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Link to publication

Download date: 07 Oct. 2022

Electrophysiological evidence for different effects of working memory load on interference control in adolescents than adults

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ARTICLE INFO

ABSTRACT

The present study investigated how the development of interference control is influenced by the development of working memory (WM) capacity during adolescence. In a dual-task, 17 adolescents (12–16 years) and 19 adults (18–48 years) performed a gender word–face Stroop task, while WM-capacity was manipulated by a concurrently performed N-back task. Behavior (reaction times, % errors and % misses) and event-related potentials associated with the detection (N450) of the Stroop conflict and response selection (sustained positivity; SP) were measured without or with a concurrent WM load. Adolescents had lower accuracy on N-back and Stroop trials than adults. N450 results showed Stroop conflict above temporal–occipital cortex which was suggested to be caused by processing of distracter faces. This N450 conflict response was smaller in adults and only present when holding a simultaneous WM-load, whereas adolescents' N450 conflict responses were already present without a concurrent WM-load and did not further increase with load. These N450 results indicate poorer distracter suppression in adolescence which is suggested to be due to insufficient attentional resources for top–down control. Irrespective of WM-load, adolescents also had larger parietal SP conflict responses than adults, suggesting inefficient response selection in case of activation of two conflicting responses. The main conclusion is that adolescents have worse distracter suppression than adults, caused by lower availability of resources for top–down control.

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1. Introduction

Inhibition-related functions are known to play an important role in the development of cognitive abilities such as fluid intelligence (Burgess and Braver, 2010), reasoning (Krawczyk et al., 2008), and problem solving (Passolunghi et al., 1999). One type of inhibition, interference control, is the ability to select task-relevant information while simultaneously suppressing the influence of distracting information that conflicts with task demands, such as for example in Stroop tasks (Stroop, 1935). In the past decade a considerable number of studies have provided evidence that the ability to control interference is related to the capacity of one's working memory (WM), i.e. the space to store and process information for short periods of time. One line of evidence comes from behavioral studies showing that adults with low WM-span experience more interference from distracters than adults with high WM-span in conflict-tasks such as Stroop and flanker tasks (Kane and Engle, 2003). On the basis of these studies Engle and Kane (2004) proposed their executive-attention theory of WM-capacity, which explained the better performance of adults with high-WM-capacity by a better ability to maintain goal-related information in memory and

resolve response conflict. In a series of studies Lavie and colleagues have used a within subjects design to study WM-capacity-selective attention/interference control relations more directly by manipulating WM-capacity and interference control experimentally within one paradigm (de Fockert et al., 2001; Lavie and De Fockert, 2005; Lavie et al., 2004). These studies led to the conclusion that WM-capacity is of crucial importance for the ability to suppress the influence of distracting or conflicting information, because reductions in WM-resources led to enhanced interference in Stroop or flanker tasks. The aim of the present study was to investigate how the development of interference control is influenced by manipulations of WM-resources (thought to reduce frontal–top–down control) during adolescence by using a WM-selective attention task similar to that used in de Fockert et al. (2001). Below more information about this task will be provided.

The present study focuses on adolescence since both WM-capacity and inhibitory control have been consistently reported to follow a protracted qualitative development into this period, especially in situations that are highly cognitively demanding (Anderson et al., 2001; Davies and Rose, 1999; Demetriou et al., 2002; Gathercole, 1999; Klingberg et al., 2002; Kwon et al., 2002; Leon-Carrion et al., 2004; Luciana et al., 2005; Luna et al., 2004, 2010; Schleepen and Jonkman, 2010; Segalowitz et al., 2010). For example in a review article, Gathercole (1999) showed that especially complex working memory (compared to phonological and visuospatial short-term memory) undergoes late development until 16 years of age. Also other studies

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have shown that mature WM-capacity is not reached before late adolescence when executive control demands are high. Luciana et al. (2005), who used nonverbal WM tasks with varying degrees of executive demands, reported that WM-capacity in a spatial WM task in which sequences of visually presented information (block tapping) had to be recalled in backward order (requiring maintenance and manipulation) did not reach mature levels in adolescents until 13 or 15 years of age. Schleepen and Jonkman (2010) showed particularly late development of non-spatial WM-capacity into adolescence in task conditions that required simultaneous maintenance, updating and suppression of irrelevant information in a verbal N-back task. Luna et al. (2004) also showed ongoing development of working memory throughout adolescence using an oculomotor delayed response task (requiring eye movements guided by a target location in memory), as well as late development in adolescence of inhibitory control in an anti-saccade task. Immature suppression of irrelevant information has furthermore been reported in adolescents by Leon-Carrion et al. (2004) who examined interference control in a Stroop task and found a decrease in interference from irrelevant information in adolescence until 17 years of age. This late development of WM-capacity and inhibitory control has been attributed to the protracted development of brain networks including frontal and parietal brain regions that are known to be involved in both WM and interference control (Bunge and Wright, 2007; Durston et al., 2002; Hopfinger et al., 2000; Klingberg et al., 2002; McNab and Klingberg, 2008; Rubia et al., 2006). Especially, the maturation of dorsolateral prefrontal cortex (DLPFC), a structure known to be involved in the resistance to interference when holding information in WM, has been shown to be immature in adolescence (Giedd, 2004; Lenroot and Giedd, 2006). DLPFC activation has been found during maintenance of items in memory and particularly when WM-load is high (Grimault et al., 2009; Rypma et al., 2002), or when WM content is threatened by distraction (Dolcos et al., 2007). Such findings indicate that frontal areas are essential in keeping cognitive performance levels high through top–down attentional control.

One way to investigate the dependency of interference control on WM-capacity is through the use of so-called dual-task paradigms. As was already shortly mentioned above, in a series of studies including healthy adults Lavie and colleagues manipulated WM-load by letting subjects hold smaller or larger amounts of information in WM while concurrently performing tasks requiring selection/enhancement of task-relevant information and simultaneous suppression of task-irrelevant information, such as in Stroop, flanker or visual search tasks (de Fockert et al., 2001; Lavie and De Fockert, 2005; Lavie et al., 2004). In all these studies higher occupancy of WM led to increased distracter interference in the concurrently performed selective attention tasks as measured by delayed reaction times and reduced accuracy when targets and distracters evoked conflicting responses, i.e. were incongruent (e.g. the word red printed in green in the Stroop task) as opposed to when both were congruent. In the fMRI study by de Fockert et al. (2001), interference in the Stroop task was manipulated by presenting subjects with names of famous people that had to be categorized as being from a politician or pop star. Names were superimposed on distracter faces that had to be ignored and could either be congruent (name and face of Bill Clinton) or incongruent with the to-be-categorized names (e.g. name of Bill Clinton and face of Mick Jagger). This fMRI study showed that healthy adults experienced more interference from distracter faces when WM was heavily loaded (leading to lower availability of frontal resources for top–down control), as shown by slower responding in the Stroop task and higher activation in fusiform face-processing areas with high WM-load, the latter being indicative of higher processing of task-irrelevant distracter faces.

