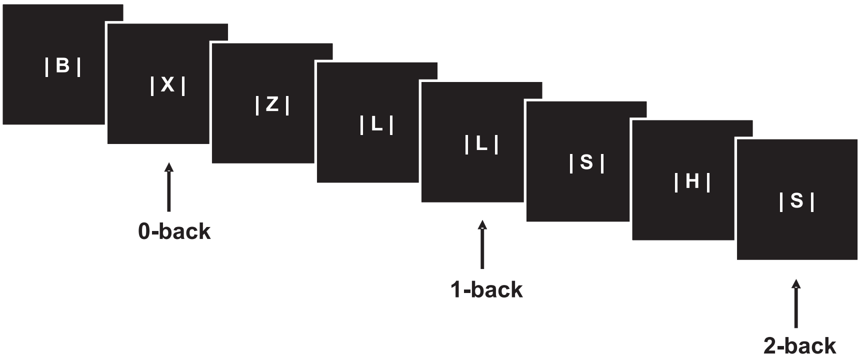

FIGURE 1 Illustration of the N-Back task with examples of 0-, 1-, and 2-back conditions.

tion and acquisition was controlled by ERTS-software. The N-Back task consisted of 0-, 1-, and 2-back conditions. Participants were instructed to press a response button with their right index finger, whenever they detected a target event. In 1- and 2-back conditions a target was defined as a letter that was identical to the letter presented 1 (e.g., T-T) or 2 (e.g., A-B-A) trials back in the sequence. In the 0-back condition, the target event was the appearance of the letter “X.”

The task consisted of a total number of 360 trials, which were presented in six blocks of 60 stimuli, two blocks per condition (0-, 1-, 2-back). The order of block presentation was randomized with the restriction that each condition was presented within the first three blocks. There were 3 versions of the task differing in the order of presentation of 0-, 1-, and 2-back conditions; *version 1*: 0, 2, 1 – 2, 1, 0 (back), *version 2:* 0, 1, 2 – 1, 0, 2 (back) and *version 3:* 2, 0, 1 – 1, 2, 0 (back). Versions were presented in a counterbalanced order between participants, within groups. To test whether there were differences in performance between groups due to order of task presentation, this variable was included as a covariate in all analyses and did not change results. All task blocks had a similar target frequency of 33.3%, they only differed with respect to the appearance of the letter X in the 0-back being 33.3%, but not in the other two conditions. Each trial lasted 2,000 msec with a stimulus duration of 500 msec and a fixed interstimulus-interval (ISI) of 1,500 msec.

Flanker task. A letter version of the flanker task was used to provide a measure of response interference effects (Eriksen & Eriksen, 1974). Subjects were presented with stimuli consisting of arrays of three letters (e.g., B B B) that were presented in the middle of the computer screen. The task instruction was to press a button in response to a centrally presented target letter, while ignoring the two flanking letters. The target letters B and H were associated with a right index finger response and the target letters F or T with a left index finger response (this was counterbalanced between subjects, within groups). The two flanking letters were presented at the left and the right of the central target letter and were always identical to each other. Response interference effects were determined by the difference in reaction time (RT) between congruent trials (i.e., the target letter was similar to the flanking letters; e.g., F F F) and incongruent trials (the target letter was surrounded by different letters that activate a response that is in conflict with the target response). A total of 320 trials were presented in four blocks consisting of 80 trials. Each trial lasted 2,500 msec, with a stimulus duration of 1,000 msec and an inter-stimulus interval of 1,500 msec.

Procedure

Adults were tested in one experimental session that lasted approximately 3 h. After informed consent was obtained from adults, they filled in the ACTeRS self-report form. The N-Back task was administered as the last task in a series of tasks that were part of a larger developmental study that included measurement of EEG, from which the data will be presented elsewhere. One of the tasks that was used in these EEG measurements was the Flanker task. The complete behavioral and ERP results of this task go beyond the present study aims and will be presented elsewhere. For the purpose of verifying whether interference control was particularly involved in the 2-back condition, in the present study only part of the behavioral (RT) data from the flanker task were used for the correlation analyses (see following section). Before the N-Back task, a digit span backward, adapted from the WISC–III, Dutch version (Wechsler, 1991) and the two IQ subtests were administered. The digit-span backward raw scores were collected as additional individual measures of "complex" WM capacity (requiring maintenance and manipulation skills; see following section for how this score was used in the correlation analyses). Children were administered the same tasks as adults, but they were tested in two separate experimental sessions in a quiet room at their school. While the EEG tasks were administered during the first session (lasting about 2 h), children had to complete the behavorial tasks (including the N-back task) during the second session (lasting about 1 h).