A task similar to that used in de Fockert et al. (2001) was used in the present study to examine whether the dependency of interference control on WM-capacity shows developmental changes from adolescence to adulthood. To prevent influences of differences in familiarity of

famous faces between adolescents and adults, Stroop interference was manipulated by presenting the words male/female (in Dutch in the present study) superimposed on male or female faces that were unfamiliar to the subjects (Egner et al., 2010; Padmala et al., 2011). Subjects had to categorize the words male/female by giving left/right responses, WM-load was manipulated by a concurrently performed letter N-back task. In addition to behavior, event-related brain potentials (ERPs) were measured to get a precise view on when in time reductions in available WM-capacity influence interference control the most in the different age groups. More specifically, the effect of loading WM was measured on two Stroop-related ERP components; the so called "N450" and the "sustained positivity" (SP), that have been reported to occur in regular color–word Stroop tasks (Lansbergen et al., 2007; Liotti et al., 2000; Markela-Lerenc et al., 2004; Qiu et al., 2006; West, 2003, 2004), but have recently also been reported in a face–name Stroop task (Jongen and Jonkman, 2011). The N450 represents a reduced positive component (negativity) in the incongruent condition relative to the congruent condition between 350 and 500 ms and has been associated with the process of conflict detection on the basis of its sensitivity to different experimental manipulations of conflict strength (Lansbergen et al., 2007; Liotti et al., 2000; Tillman and Wiens, 2011; West and Alain, 2000). The conflict SP (sometimes also called the P600 in the Stroop-ERP literature) that follows the N450 in time represents an enhanced positive component in the incongruent condition relative to the congruent condition starting around 600 ms. On the basis of the Stroop-ERP literature parietal-SP effects are suggested to reflect enhanced processing of response-relevant information used to guide response selection in incongruent trials (Chen et al., 2011; Jongen and Jonkman, 2008; Lansbergen et al., 2007; Liotti et al., 2000; Markela-Lerenc et al., 2004; Qiu et al., 2006; West, 2003). Parietal-SP effects have been localized to parietal cortex in adults (Chen et al., 2011) and fMRI studies have reported evidence for a role of parietal cortex in supporting stimulus–response mappings that facilitate response selection in the Stroop task (Bunge et al., 2002; Casey et al., 2000; Rushworth et al., 2001).

Whereas these N450 and SP conflict components have been studied frequently in adults, studies in children or adolescents are scarce. In a developmental study using an object-Stroop task stimulus–response mappings were manipulated to study the differential contributions of stimulus and response interference to behavioral and electrophysiological Stroop effects across age (Jongen and Jonkman, 2008). Stimulus interference was not present in children (6–12 years of age) or adults. Response interference effects were present on reaction time and accuracy in all 6–12 year-old children and adults, but children made relatively more errors than adults in the response-incongruent than the stimulus-incongruent condition. The fact that 12-year-olds still made more errors in the response-incongruent condition than adults points to continued maturation of response conflict processing during adolescence. An N450 conflict response with a parietal, lateral occipital distribution was larger to response incongruent than stimulus incongruent stimuli in 10–12 year-old children and adults, but was not present below 10 years of age. An SP effect with a broad scalp distribution across frontal, central and parietal electrodes was present in all children and adults. The facts that this SP-conflict response was larger on response- than stimulus-incongruent trials and that its magnitude was correlated with the RT response interference effect confirmed its relation to the process of conflict resolution also in children.

To our knowledge, no ERP studies have so far been done to directly examine the relationship between WM and interference control in adolescents in a dual-task. In a prior ERP study by Jongen and Jonkman (2011) the time-course of WM-load effects on Stroop interference in a name–face task similar to that used in the fMRI study by de Fockert et al. (2001) was investigated in university students. They found that only the SP interference effect associated with conflict resolution was modulated by WM-load; SP interference effects at parietal electrodes increased linearly with higher concurrent WM-loads, and only when holding the highest WM-load of 4 letters in memory additional frontal

SP activation was found. This suggests that in healthy young adults additional frontal top–down control on posterior areas to prevent distracter processing is only needed when holding concurrent loads that are close to maximum WM-capacity. Because of the relative immaturity of fronto-parietal networks in adolescence we expect that they will show an inability to suppress distracter processing in the Stroop task already with lower concurrent WM-loads and/or that processing bottlenecks will become visible earlier in the information processing chain, e.g. at the level of conflict detection. In the present Stroop task, conflict is expected to occur when the genders of the name and distracter face do not match and can only occur after the gender of the face has been processed. Since neuroimaging studies have shown that the processing of stable aspects of faces such as gender takes place in inferior occipito-temporal regions and fusiform gyrus (Haxby et al., 2000, 2002) we expect the first (N450) interference effects associated with conflict detection (and effects of WM load manipulation on this) to take place in occipito-temporal cortex. Support for this also comes from studies by Fruhholz et al. (2009a,b), who previously investigated the effects of congruent and incongruent contextual information on the processing of facial expressions (valence recognition of faces). Their fMRI study revealed increased activity for incongruent compared to congruent trials in V4, the mid-lateral fusiform gyrus (BA 37) and the inferior occipital gyrus (BA 18). The activity in fusiform gyrus was thought to be related to categorical face processing (Fruhholz et al., 2009b). In another study, ERP data collected with the same task showed interference effects similar to the N450 (reduced positivity for incongruent compared to congruent trials) at parietal and occipital electrodes; source activity for these effects as shown by principal component analysis were located in parietal cortex (Fruhholz et al., 2009a).

2. Methods

2.1. Subjects

Originally, 40 healthy subjects (native Dutch speakers) participated in the study (20 adolescents and 20 adults), of which 4 were excluded during statistical analyses due to outliers in behavioral measures (3 adolescents and 1 adult). The 17 subjects (8 boys and 9 girls) in the adolescent group were recruited from preparatory secondary vocational education schools, which is the lowest secondary level of regular education attended by 60% of the Dutch adolescents, and therefore thought to be most representative of typically developing adolescents. The 19 adults (11 male and 8 female) were recruited from the normal population via advertisements in local newspapers and had educational levels similar to the adolescents (i.e. all adults completed non-compulsory post-secondary education). Mean age was 14.5 years in the adolescent group (range 12.9–16.4 years; SD = 1.1) and 32.6 years in the adult group (range 18.7–48 years; SD = 11.4).

To check for absence of attention- and/or ADHD behavioral problems, the adolescents themselves filled out the Youth Self Report form (YSR; Achenbach, 1991b) and one of their parents filled out the Child Behavior Checklist (CBCL; Achenbach, 1991a). In adolescents, mean score on the ADHD subscale was 54.5 on the CBCL (SD3.8, range 50–62) and 53.5 on the YSR (SD 3.7, range 50–63), and on the Attention subscale mean score was 54.1 on the CBCL (SD3.8, range 50–61) and 52.2 on the YSR (SD 2.6, range 50–57). Participating adults filled out the Adult Self Report (ASR; Achenbach and Rescorla, 2003). Mean score was 53.4 on the ADHD subscale (SD 4.2, range 50–65) and 54.1 on the Attention subscale (SD 4.5, range 50–63). None of the subjects scored within the clinical range on the ADHD or attention subscales. Furthermore, all subjects were free of other neurological or somatic health problems.

To check for IQ, subjects in the adolescent group were administered the Vocabulary and Block design subtests of the Wechsler Intelligence Scale for Children (WISC-III; Wechsler, 1991). Subjects in the adult group were administered the same subtests of the Wechsler

Adult Intelligence Scale (WAIS-III; Wechsler, 1997). Mean reliability and validity of this estimated IQ-score compared to the complete IQ-test has been reported to be .9 for both scales (Jeyakumar et al., 2004; Spreen and Strauss, 1998). The mean IQ-score was 95.0 (SD 11.0) in the adolescent group and 102.2 (SD 12.4) in the adult group. IQ-scores did not significantly differ between groups. The present study was approved by the Local Ethical Committee of the Faculty of Psychology and Neuroscience at Maastricht University, and prior to the study a written informed consent was obtained from the children and their caretakers and the adults according to the Declaration of Helsinki. All subjects were paid for their participation in the experiment.

2.2. Procedure

The entire experimental session lasted 2.5–3 h. The session started with the Block Design test, Vocabulary test and the Digit Span test, followed by the attachment of the electrodes. During the experimental session all participants sat in front of a 17-inch VGA monitor with their eyes aligned to the center of the screen at a distance of approximately 70 cm. They were instructed to minimize eye blinks and refrain from making movements during task performance. The experimental session started when all tasks were practiced until a predetermined performance criterion (75% correct responses) was reached.