All experimental tasks were practiced until participants reached a predetermined performance criterion (75% correct responses). This criterion was used to verify that participants were able to perform the task above chance level before the experimental task was started. In the practice task of the N-Back task, subjects practiced each of the three conditions (0-, 1-, and 2-back) that were administered in three blocks of 25 trials each. During these practice blocks, each trial was provided with feedback: *correct* in case participants correctly identified the target, *false* whenever participants responded to a non-target, and *forgotten* when participants did not react before the end of the trial. In the experimental task, no feedback was provided anymore.

Data Analysis

Mean reaction times to correctly identified targets (RT), mean percentage of correctly identified targets (hit %), mean percentage of false alarms (defined as responses to non-targets) and the signal-detection parameter d-prime (*d'*) were computed in 0-, 1-, and 2-back conditions. To test for developmental trends in performance in the N-Back task depending on WM load, repeated measures analysis of variance was performed entering the between subjects factor Group (4 groups, children aged 6–7, 8–9, 10–12, and adults) and the within subjects factor WM load (0-, 1-, and 2-back). Separate analyses were performed for the dependent variables RT, % hits, % false alarms, and *d'*. Whenever a significant Group (4) × Load (3) interaction was found, two planned ANOVAs with a factor Group (4 groups) and Load (now consisting of two load levels) were carried out to examine developmental differences in Load effects separately for 0- versus 1-back and 1- versus 2-back. In case of significant Group × Load 0 versus 1-back or Group × Load 1 versus 2-back interactions, further post-hoc group comparisons were performed.

In addition to the ANOVA tests and post-hoc between group comparisons, polynomial contrast analysis was performed including the Group factor to study developmental trends in the data across all four age groups in 0-, 1-, and 2-back conditions. Because the present study included four age groups, linear, quadratic, and cubic trends were explored for all N-Back levels and for the separate dependent measures. A significant linear trend would indicate a linear increase of performance across age, whereas significant quadratic and cubic contrasts would signify nonlinear developmental patterns. For all statistical analyses a two-tailed significance level of $p < .05$ was adopted.

To asses the assumed differential involvement of interference control processes in the different N-Back conditions, the % hit difference in 0- versus 1- and 1- versus 2-back conditions was correlated with RT-interference effects as obtained in the flanker task. To investigate the involvement of WM maintenance and manipulation processes in the different N-Back task conditions, correlations were also computed between the individual raw scores on the digit span backward task and the accuracy (hit %) decrement in 0- versus 1- and 1- versus 2-back tasks.

RESULTS

Mean RT, % hits, % false alarms, and *d'* (and *SD*s) in 0-, 1-, and 2-back conditions are presented in Table 2. To enhance readability of the results section, statistical (*F* and *p*) values for Group × Load interactions as well as for post-hoc group comparisons are shown in Table 3.

TABLE 2
Mean Reaction Times (RT), Mean Percentage of Hits, Mean Percentage of False Alarms and Mean d-prime (d') Scores (Standard Deviations in Parentheses) per N-Back Load per Age Group

	WM-Load		
	0	*1*	*2*
RT (msec)			
6–7	613 (94)	816 (172)	865 (151)
8–9	539 (91)	675 (147)	787 (154)
10–12	469 (71)	541 (93)	650 (157)
adults	392 (49)	428 (63)	514 (112)
Hits (%)			
6–7	98 (3.0)	83 (10.5)	55 (20.4)
8–9	99 (1.8)	90 (7.2)	63 (12.9)
10–12	100 (1.3)	98 (1.9)	80 (12.4)
adults	100 (0.5)	96 (3.9)	92 (6.4)
False alarms (%)			
6–7	6.05 (5.55)	14.1 (15.8)	22.6 (19.2)
8–9	3.21 (3.38)	5.48 (3.76)	15.6 (6.80)
10–12	2.50 (2.50)	5.29 (4.83)	16.2 (7.34)
adults	0.95 (1.47)	0.71 (2.26)	5.2 (5.2)
Memory recognition: *d'*			
6–7	4.18 (.70)	2.67 (.73)	1.34 (.65)
8–9	4.75 (.46)	3.4 (.53)	1.68 (.39)
10–12	4.83 (.47)	4.28 (.60)	2.33 (.58)
adults	5.1 (.25)	4.42 (.43)	3.64 (.86)

WM = working memory.

TABLE 3
Statistical (F and p) Values for Group × Load Interactions, and for Post-Hoc Group Comparisons

	Group × Load 0-1-2 (back)	*Group × Load 0-1 (back)*	*Group × Load 1-2 (back)*
RT (msec)	$F(6,148) = 6.3, p < .0001, \eta^2_{p} = .20$	$F(3,74) = 16.3, p < .00001, \eta^2_{p} = .39$	ns.
Hits (%)	$F(6,148) = 23.9, p < .00001, \eta^2_{p} = .49$	$F(3,74) = 17.1, p < .00001, \eta^2_{p} = .41$	$F(3,74) = 18.6, p < .00001, \eta^2_{p} = .43$
False alarms (%)	$F(6,148) = 4.3, p < .01, \eta^2_{p} = .15$	$F(3,74) = 4.9, p < .005, \eta^2_{p} = .17$	ns.
Memory recognition: *d*‘	$F(6,148) = 15.9, p < .00001, \eta^2_{p} = .39$	$F(3,74) = 11.7, p < .00001, \eta^2_{p} = .32$	$F(3,74) = 11.4, p < .00001, \eta^2_{p} = .32$
		Age Group	
	6–7	*8–9*	*10–12*
RT (msec) 0–1 back			
8–9	ns.*	—	$F(1,36) = 6.4, p < .05, \eta^2_{p} = .15$
10–12	$F(1,34) = 19.5, p < .0001, \eta^2_{p} = .37$	$F(1,36) = 6.4, p < .05, \eta^2_{p} = .15$	—
adults	$F(1,38) = 39.7, p < .00001, \eta^2_{p} = .51$	$F(1,40) = 19.6, p < .0001, \eta^2_{p} = .33$	$F(1,36) = 8.7, p < .01, \eta^2_{p} = .19$
Hits (%) 0–1 back			
8–9	ns.*	—	$F(1,36) = 21.8, p < .0001, \eta^2_{p} = .38$
10–12	$F(1,34) = 34.5, p < .00001, \eta^2_{p} = .50$	$F(1,36) = 21.8, p < .0001, \eta^2_{p} = .38$	—
adults	$F(1,38) = 24.3, p < .0001, \eta^2_{p} = .39$	$F(1,40) = 10.6, p < .01, \eta^2_{p} = .21$	$F(1,36) = 5.1, p < .05, \eta^2_{p} = .12$

(continued)

TABLE 3 (*Continued*)

	Age Group		
	6–7	*8–9*	*10–12*
Hits (%) 1–2 back			
10–12	$F(1{,}34) = 4.1$, $p = .05$, $\eta^2_p = .11$	$F(1{,}36) = 6.3$, $p < .05$, $\eta^2_p = .15$	—
adults	$F(1{,}38) = 38.9$, $p < .00001$, $\eta^2_p = .51$	$F(1{,}40) = 83.9$, $p < .00001$, $\eta^2_p = .68$	$F(1{,}36) = 20.9$, $p < .0001$, $\eta^2_p = .37$
False alarms (%) 0–1 back			
8–9	$F(1{,}38) = 4.2$, $p < .05$, $\eta^2_p = .10$	—	ns.
adults	$F(1{,}38) = 8.9$, $p < .01$, $\eta^2_p = .19$	$F(1{,}40) = 6.0$, $p < .05$, $\eta^2_p = .13$	$F(1{,}36) = 5.6$, $p < .05$, $\eta^2_p = .13$
Memory recognition (*d*‘) 0–1 back			
10–12	$F(1{,}34) = 19.3$, $p < .001$, $\eta^2_p = .36$	$F(1{,}36) = 15.4$, $p < .001$, $\eta^2_p = .30$	—
adults	$F(1{,}38) = 19.7$, $p < .0001$, $\eta^2_p = .34$	$F(1{,}40) = 14.9$, $p < .001$, $\eta^2_p = .27$	$F(1{,}36) = 15.4$, $p < .001$, $\eta^2_p = .30$
Memory recognition: (*d’*) 1–2 back			
8–9	$F(1{,}38) = 5.6$, $p < .05$, $\eta^2_p = .13$	—	ns.
10–12	$F(1{,}34) = 6.1$, $p < .05$, $\eta^2_p = .15$	ns.	—
adults	$F(1{,}38) = 6.3$, $p <. 05$, $\eta^2_p = .14$	$F(1{,}40) = 26.7$, $p < .00001$, $\eta^2_p = .40$	$F(1{,}36) = 20.4$, $p < .0001$, $\eta^2_p = .36$

ns. = not significant,*$p = .054$. RT = reaction times. The upper panel of the table displays the results for Group × Load interactions including all three N-Back load levels (overall ANOVA) and the planned Group × Load contrasts for 0 versus 1 (maintenance) and 1 versus 2 (maintenance and interference control) that were done to follow up significant interactions in the overall ANOVA. In the lower panel of the table only results of post-hoc group comparisons are displayed for the dependent variables for which significant overall Group × Load (0–1 back or 1–2 back) interactions were obtained. See Results section for more specific information about the group comparisons (i.e., which group had smaller load effects compared to the other).