2.3. Experimental task

The experimental task, programmed in Presentation (version 11.0) consisted of a Stroop task combined with an N-back task, in such a way that each N-back trial was followed by a Stroop trial (see Fig. 1). A gray background (131, 131, 131) was displayed throughout the task. Stroop stimuli consisted of the Dutch equivalents of the words MALE/-FEMALE ("MAN" or "VROUW" printed in white color, font size 60) superimposed on faces of men and women (width 450 pixels, height 600 pixels) that were either congruent (e.g. the face of a man and the word "MAN") or incongruent (e.g. the face of a woman and the word "MAN") with each other, and were presented at the center of the screen. The face stimuli consisted of a selection of 16 neutral faces from the Karolinska Emotional Faces Set (Lundqvist et al., 1998) from which 8 men and 8 women were matched as much as possible on hair color and hair length. Pictures were displayed in grayscale. In the Stroop task subjects were instructed to attend to the word and ignore distracter faces and press a left button with the left index finger when the word stimulus shown was "MAN" (50% of all trials; 25% congruent with distracter face of a man, 25% incongruent with distracter face of a woman) or press a right button with the right index finger when the word stimulus was "VROUW" (other 50% of trials; 25% congruent with distracter face of a woman, 25% incongruent with distracter face of a man). The level of interference is determined by comparing reaction time and accuracy between congruent and incongruent Stroop stimuli.

To vary the level of WM-load, different N-back trials were presented. N-back stimuli were the letters A, S, X, B, T, F, H, G, K, L, W and Z (white color, font size 50). In the 0-load condition, subjects performed a simple detection task by pressing the left button whenever a letter X was presented and pressing the right button to all other letters (A, S, B, T, F, H, G, K, L, W and Z). The 1-load condition was a 1-back task and subjects reported whether the presented letter was similar to (left button press) or different from (right button press) the preceding letter. Comparable WM-face/name Stroop dual-tasks have been used in other studies that investigated WM-load interference/attention control interactions in healthy adults (de Fockert et al., 2001; Jongen and Jonkman, 2011; Pecchinenda and Heil, 2007). Note that 0-back and 1-back dual tasks consisted of exactly the same stimuli and required similar goal maintenance and dual-task responses. The task goals and response requirements in the Stroop task were exactly the same
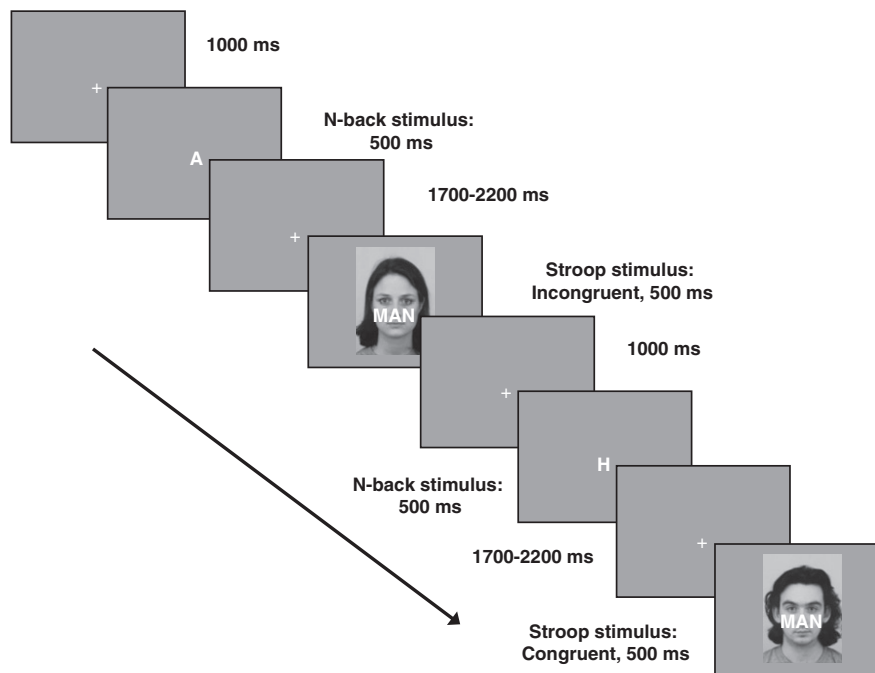
Fig. 1. Illustration of two trials from the combined N-back and face–word Stroop task. In this task a presentation of a letter was followed by a Stroop trial in which the subject had to discriminate between the word "MAN" (male) and "VROUW" (female). In the WMload-0 condition the subject had to indicate for each letter whether it was an X or not. In the WMload-1 condition the subject had to indicate for each letter whether it was the same letter as the previous one, or different.

between 0- and 1-back conditions, so the only difference was that in the 1-back condition one had to maintain the letter in memory during Stroop performance whereas no maintenance was required in the 0-back task.

The WM-Stroop task was administered in two blocks, differing in WM-load (one 0-back block and one 1-back block), and the order of the blocks was counterbalanced between participants within groups. Each block consisted of 112 N-back and Stroop trials, with 50% congruent and 50% incongruent trials in the Stroop task (56 trials per condition). Similarly, N-back trials required an equal amount of left button presses (preceding 25% of congruent and 25% of incongruent Stroop trials) and right button responses (preceding 25% of congruent and 25% of incongruent Stroop trials).

A total trial (one N-back + one Stroop stimulus) lasted 3700–4200 ms, a trial started with a fixation cross presented for 1000 ms, followed by an N-back letter stimulus presented for 500 ms, followed by a fixation cross with a duration varying between 1700 and 2200 ms, followed by a Stroop stimulus of 500 ms duration (see Fig. 1).

2.4. Electrophysiological recording and analysis

For measurement of the EEG, an Easycap consisting of 60 Ag/AgCl electrodes was used (Fpz, Fz, FCz, Cz, CPz, Pz, Oz, Fp1, Fp2, AF7, AF8, AF3, AF4, F7, F5, F3, F1, F2, F4, F6, F8, FT7, FC5, FC3, FC1, FC2, FC4, FC6, FT8, T7, C5, C3, C1, C2, C4, C6, T8, TP7, CP5, CP3, CP1, CP2, CP4, CP6, TP8, P7, P5, P3, P1, P2, P4, P6, P8, PO7, PO3, PO4, PO8, O1, O2, and the right mastoid A2). During measurement all electrodes were referenced to the left mastoid (A1) and one of the electrodes in the cap (AFz) was used as ground. Offline, EEG data were re-referenced to the average of the right and left mastoids. The vertical EOG was recorded from infraorbital and supraorbital electrodes placed in line with the pupil of the left eye. The horizontal EOG was recorded from two electrodes that were attached to the outer canthi of both eyes. All electrode impedances were kept below 10 kΩ, with the exception of reference and ground electrodes that were held below 5 kΩ. Signal acquisition was accomplished using Neuroscan synamps amplifiers and Brain Vision Recorder software (version 1.10). EEG and

EOG signals were continuously sampled at 250 Hz with a high-pass filter of 0.05 Hz and a low-pass filter of 30 Hz.

The continuous EEG of the Stroop trials was divided into 112 epochs of 1850 ms, from 200 ms prestimulus to 1650 ms poststimulus, all aligned to a baseline from −200 to 0 ms preceding the Stroop stimulus. First, vertical EOG artifacts (blinks) were removed from the data by applying an eye-movement correction algorithm (Semlitsch et al., 1986) provided in the Neuroscan analysis software package. Instead of using the automatic procedure, for the computation of regression coefficients between VEOG and the EEG-signals at the different electrodes, adequate eye blinks were manually selected and checked. After having removed eye blinks from the EEG via the above described procedure, epochs containing artifacts or horizontal eye movements exceeding ± 100 μV were rejected from the database.

Next, average ERPs were computed separately for each subject in four different task conditions: (1) 0-load congruent stimuli, (2) 0-load incongruent stimuli, (3) 1-load congruent stimuli, and (4) 1-load incongruent stimuli. In the averaging procedure, only trials with correct responses on the Stroop trials as well as on the following N-back trial were included. There were a maximum number of 224 trials in the task (112 trials in the 0-back-Stroop block and 112 trials in 1-back-Stroop block). The minimum number of included trials per block (WM load 0 or 1) was 60. The mean number of artifact-free EEG epochs contained in the single-subject averages was 184 trials (SD 27) in the adult group and 143 trials (SD 29) in the adolescent group.

Based on findings in previous studies (see introduction) two effects of Stroop interference were expected in the present ERP data. For incongruent relative to congruent trials an increased negativity has been observed around 450 ms (in the Stroop literature also referred to as the "N450"; Lansbergen et al., 2007; Liotti et al., 2000; Tillman and Wiens, 2011; West and Alain, 2000) and an increased positivity was expected around 600 ms (in the literature referred to as the "P600" or the "SP"; Chen et al., 2011; Jongen and Jonkman, 2008, 2011; Lansbergen et al., 2007; Liotti et al., 2000; Markela-Lerenc et al., 2004; Qiu et al., 2006; West, 2003). Consistent with this, inspection of global field power (GFP) plots of grand average ERP activity in both groups (averaged across all leads and all subjects in the separate groups) confirmed the

presence of these interference effects (with similar timing) in our face–name Stroop task in both adults and adolescents (see Figs. 4 and 5; plots derived from BESA 5.0 software). In both groups the N450-interference effect was most pronounced between 420 and 460 ms and was distributed over parietal (P1, P2) and parietal–occipital (PO7, PO8) sites. The SP interference effect was most pronounced between 620 and 780 ms in adolescents and between 760 and 840 ms in adults at centro-parietal (CP1, CP2) and parietal (P1, P2) sites.

2.5. Statistical analysis

2.5.1. Behavioral measures

To be able to check for potential group differences in verbal short-term memory (STM) and verbal working memory span Forward and Backward Digit span measures were obtained from all adolescents and adults (derived from WISC-III for adolescents and WAIS-III for adults). Forward-span scores are considered to be measures of verbal STM, whereas backward-span scores are considered measures of verbal WM-capacity, at least in children (St. Clair-Thompson, 2010). Raw scores on forward and backward digit span tests were entered in univariate ANOVA to check for age differences. Apart from raw scores, standardized digit span scores were also computed (according to the WISC-III and WAIS-III manuals) in each group.

For 0-back and 1-back WM trials, reaction time (RT) for correctly detected targets (0-back) or WM-probes (1-back), percentage of incorrect responses (% errors) and percentage of missed responses (% omissions) were computed. A repeated measures ANOVA with within-subjects factor Load (0-back, 1-back) and between-subjects factor Age (adolescents, adults) was conducted.

Furthermore, reaction time for correct responses (RT), % errors and % omissions for Stroop trials were computed. Tests were performed for all behavioral Stroop measures to examine effects of WM-load (low or high) on Stroop interference (congruent vs. incongruent trials) by conducting a repeated measures ANOVA with within-subjects factors Load (Stroop trials preceded by a 0-back or a 1-back trial) and Congruence (congruent, incongruent), and between-subjects factor Age (adolescents, adults). Significant Load × Congruence interactions were further explored by testing the congruence effects of the separate levels of WM-load. Two-tailed significance levels of 5% were adopted.

2.5.2. ERP measures

For both expected components of Stroop interference, conflict detection (N450) and conflict resolution (SP), mean voltage values in the specified time windows and at the specified locations were entered into a 2 (Load; 0-load, 1-load) × 2 (Congruence; congruent, incongruent) × 2 (Location; see specified locations per component) × 2 (Hemisphere; Left, Right) × 2 (Age; adolescents, adults) repeated measures ANOVA. Significant 5 or 4-way interactions were followed up by performing 4 or 3-way ANOVA's respectively at the different levels of the Location factor. In case such interactions (involving levels of Load, Congruence and Age) were found, further testing was done by first splitting

up on the Load factor to explore Age × Congruence effects in both Load (0-back vs. 1-back) conditions. Age × Congruency interactions were explored further by testing Congruency effects in the separate Age groups. For all repeated measures ANOVAs two-tailed significance levels of 5% were adopted. Partial-eta squared effect sizes are reported with the ANOVA effects.

3. Results

3.1. Behavioral results

3.1.1. STM and WM-capacity (digit span)

No significant Age differences were found for raw Forward and Backward digit span scores: Forward digit span was 8.8 (SD 2.1) in adolescents, and 9.6 (SD 2.4) in adults (Age effect F(1,34) = 1.0, P = .32), and Backward digit span was 6.1 (SD = 1.8) in adolescents, and 6.7 (SD = 2.8) in adults (Age effect F(1,34) = 0.6, P = .44). Mean standardized digit span scores (including both forward and backward scores; for computation see WISC-III/WAIS-III manual) were 10.1 (SD 3.3) and 10.4 (SD 3.5) in adolescent and adult groups respectively and were not significantly different (Age effect: F(1,34) = 0.1, P = .83).

3.1.2. N-back task performance

Means of RT, percentage of incorrect responses (errors) and percentage of missed responses in the 0-back and 1-back tasks are displayed in Table 1. Reaction times for correctly responded trials (F(1,34) = 19.4, P < .0005, $\eta_p^2 = 0.36$), % errors (F(1,34) = 98.3, P < .00001, $\eta_p^2 = 0.74$) and % omissions (F(1,34) = 7.30, P < .05, $\eta_p^2 = 0.18$) increased in the 1-back condition compared to the 0-back condition in which no information had to be retrieved from memory, but similar left/right categorization responses had to be given (see Fig. 2A and B for reaction times and % errors). A main effect of Age (F(1,34) = 4.7, P < .05, $\eta_p^2 = 0.12$) for % errors confirmed worse performance in adolescents (compared to adults) in the 1-back as well as the 0-back task. No Age × Load interaction and no Age effects for RT and % omissions were found in the N-back task.

3.1.3. Stroop task performance

Means of RTs, percentage of incorrect responses and percentage of missed responses in the Stroop task are displayed in Table 1. For reaction time (RT), a main effect of Load (F(1,34) = 10.3, P < .005, $\eta_p^2 = 0.23$) showed slower Stroop responses in the 1-back condition compared to the 0-back condition (see Fig. 3A). A main effect of Congruence (F(1,34) = 17.1, P < .0005, $\eta_p^2 = 0.34$) showed slower responding to incongruent than to congruent Stroop stimuli. Similar to RT, the percentage of errors also increased with Load (F(1,34) = 55.0, P < .0001, $\eta_p^2 = 0.62$; more errors in 1-back than 0-back) and Congruence (F(1,34) = 7.7, P < .01, $\eta_p^2 = 0.18$; more errors in response to incongruent vs. congruent Stroop stimuli) (see Fig. 3B). Main Age effects were present for % errors (F(1,34) = 15.2, P < .001, $\eta_p^2 = 0.31$) and % omissions (F(1,34) = 9.8, P < .005, $\eta_p^2 = 0.22$), indicating less accurate Stroop

Table 1
Group means (standard deviations between brackets) of the behavioral parameters for the N-back trials and Stroop trials in the combined N-back and face-word Stroop task.

		N-back trials				Stroop trials		
		RT (ms)	Errors (%)	Omissions (%)		RT (ms)	Errors (%)	Omissions (%)
Adolescents (N = 17)	WMload 0	708 (133)	7 (8)	4 (3)	C	740 (176)	18 (13)	0.7 (1.6)
					IC	755 (184)	20 (17)	1.4 (2.5)
	WMload 1	790 (171)	18 (12)	11 (15)	C	781 (178)	36 (18)	1.2 (1.4)
					IC	816 (197)	39 (14)	1.4 (1.9)
Adults (N = 19)	WMload 0	752 (120)	3 (3)	3 (2)	C	778 (129)	6 (6)	0.1 (0.4)
					IC	803 (132)	9 (8)	0.4 (1.3)
	WMload 1	852 (129)	12 (6)	6 (7)	C	835 (100)	20 (12)	0.0 (0.0)
					IC	865 (105)	20 (15)	0.5 (0.8)

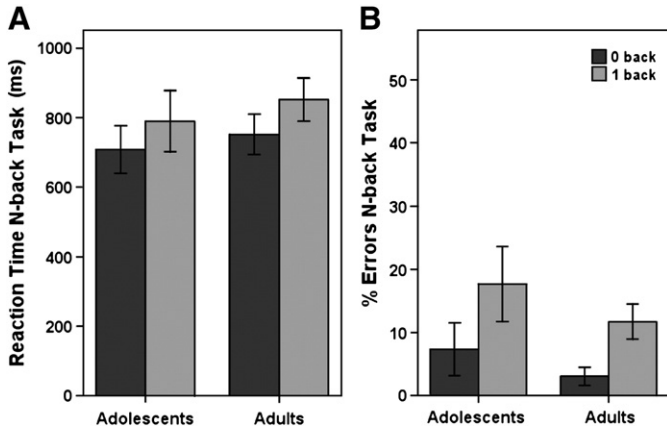RT = reaction time, C = Congruent, IC = Incongruent

A

B

Fig. 2. Bar graphs of (A) average reaction times (in ms) and (B) percentage of errors for adolescents and adults in the WMload-0 and WMload-1 conditions of the N-back task. Error bars indicate 95% confidence intervals.

performance in adolescents than adults, reaction times were not different between the age groups. No Load × Congruence or Age × Load × Congruence interaction effects were found.