Reaction Times

A significant Group × Load interaction was found ($p < .0001$) when comparing reaction times in 0-, 1-, and 2-back conditions. This interaction effect was followed up by two planned contrasts examining Group × Load interactions respectively comparing 0- and 1-back and 1- and 2-back tasks.

This analysis showed a significant Group × Load interaction when comparing *0- and 1-back conditions* ($p < .00001$) (maintenance). Further group comparisons showed significantly smaller load effects on RT in adults than in 10–12, 8–9, and 6–7-year-olds (all *p*s < .01). In turn, 10–12-year-old children had smaller 1-back load effects on RT than 8–9- ($p < .05$) and 6–7-year-olds ($p < .0001$).

The planned ANOVA investigating effects of age on Load effects between *1- and 2-back conditions* (maintenance + interference control) yielded significant main Load, $F(1,74) = 50.1$, $p < .00001$, $\eta^2_p = .40$, and Group effects, $F(3,74) = 33.8$, $p < .00001$, $\eta^2_p = .58$, indicating that Load effects were present equally strong in all age groups, and irrespective of load there was a decrease in RT across childhood and adolescence.

The polynomial trend analysis yielded significant linear effects (and non-significant quadratic or cubic effects) for the factor Group in all N-Back conditions ($p < .0001$). These effects reveal a nonspecific linear decrease in RT across childhood and adolescence into adulthood (see Figure 2).

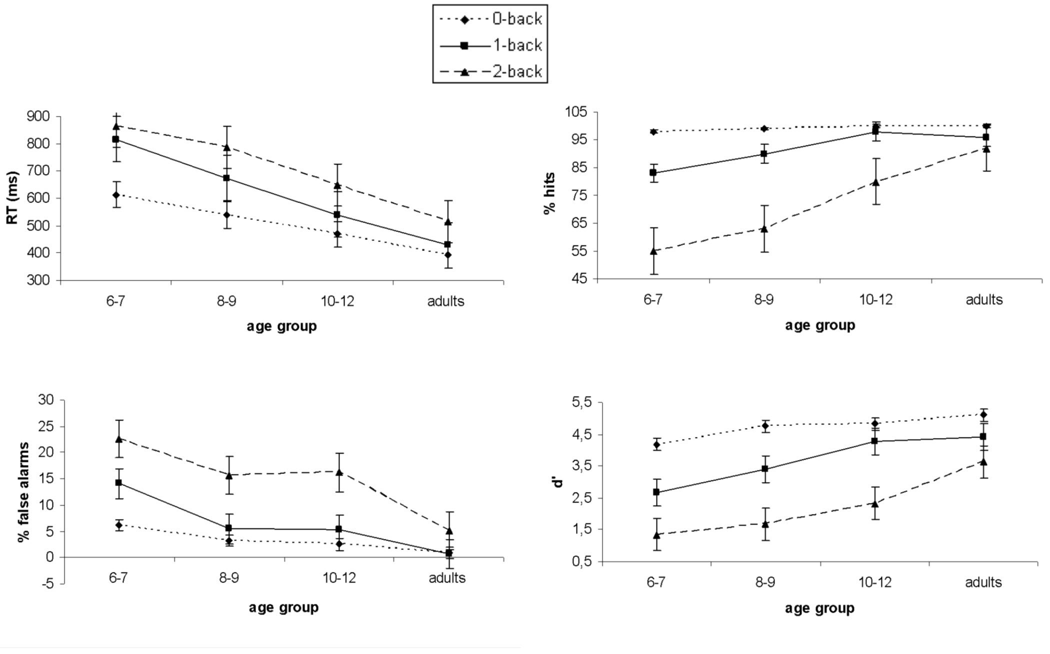

FIGURE 2 Developmental trends in reaction time, percentage of hits, percentage of false alarms and d-prime scores (*d'*) in 0-, 1-, and 2-back conditions.

Percentage of Hits

For % hits, a significant Group × Load interaction was found ($p < .00001$) when all load levels were included.

The planned ANOVA investigating effects of age on Load effects between *0- and 1-back conditions* yielded a significant Group × Load interaction ($p < .00001$). Further group comparisons showed smaller Load effects in 10-12 year-olds than in adults ($p < .05$), but both groups had smaller Load effects than 8–9- ($p < .0001$ and $p < .01$, respectively) and 6–7-year-old children ($p < .00001$ and $p < .0001$, respectively).

The planned ANOVA investigating effects of age on Load effects between *1- and 2-back conditions* also yielded a significant Group × Load interaction ($p >.00001$). Further group comparisons showed that adults had significantly lower decreases in accuracy from the 1- to the 2-back condition than all children groups (all ps < .0001). Furthermore, the 10–12-year-olds had a smaller Load effect than 8–9- ($p < .05$) and 6–7- year-olds ($p = .05$) (see Table 3).

These patterns were supported by polynomial trend analyses that tested for linearity or nonlinearity of Group effects in the 0-, 1-, and 2-back conditions separately. In the 0-back condition a significant linear trend for the factor Group was found, $F(1,74) = 12.1$, $p < .01$, indicating a linear increase in percentage of hits with age (however, as can be seen in Figure 1, percentages of hits were almost at ceiling level in the 0-back condition). A quadratic Group effect was found in the 1-back condition, $F(1,74) = 8.1$, $p < .01$, revealing an increase in percentage of hits during childhood years reaching a plateau at age 10–12, and displaying no (or minimal) accuracy differences between 10–12-year-olds and adults. As opposed to in the 1-back condition, a significant linear trend for the Group factor was found for the 2-back condition, $F(1,74) = 86.5$, $p < .00001$, indicating a steady increase in the percentage of hits across childhood and adolescence into young adulthood (see Figure 2). These quadratic (1-back) and linear (2-back) trends (and the ANOVA results) supported the hypotheses of early maturation of relatively simple WM skills, such as maintenance in the 1-back task, and protracted development of active WM maintenance during interference in the 2-back task.

Percentage of False Alarms

A significant Group × Load interaction was found ($p < .01$) when comparing the three load levels. Further planned ANOVA analysis yielded a significant Group × Load interaction when comparing *0- and 1-back* conditions ($p < .005$). Further group comparisons indicated significantly smaller (or absent) increases in false alarms in the 1-back condition (compared to 0-back) in adults than in 10–12-, 8–9-, and 6–7-year-old children (all ps < .05). Between the children groups, there was a significantly larger increase in false alarms in the 1-back (vs. 0-back) condition in 6–7- than 8–9-year-olds ($p < .05$), but not between ages 8–9 and 10–12 (see Table 3).

The planned ANOVA including the *1- versus 2-back* contrast yielded significant main effects of the factors Load, $F(1,74) = 69.1$, $p < .0001$, $\eta^2_p = .48$, and Group, $F(3,74) = 10.4$, $p < .0001$, $\eta^2_p = .29$, but no interaction. The main Load effect implies that there were significant and comparable increases in false alarms in the 2-back task (compared to 1-back) in all age groups. The main group effect reflects a general decrease in false alarms from young childhood to adulthood that is independent of WM-load (see Figure 2).

Trend analyses showed significant linear trends for the factor Group in the 0-back, $F(1,74) = 20.4$, $p < .0001$, 1-back, $F(1,74) = 22.8$, $p < .00001$, and 2-back conditions, $F(1,74) = 21.8$, $p < .0001$, indicating linear decreases in false alarms from young childhood to adulthood in all task conditions.

Memory Recognition: *d'*

To investigate developmental differences in the perceptual sensitivity to discriminate letters that had or had not been presented as WM-probes, the signal detection parameter *d'* (that takes into account both the proportion of hits and false alarms) was calculated according to Boice and Gardner (1988). The overall ANOVA including all three load levels yielded a significant Group × Load interaction ($p < .00001$). Planned follow-up analyses showed highly significant Group × Load interactions comparing the 0- and 1-back conditions and the 1- and 2-back conditions (both *p*s < .00001). Group comparisons for *0 versus 1-back* showed that adults and 10–12-year-olds had comparable load effects on *d'*, that were smaller than those of 6–9-year-olds (all *p*s < .00001). Load effects did not differ between 6–7- and 8–9-year-olds. Group comparisons for *1 versus 2-back* showed that Load effects on *d*' were significantly smaller in adults than in 8–12- ($p < .00001$) and 6–7-year-old children ($p < .05$). Furthermore, 8–12-year-old children had smaller load effects than 6–7-year-olds ($p < .05$).