3.2. ERP results

3.2.1. N450

The N450 interference effect was analyzed in a window from 420 to 460 ms at left and right occipito-temporal (PO7, PO8) and at parietal (P1, P2) electrodes. Selection of this time window and electrodes for analyses is based on: 1) global field power information, 2) topographic maps of N450 interference effects at maximum amplitude (for points 1 and 2; see Fig. 4), 3) the average ERPs (see Fig. 5) and 4) prior neuroimaging studies reporting on the location of gender face processing in occipito-temporal cortex (Haxby et al., 2000, 2002).

The ANOVA analyses yielded a significant Load × Congruence × Age × Location × Hemisphere interaction F(1,34) = 6.0, P<.05, $\eta_p^2 = 0.15$. This 5-way interaction was further explored by performing Load × Congruence × Age × Hemisphere analyses separately at parietal and occipito-temporal electrodes (per level of the Location factor). For the *occipital–temporal* (PO7, PO8) electrodes the 4-way Load × Congruence × Hemisphere × Age interaction (F(1,34) = 4.11, P = .051, $\eta_p^2 = 0.11$) was significant. This 4-way interaction was further explored by testing for 2 (Age) × 2 (Congruence) × 2 (Hemisphere) interactions per level of the Load factor. In the *Load-0 (0-back) condition*, the analyses yielded significant Congruence (F(1,34) = 4.7, P<.05, $\eta_p^2 = 0.12$) and significant Age × Congruence effects F(1.34) = 10.6, P<.005, $\eta_p^2 = .24$). There were no effects of Hemisphere. Further testing per

Age group showed that adults had no significant N450 interference effect in the 0-back condition (Load 0: Congruence: F(1,18) = 1.1, P = .307, $\eta_p^2 = 0.06$) whereas adolescents did show a N450 interference effect (F(1,16) = 8.3, P<.05, $\eta_p^2 = 0.34$), marked by larger negativity to incongruent trials (see Fig. 5). *In the Load-1 (1-back) condition*, the analysis yielded significant effects of Congruence (F(1,34) = 11.6, P<.005, $\eta_p^2 = 0.28$), Congruence × Hemisphere (F(1,34) = 9.8, P = <.005, $\eta_p^2 = 0.22$) and a trend-significant Age × Congruence × Hemisphere interaction (F(1,34) = 3.9, P = .06, $\eta_p^2 = 0.10$). Follow-up testing of this 3-way interaction did not reveal significant Age × Congruence interactions at PO7 (P = .08) or PO8 (P = .58), but main Congruence effects were significant at PO7 (F(1,34) = 16.5, P = <.0001, $\eta_p^2 = 0.33$) and PO8 (F(1,34) = 5.1, P<.05, $\eta_p^2 = 0.13$), although the latter effect would not survive Bonferroni correction. This signifies similar N450 interference effects in adolescents and adults above left occipital cortex in the 1-back condition.

Further 2 (Load) × 2 (Congruence) × 2 (Hemisphere) × 2 (Age) analyses at *parietal* (P1, P2) electrodes only showed significant Congruence (F(1,34) = 15.4, P<.001, $\eta_p^2 = 0.31$) and Age × Congruence effects (F(1.34) = 7.4, P<.05, $\eta_p^2 = 0.15$) and a marginally significant Hemisphere effect (P = .07), no further effects of Hemisphere or Load effects were found. The Congruence × Age interaction was followed up by testing for Congruence effects in separate groups. Adolescents showed a significant main Congruence effect at parietal electrodes (Congruence: F(1,16) = 12.8, P<.005, $\eta_p^2 = 0.45$), indicating higher parietal negativity to incongruent than congruent Stroop stimuli, irrespective of n-back condition. Adults did not show a significant main Congruence effect (F(1,18) = 1.7, P = .20, $\eta_p^2 = 0.09$) at parietal leads. A post-hoc analyses however showed that this was caused by the presence of a Load × Congruence interaction at parietal leads in adults (F(1,18) = 5.6, P<.05, $\eta_p^2 = 0.24$), further testing per Load level revealed no significant N450 interference effect in the 0-back condition (F(1,18) = 0.37, P = .55, $\eta_p^2 = 0.02$), but there was a significant N450 interference effect in the 1-back condition when a concurrent load had to be maintained in WM (F(1,18) = 9.4, P<.01, $\eta_p^2 = 0.34$).

Summarizing these N450 results; in the 0-back condition when there was no concurrent WM-load adolescents showed significant N450-interference effects at all parieto-occipital (PO7, PO8) and parietal (P1, P2) electrodes whereas adults did not. In the 1-back condition, when a letter had to be maintained in WM while performing the Stroop task, adolescents and adults now both showed significant N450-interference effects at PO7, P1 and P2 electrodes, but not at PO8.

3.2.2. SP/P600

The SP interference effect was analyzed in a window from 760 to 840 ms in adults and from 620 to 780 ms in adolescents at centro-parietal (CP1, CP2) and parietal (P1, P2) electrodes at which the SP reached maximal amplitude (see topographic maps and GFP plots in Fig. 4). Mean area amplitude measures in the above mentioned time windows were

Table 2
Mean area values and standard deviations (between brackets) of the N450 (420–460 ms for adolescents and adults) and SP and frontal effect (adolescents: 620–780 ms; adults: 760–840 ms) windows in the Stroop task, for congruent and incongruent stimuli in load-0 and load-1 conditions.

			Stroop trials				
			N450	N450	SP	SP	Frontal effect
			(P1/2)	(PO7/8)	(P1/2)	(CP1/2)	(F5/7)
Adolescents (N = 17)	WMload 0	C	14.5 (9.1)	8.2 (6.0)	5.9 (6.0)	5.1 (5.1)	0.3 (6.5)
		IC	12.3 (8.8)	6.1 (5.7)	8.5 (7.6)	7.2 (6.8)	1.6 (6.0)
	WMload 1	C	13.4 (10.7)	7.2 (6.9)	7.4 (6.5)	6.1 (5.7)	2.6 (6.7)
		IC	10.7 (9.1)	5.3 (5.2)	10.5 (7.3)	9.4 (6.3)	3.4 (5.7)
Adults (N = 19)	WMload 0	C	6.7 (6.8)	2.7 (4.2)	2.0 (3.2)	2.1 (3.7)	−.7 (4.1)
		IC	7.0 (6.9)	3.1 (4.6)	3.1 (3.5)	3.2 (3.8)	−.1 (3.9)
	WMload 1	C	7.0 (5.5)	3.0 (3.7)	3.8 (2.8)	3.6 (2.8)	1.9 (2.1)
		IC	5.8 (5.5)	2.1 (3.6)	4.2 (3.1)	4.2 (3.5)	1.8 (3.8)
C = Congruent, IC = Incongruent							

entered in Repeated Measures Age×Load×Congruence×Location (CP, P)×Hemisphere (left, right) ANOVAs. This analysis did yield no five-, four- or three-way interactions, but revealed only three two-way interactions:

1) A significant Congruence×Age interaction (F(1,34)=7.8, P<.01, $\eta_p^2=0.17$), of which further testing showed significant centro-parietal SP Congruence effects in both groups (e.g. higher SP amplitude in incongruent Stroop trials), but effects had larger effect sizes in adolescents (Congruence: F(1,16)=16.8, P<.001, $\eta_p^2=0.51$) than in adults (F(1,18)=7.3, P<.05, $\eta_p^2=0.29$).
2) A Location×Age interaction (F(1,34)=5.0, P<.05, $\eta_p^2=0.13$) showed maximum centroparietal SP amplitude in adolescents (Location: F(1,16)=5.7, P<.05, $\eta_p^2=0.26$), whereas SP amplitude did not differ between centroparietal and parietal locations in adults (Location: F(1,18)=.002, P=.967, $\eta_p^2=0.00$).
3) A Load×Hemisphere interaction (F(1,34)=11.5, P<.005, $\eta_p^2=0.25$) showed that SP amplitude increased on both congruent and incongruent trials when a concurrent WM-load was imposed (1-back) as compared to when no load was imposed (0-back) (see Table 2), this increase was larger above the left (F(1,34)=8.3, P<.01, $\eta_p^2=0.20$) than right (F(1,34)=5.8, P<.05, $\eta_p^2=0.15$) centroparietal cortex.

3.2.3. Frontal activity in the SP window

An additional analysis at frontal leads in the SP time window was conducted since clear amplitude differences between conditions were observed in the average ERPs and topographic maps over left frontal leads (see SP/P600 maps in Fig. 4). A 2 (Age)×2 (Load)×2 (Congruence)×2 (Electrode; F5, F7) repeated measures ANOVA did not yield a four-way interaction or any effects of the Congruence factor. There however was a three-way Load×Electrode×Age interaction (F(1,34)=4.7, P<.05, $\eta_p^2=0.12$). This interaction was further explored by testing for Electrode×Load effects in separate groups. In adults there was a main Load effect (F(1,18)=19.0, P<.001, $\eta_p^2=0.51$), indicating larger left frontal SP activity with increased load during processing of both congruent and incongruent stimuli at both F5 and F7. In adolescents, a Load×Electrode interaction was found (F(1,16)=5.1, P<.05, $\eta_p^2=0.24$); the Load effect was only significant at F5 (F(1,16)=6.0, P<.05, $\eta_p^2=0.27$), but not at F7 (F(1,16)=2.8, P=.11, $\eta_p^2=0.15$).

4. Discussion

In this study a dual-task paradigm was used to measure the effects of WM-load manipulation on the control of interference by distracting stimuli (faces) in a word–face Stroop task in adolescents and adults. In adults, decreases in interference control or the ability to suppress the influence of distracters have previously been reported when WM is occupied by holding high loads of information (de Fockert et al., 2001; Lavie and De Fockert, 2005; Lavie et al., 2004). Since fronto-parietal networks that are involved in the regulation of such WM-maintenance-interference control interactions are still immature in adolescents, we expected adolescents to have more problems than adults with suppressing the processing of distracter faces, especially when demands on prefrontal cortex (PFC) increase by manipulating distraction and WM-load at the same time.

4.1. Behavioral Stroop interference and effects of WM-load

Manipulation of WM-load was successful as shown by significantly lower accuracy and slower responding in the 1-back than 0-back task. Manipulations of Stroop congruence (interference) were also successful. Both with and without a concurrent WM-load, responding slowed and errors and omissions increased in the presence of incongruent distracter faces, compared to when faces were congruent with the to be categorized word (e.g. face of a female and word female). Besides these effects for all participants, it was found that adolescents made more errors than adults in 0-back, 1-back and Stroop tasks and also missed more trials in the latter. This suggests that attention/cognitive control functions still continue to develop throughout adolescence, as was suggested in previous studies (Casey et al., 2005; Luna et al., 2001, 2010).

The expected extra increase in interference with a concurrent WM-load was however not revealed by the behavioral data, not in adults nor in adolescents. According to Load theory, an active top–down mechanism of attentional control mediated by prefrontal cortical areas depends on WM and plays an important role in the maintenance of goal directed behavior in the presence of interference (Lavie et al., 2004). When WM is loaded, distracter interference in a Stroop task is suggested to increase because resources necessary for goal maintenance are consumed by concurrent WM processes. Evidence for this theory has been shown, mainly by Lavie and co-workers, in a number of studies (for a review, see Lavie and De Fockert, 2005).
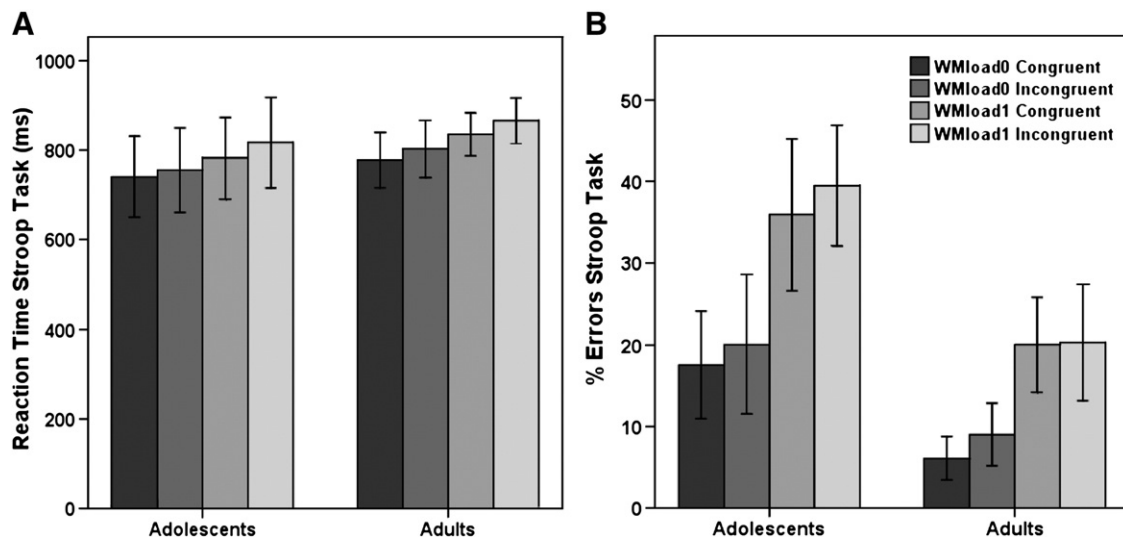

Fig. 3. Bar graphs of (A) average reaction times (in ms) and (B) percentage of errors for adolescents and adults in the WMload-0 Congruent, WMload-0 Incongruent, WMload-1 Congruent and WMload-1 Incongruent conditions of the Stroop task. Error bars indicate 95% confidence intervals.
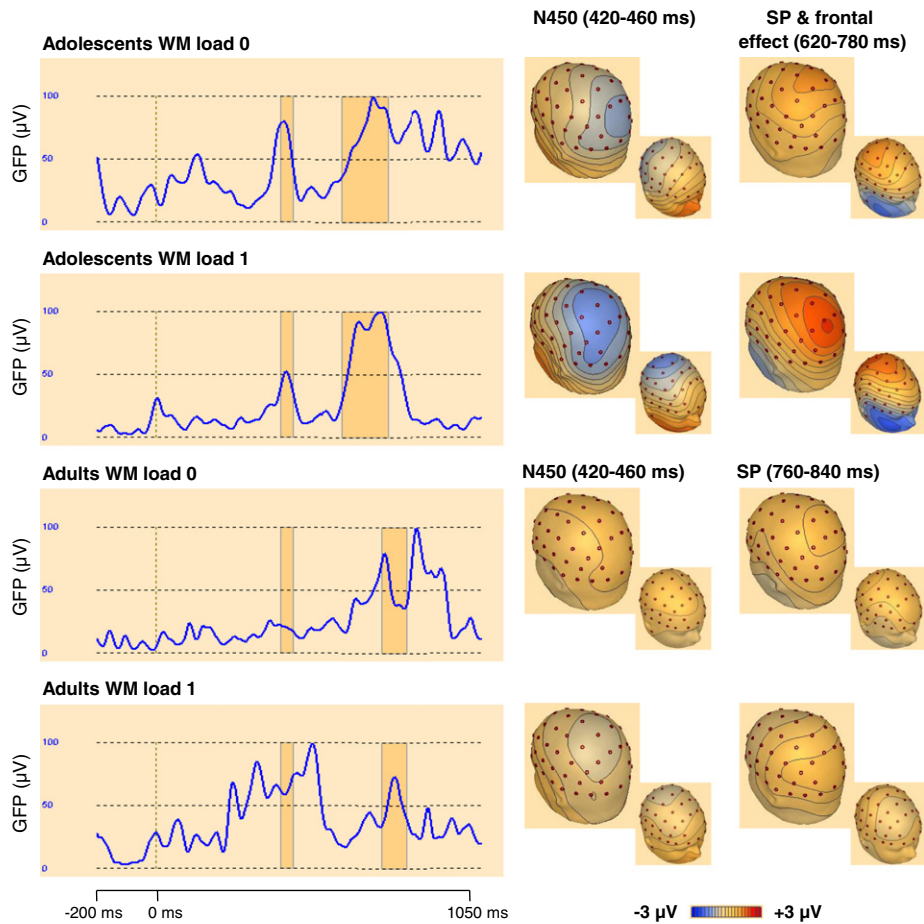
Fig. 4. Global Field Power of Stroop trials and Topographic maps of Stroop N450 effects (420–460 ms in adults and adolescents) and SP and frontal effects (620–780 ms in adolescents and 760–840 ms in adults) across 60 electrodes in WMload-0 and WMload-1 conditions. The plots and maps are based on the amplitudes of Incongruent minus Congruent conditions; maps depict time points at which the effects were maximal.