These patterns were confirmed by trend analyses that revealed a linear Group effect in the 0-back task, $F(1,74) = 33.4$, $p < .00001$, and quadratic Group effects in 1-back, $F(1,74) = 5.12$, $p < .05$, and 2-back, $F(1,74) = 10.8$, $p < .001$, tasks (see Figure 2). The quadratic Group effect in the 1-back task revealed an increase in target/non-target discrimination during childhood years reaching a plateau at age 10–12. In the 2-back task, there was an increase in discrimination ability across age, but the quadratic effect showed that the steepest increase in *d*' took place after age 10–12 (see Figure 2). These results confirm the hypotheses of early maturation of maintenance in the 1-back task, and protracted development of active WM maintenance during interference in the 2-back task.

Correlation Analyses

To asses the assumed involvement of interference control processes in especially the 2-back condition, Pearson's correlations were computed between the % hit difference in 0- versus 1-back and 1 versus 2-back conditions and response interference effects (i.e., RT difference between congruent vs. incongruent trials) as obtained in the parallel performed flanker task. Supporting the hypothesis, a positive correlation between the difference in % hits between 2- and 1-back conditions and the flanker interference effect was found, $r = .29$, $p = .008$. This positive correlation indicates that subjects that showed the strongest performance decrease from 1- to 2-back, had worse interference control (largest interference effects) in the flanker task. As hypothesized, the % hit difference between 0- and 1-back conditions did not correlate significantly with flanker interference effects, $r = .02$, $p = .89$.

Examining the correlation between performance on WISC–III (Dutch version)—backward counting (as an index of WM updating and manipulation) and performance on the N-Back task, Pearson's correlations were also computed between differences in hit % in 0- versus 1- and 1- versus 2-back conditions and raw backward counting scores. While significant negative correlations were found for 0 versus 1, $r = -.37$, $p = .001$, and for 1- vs. 2-back and backward counting, $r = -.49$, $p = .0001$, the correlation was higher for the 1–2-back comparison. The absence of a correlation between flanker interference effects and backward counting scores, $r = -.065$, $p = .56$, suggests that both are independent contributors to the accuracy decrease in the 2-back condition. Note that the data was checked for outliers, but none were present.

DISCUSSION

The purpose of the present study was to investigate the development of the ability to maintain information in WM in conditions differing in the amount of needed interference control. It was hypothesized that performance of WM tasks requiring relatively high levels of interference control would undergo delayed maturation into adolescence due to the protracted development of brain circuitry involved in exertion of executive control processes such as interference control (Casey, Giedd, & Thomas, 2000; Giedd et al., 1999; Gogtay et al., 2004; Luciana & Nelson, 1998; Pandya & Barnes, 1987). To test these hypotheses, three groups of children of 6–7, 8–9 and 10–12 years and adults performed a non-spatial N-Back task with 0-, 1-, and 2-back conditions. Whereas age-related changes in the 1- (relative to 0-) back condition were assumed to reflect the development of WM maintenance, the development of WM maintenance during the simultaneous control for interference was inferred from age-related changes in the 2- (relative to 1) back condition.

The Involvement of Interference Control and Manipulation in the N-Back Task

It was hypothesized that interference control processes were particularly involved in the 2-back task, since besides an increase in WM-load, the intervening, to-be-maintained, letter was assumed to interfere with the current response decision. This hypothesis was supported by the positive ($r = .29$) correlation between the size of the accuracy decrement from the 1- to the 2-back condition and the size of RT-interference effects in a parallel performed flanker task. This correlation was not found for the % hits decrement from the 0- versus the 1-back condition, indicating that cognitive control is not needed in relatively simple WM tasks that only require the maintenance of information, as was shown before by Stins, Polderman, Boomsma, and De Geus (2005). Such a correlation between accuracy of performance in the 2-back condition and interference control in children and adults was earlier reported by Ciesielski et al. (2006), but by comparing results across multiple load levels, the present data show that this correlation is specific for the 2-back condition. This finding is also in compliance with PET results from Smith and Jonides (1997) that showed activation of DLPFC, an area strongly associated with executive control, only in 2- and 3-back, and not 1- or 0-back conditions. Furthermore, significant negative correlations between accuracy decrements in 1- (vs. 0) and 2- (vs. 1)-back tasks and scores on a digit-span-backward task were found; the larger the performance decrements in 1- or 2-back tasks, the lower the WM-span scores on the digit span-backward task. This finding is interpreted as showing the involvement of WM maintenance and manipulation skills in both 1- and 2-back tasks. The higher correlation in the 2-back task might reflect relatively higher manipulation requirements in this task (Groeger, Field, & Hammond, 1999). Finally, the absence of a correlation between digit-span backward scores and interference effects in the flanker task might indicate that WM maintenance and manipulation ability on the one hand and interference control ability on the other hand, contribute in an independent way to WM-performance in the 2-back task.