However, there are also behavioral studies that did not replicate WM load effects on interference control in adults when using similar face–word or other paradigms (Jongen and Jonkman, 2011; Kim et al., 2005; Park et al., 2007; Woodman et al., 2001). One explanation might be that subjects do experience higher distracter interference with load but have enough capacity to resolve conflict online so that it is no longer visible in the response. In this case load × congruence effects should be visible in ERPs, for which there is some evidence that will be discussed below.

4.2. Effects of WM-load on conflict detection (N450)

Stroop interference effects (N450 and SP) were observed in adults and adolescents. In line with previous studies (Chen et al., 2011; Jongen and Jonkman, 2011; Lansbergen et al., 2007; Liotti et al., 2000; Markela-Lerenc et al., 2004; Qiu et al., 2006; West, 2003, 2004) the N450 effect was the first interference effect in the brain and was marked by enhanced negativity around 450 ms in response to incongruent compared to congruent stimuli. On the basis of its sensitivity to different experimental manipulations of conflict strength the N450 has been linked to the process of conflict detection (Lansbergen et al., 2007; Liotti et al., 2000; Tillman and Wiens, 2011; West and Alain, 2000; West et al., 2005). In our study the N450 response had a posterior distribution above parietal and occipital–temporal cortex in contrast to the central–frontal distribution reported in color–word Stroop tasks. This posterior distribution is similar to "N450" distributions reported in the only other ERP study that we know of that used a highly similar word–face Stroop task (Jongen and Jonkman, 2011) and in a developmental

study in which a color–object Stroop task was used (Jongen and Jonkman, 2008). The present occipital–temporal N450 effect would be in line with higher attentional processing of the (gender of) the distracter face in the incongruent condition. Whereas we did no source localisation in the present study, prior fMRI (Haxby et al., 2000, 2002) and ERP studies (Sun et al., 2010) have provided evidence for gender–face processing in/above fusiform cortex and face processing studies have localized activity above temporal–occipital cortex to fusiform cortex (Rossion et al., 2003; Schweinberger et al., 2002). Furthermore two studies by Fruhholz et al. (2009a,b) provided evidence that interference effects similar to N450 can be observed at parietal and occipital electrodes when processing face stimuli (in the presence of irrelevant contextual information), and that increased activity for incongruent trials in the fusiform cortex is related to this face categorization. On the basis of this literature we suggest that the posterior N450 response in our word–face Stroop task reflects enhanced processing of the distracter faces when to-be categorized gender names are incongruent with the distracter.

Based on Load theory and the protracted development of frontal–parietal networks used for interference control in adolescents (Luna et al., 2004, 2010) we expected ERP conflict responses (N450 and/or SP) to be increased in adolescents due to reduced availability of resources for top–down control, especially in situations when high demands are put on top–down executive control such as when one has to hold a load in working memory while simultaneously suppressing Stroop-induced conflict (as in the current 1-back-Stroop task). This hypothesis was partly confirmed by a 5-way Load × Congruence × Age × Location × Hemisphere interaction effect for the N450. Further testing of this interaction showed
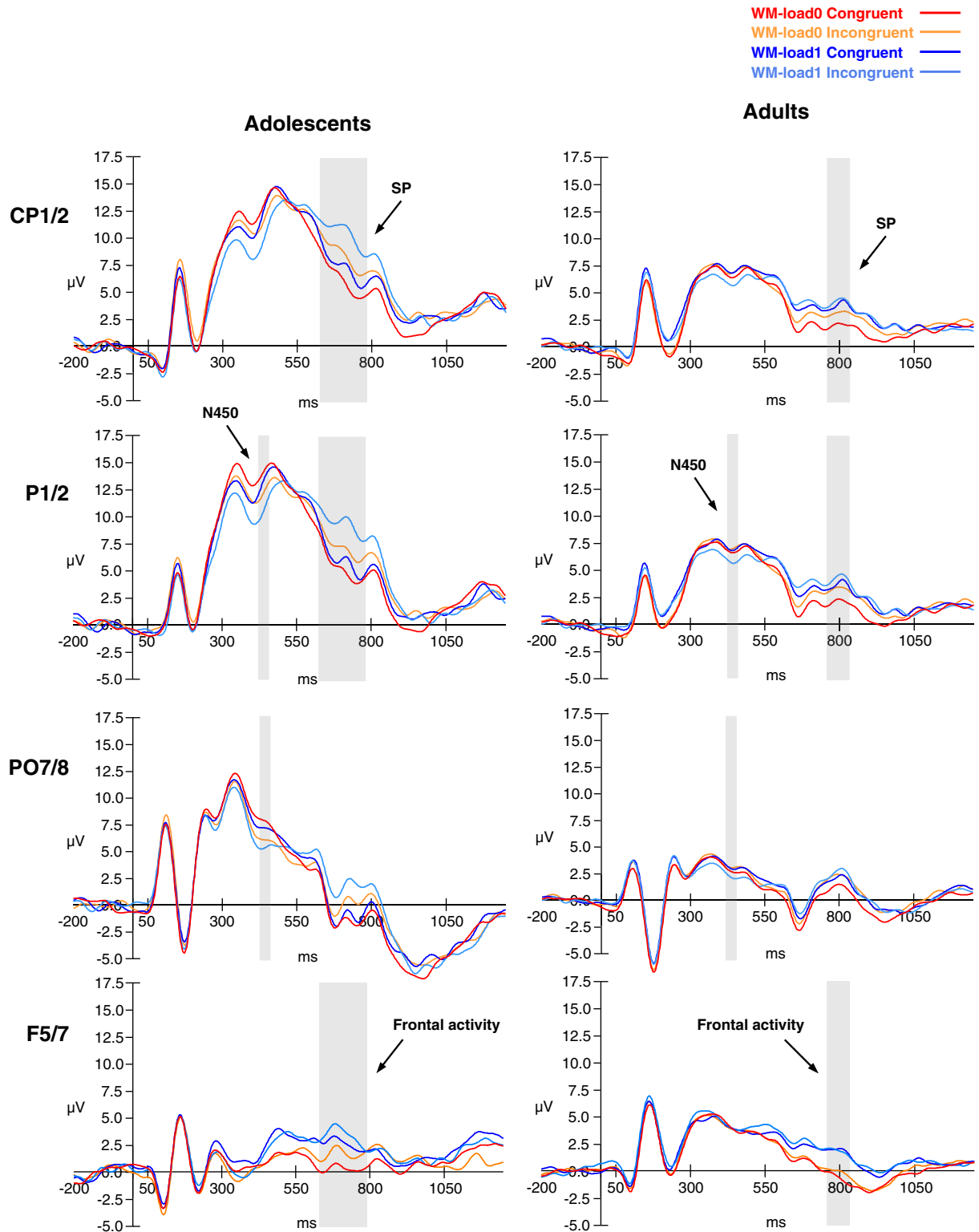
Fig. 5. Grand-averaged ERPs of adults and adolescents at combined (averaged) electrodes CP1&CP2, P1&P2, PO7&8 and F5&F7 in WMload-0, WMload-1, Congruent and Incongruent conditions elicited by face-word Stroop stimuli. Analyzed windows for N450 and SP and frontal activity are indicated by gray rectangles.