The Development of WM Maintenance During Low or High Distraction

First, main effects of the load manipulation (0-, 1-, 2-back) on memory accuracy (hits, false detections, *d'*) and reaction time (RT) measures were present in all groups and showed a linear decrease (accuracy, *d'*) or increase (RT) with increasing N-Back load. The decrease in hits and increase in false recognitions in the 2-back relative to the 1-back task is suggested to be caused by a disruption of the memory trace of the letter stored at the preceding trial due to the requirement to update WM with yet another letter.

With respect to development, supporting the hypotheses, for percentage correctly identified memory probes, a quadratic trend in the 1-back and a linear trend in the 2-back condition indicated different developmental patterns for WM maintenance in tasks that do or do not require simultaneous suppression of interfering information. While the quadratic trend in the 1-back task indicated that adult accuracy levels were reached at age 10–12, the linear trend in the 2-back task showed that WM accuracy continued to increase during adolescence when simultaneous interference control is required. This developmental pattern was supported by analyses of the signal detection parameter *d'* that takes into account both the proportion of true (hits) and false recognitions and thus reflects the perceptual sensitivity to discriminate between items that were or were not presented as memory probes (e.g., memory recognition). In the 1-back task, *d'* reached mature levels at age 10–12, whereas in the 2-back task, statistical analyses confirmed that the strongest improvement in memory recognition (*d'*) took place during adolescence (e.g., between age 10–12 and adulthood). This was for a large part caused by a strong (11%) decrease in the number of false recognitions in the 2-back task after age 10–12. This decrease might well be related to frontal cortex development during adolescence since increased false recognitions have been reported in patients with damage to the frontal lobes and it has been suggested that the prevention of false memories requires PFC recruitment (for review see Schacter & Slotnick, 2004). Finally, a comparable distinctive developmental pattern between 1- and 2-back tasks was not present when looking at speed of processing. Although reaction time increased considerably with N-Back load, equally strong reductions in processing speed were seen during early childhood and adolescence in 0-, 1-, and 2-back conditions. This is suggested to reflect a more global developmental increase in basic processing speed (Hale, 1990; Kail & Park, 1992).

The delayed development of WM-accuracy and recognition memory into adolescence only in the 2-back task (which involves interference control), is in agreement with previous studies. These studies show that when children approach age 12, they perform at adult accuracy levels in more simple WM storage tasks (Cowan, 1997), whereas in WM tasks requiring simultaneous higher-order cognitive control processes, mature levels are only reached in adolescence (Diamond, 2002; Crone et al., 2006). Oleson, Macoveanu, Tegnér, and Klingberg (2007) reported similar late development of WM accuracy in a spatial-WM task involving interference control. These authors showed that the WM performance of 13-year-old children was particularly less accurate than that of adults when maintenance was challenged by distraction. The present data support such late maturation of WM-capacity in tasks demanding interference control by parametrically varying WM-load and executive control demands within one task in the same subjects, and using subtractive logic to disentangle effects of load and executive control. Furthermore, the present study included four age groups, covering a much broader age range of 6–28 years. This delayed development of the ability to protect memory content from disruption when processing of potentially interfering information is required, is most likely due to protracted development of fronto-parietal brain circuitry underlying such a proficiency (Bunge & Wright, 2007; Crone et al., 2006; Oleson et al., 2007). In particular, several developmental fMRI studies have reported that mature performance in tasks that involve relatively high levels of cognitive control goes along with increased recruitment and activation of PFC-parietal brain networks (Casey et al., 1995; Crone et al., 2006; Luna et al., 2001).

The exact mechanisms, by which the impact of distracting information on active WM maintenance is controlled is not yet clear, although some suggestions have been made by different research groups investigating this in primates or healthy adults. In monkeys, sustained activity in PFC and posterior association areas was found during maintenance of information in the retention interval of a visuospatial WM task (Miller, Erickson, & Desimone, 1996). When intervening distractors were presented, the PFC sustained stimulus-selective activity whereas posterior association areas did not and this led to the conclusion that PFC plays an important role in protecting memory against distraction. Several fMRI studies investigating such WM-interference control interactions in healthy adults have found activation of similar PFC (DLPFC)-posterior brain networks during active WM maintenance in visuospatial (Sakai et al., 2002) and non-spatial (Yoon, Curtis, & D’Esposito, 2006) WM tasks. Both studies suggest that the protection of memory representations against distraction is established through higher-order interactions between prefrontal (DLPFC) and posterior association areas. The DLPFC is thought to be specifically involved in executive control in WM (manipulation, interference control), and is assumed to exert top-down control over posterior association areas that are involved in storage of memory representations. Yoon et al. (2006) showed disturbed functional connectivity between DLPFC and posterior association areas during distraction trials.

In light of these findings, the increased memory disruption during distraction in the 2-back task in childhood and adolescence in the present study might be the result of immaturity of the connections and communication between (dorso-lateral) PFC and posterior association areas, instead of immaturity of PFC as such. Supportive of such a conclusion, using diffusion tensor imaging (DTI), Nagy and colleagues (2004) reported that developmental increases in WM capacity were positively correlated with prefrontal-parietal connectivity. Further, findings from computational brain modeling by Edin, Macoveanu, Olesen, Tegnér, and Klingberg (2007) showed that, at the structural level, synaptic connections between cells in fronto-parietal networks explained the observed increase in brain activity associated with development of WM during adolescence. The aforementioned studies, however, made no distinction between developmental differences in brain activation and connectivity patterns evoked by simple tasks involving only storage or maintenance, and more complex WM tasks involving higher-order (interference) control functions, thereby limiting the applicability of these results to the present findings.

Since the present study only used a verbal N-Back task, an important question is to what extent the results might generalize to spatial WM development. Smith and Jonides (1998) review fMRI and PET evidence for domain-specific differences in functional networks activated during simple WM-tasks requiring low executive control. More specifically, they reported that the neural architecture of storage and rehearsal components, that are necessary for simple maintenance of information, differs between verbal and spatial tasks. However, during complex WM tasks that also demand high levels of attention or executive control, such as the 2-back task, activation of similar

DLPFC-parietal networks for verbal and visuospatial tasks has been reported (Gevins et al., 1996; McEvoy, Smith, & Gevins, 1998; Smith & Jonides, 1998). In view of this literature, it seems reasonable to assume that the late development of executive-control-demanding WM-abilities will also be present for spatial tasks. Supportive evidence comes from reports of immature DLPFC functioning in childhood during performance of a spatial WM task (Scherf et al., 2006) and highly comparable delays in development of verbal and spatial WM skills requiring high executive control (Conklin et al., 2007). But to keep the type of executive control in spatial and verbal tasks exactly comparable future developmental studies should include verbal and spatial N-Back tasks and compare development across different load levels; also neurobiological measures should be included. If such a study would provide evidence for involvement of similar DLPFC-parietal networks in the development of executive working memory in both verbal and spatial tasks, this would be evidence in favor of the process-specific theory (Petrides, 1995). This theory states that dorsal regions of the PFC are particularly involved in complex WM skills such as manipulation, which require high levels of executive control.

Given the strong links between working memory (capacity) and cognitive functions as reading and mathematics (Pickering, 2006), it is important to discuss the practical implications of the current data. Our findings suggest that before their adolescent years, children experience disproportionate difficulties in tasks that call on simultaneous maintenance and executive (interference) control processes. Considering that such concurrent cognitive operations are often required in everyday school-exercises, different or additional educational approaches might be useful for this population. For example, where possible, teachers might try to reduce secondary task demands during tasks requiring complex WM-skills. Furthermore, training in the use of WM-strategies might enhance the efficiency with which school-aged children can hold information online. This might lead to an increase of available resources that can be used for suppressing the influence of the simultaneously executed (interfering) operations, thereby protecting WM content against distraction.

In conclusion, to our knowledge, the present study is the first study comparing development of WM-capacity across a broad age range of 6–28 years, in simple and complex WM tasks (N-Back task varying in load) that do or do not require simultaneous interference control. It was demonstrated that the ability to maintain information in WM during the simultaneous suppression of irrelevant information (2-back task) undergoes prolonged maturation into adolescence. In contrast, the ability to hold information online in tasks that demand no interference control (1-back task) reaches adult levels at age 10–12. Based on neuro-cognitive findings from the primate and adult literature (Miller et al., 1996; Sakai et al., 2002: Yoon et al., 2006), this finding of prolonged development of WM maintenance during interference control was suggested to be linked to relative immaturity of functional connectivity between PFC (being involved in executive control in WM) and posterior association cortex where memory representations are stored.

Limitations of the Present Study

Several limitations of this study deserve further comment. Although the current behavioral findings have important implications for the developmental cognitive neuroscience field, direct brain–behavior links and developmental interactions herein cannot be derived from the present data. Future research should incorporate neuroimaging techniques in order to test more directly which network of brain regions supports development of WM performance during distraction or high executive control demanding situations. Another possible limitation concerns the cross-sectional nature of the study. This type of design does not allow us to make any causal interpretations of the observed results. The current findings await replication using a longitudinal design.

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