that in adults the posterior N450-interference response was modulated by WM-load (Load×Congruence interaction) as predicted by Load theory. More specifically, adults did not show an N450 interference effect when no concurrent WM-load had to be maintained (in the 0-back condition). However, when simultaneous refreshing of letter information in the 1-back task was required during performance of the Stroop task, there was a significant N450 Stroop interference effect above left occipital

cortex (PO7) and parietal cortex. In contrast, adolescents already showed a significant N450 Stroop interference effect when no information had to be maintained concurrently in WM (e.g. in the 0-back condition). When a concurrent WM task was performed, the N450-interference effect was still present above left temporal–occipital cortex and parietal cortex, but did not further increase. We suggest that the higher parietal–occipital N450 conflict response found in adults when holding a concurrent WM-

load is caused by reduced (frontal) top–down control on distracter, in this case face, processing. Such an interpretation would be consistent with findings from a prior fMRI study that used a similar WM-face-name Stroop task and reported increased activation in fusiform face areas associated with distracter face processing when higher WM-loads were imposed in their adult subjects (de Fockert et al., 2001). It is not clear why adolescents did not show a further increase in the N450 interference effect with increasing WM-load. One explanation might be that adolescents already reached a maximum level of resource depletion in the 0-back condition (due to dual-task demands) allowing no further rise in interference effects (or distracter processing), but such a conclusion would need further experimentation. Nevertheless, the overall reduced accuracy in the Stroop and 0- and 1-back tasks and the larger N450-interference effect in the 0-back condition in adolescents suggest that they have still immature attentional or interference control functions. Although this cannot be confirmed in the present study this is suggested to be caused by the protracted development of the networks including frontal, striatal and parietal brain regions (Sowell et al., 1999) known to be involved in WM and distracter suppression (Bunge and Wright, 2007; Hopfinger et al., 2000; Klingberg et al., 2002; Luna et al., 2010; McNab and Klingberg, 2008).

4.3. Effects of WM-load on the SP/P600 interference effects

A conflict SP effect (sometimes also called a P600 effect in the Stroop literature) followed the N450 and was marked by enlarged positivity above centro-parietal cortex when the gender of the distracter face was in conflict with the to-be-categorized gender–word compared to when it was not. A significant Age × Congruence interaction showed that this centro-parietal SP Stroop interference effect was significantly larger in adolescents than adults in both load conditions. On the basis of the Stroop-ERP literature parietal-SP effects are suggested to reflect enhanced processing of response-relevant information used to guide response selection in incongruent trials (Chen et al., 2011; Jongen and Jonkman, 2008, 2011; Lansbergen et al., 2007; Liotti et al., 2000; Markela-Lerenc et al., 2004; Qiu et al., 2006; West, 2003). Parietal-SP effects have been localized to parietal cortex in adults (Chen et al., 2011) and fMRI studies have reported evidence for a role of parietal cortex in supporting stimulus–response mappings that facilitate response selection in the Stroop task (Bunge et al., 2002; Casey et al., 2000; Rushworth et al., 2001). When adopting this response-selection SP relation, the higher SP interference effects in adolescents might reflect the recruitment of more resources to guide response selection in situations with high response-conflict. Such increased resource demands for response selection on incongruent trials in adolescents is not surprising in light of the above discussed N450 findings of their higher conflict detection responses above occipital cortex. Higher detection of conflict (e.g. higher processing of distracter-faces) might have led to higher activation of the incorrect response requiring more resources for subsequent selection of the correct response. The centro-parietal SP increased in amplitude in both age groups when a WM-load was imposed, but this increase occurred for both the congruent and incongruent Stroop trials (main Load effect) and was hence thought to be associated with general depletion of resources. In an earlier ERP study using a similar WM-Stroop task (Jongen and Jonkman, 2011), adults only showed a WM-load effect on the later SP/P600 and only on incongruent trials. In our adults processing bottlenecks occurred earlier in time, already on the N450, and during the response selection (SP/P600) stage affected both congruent and incongruent processing. This might be due to the fact that our subjects were collected from a community sample to match them with our adolescents on education level and thus had lower verbal STM/WM capacity and considerably lower IQ scores than the adults in the Jongen and Jonkman (2011) study, perhaps causing earlier depletion of resources.

Adults additionally showed a higher load-related amplitude increase above left frontal cortex in the time window in which the centro-parietal SP occurred. This load-related increase in left frontal activity was also seen in adolescents but only at electrode F5 and with a much smaller effect size. Since these load-related increases were not specific for situations in which there was conflict between names and faces they are thought to reflect enhanced attention control needed for dual-task performance. There are two possible explanations for this higher left frontal activity when subjects had to hold a letter from the 1-back task in WM during Stroop processing. The first explanation is that it reflects higher top–down control on posterior conflict processing areas when holding a concurrent load. Such a conclusion is supported by an fMRI study from Egner and Hirsch (2005) in which a similar face–name Stroop task was used (without WM load manipulation) and PFC activation was accompanied by a decrease in behavioral Stroop interference. But since ERP results do not allow for strong conclusions about sources based solely on scalp topography such conclusions remain speculative at this stage. The weaker load effect on frontal activity in the Stroop task in adolescents is supported by earlier Stroop and inhibition studies also reporting reduced PFC activity in adolescents (Adleman et al., 2002; Rubia et al., 2000). A second possibility is that the load-related left PFC activity increase is a reflection of the rehearsal or refreshment of letters from the n-back task during Stroop processing. Left PFC activation has been linked to processes of rehearsal in prior studies (Braver et al., 1997; Curtis and D'Esposito, 2003). Adopting such a rehearsal account, the weaker left frontal load effects of adolescents might mean that they engaged in less rehearsal and this would be congruent with the larger number of memory errors made by adolescents in the 1-back task and with findings that individuals with higher WM-capacity show more PFC recruitment in WM tasks that are demanding (Osaka et al., 2003). Moreover, in a previous study adults were also found to have larger increases in frontal activation with increases in WM-load than children (Thomason et al., 2009). But such conclusions need further investigation.

5. Conclusion

The present combination of a WM-Stroop dual-task and the application of ERPs has provided new information about the time-point at which WM-capacity influenced selective attention processes needed during interference control in adolescents and adults. ERP results suggest that interference control is differentially affected by changes in WM-capacity in adolescents than adults. Adolescents performed worse than adults on Stroop trials and WM trials. In adults, enhanced N450 interference effects were found above face processing areas when a concurrent WM-load had to be held in memory and based on the literature this was interpreted as evidence for enhanced interference from distracter faces in the face–name Stroop task. N450 results in adolescents showed that they experienced stronger interference from distracter faces than adults and this interference was already present when WM was not loaded. SP results showed higher conflict responses at parietal sites in adolescents than adults, irrespective of WM-load. Based on the literature these parietal SP interference effects were suggested to reflect higher recruitment of resources for selection/enhancement of the correct response and/or suppression of the incorrect response in incongruent trials. This higher SP response in adolescents is consistent with their larger N450 conflict detection response that might have evoked larger incorrect response activation the suppression of which needed more resources during the later SP-response-processing stage. In addition, load-related increases above left frontal cortex in the SP interval were present in both groups, but were weaker in adolescents and might reflect immature rehearsal processes or reduced top–down attentional control over posterior areas involved in conflict processing. The main conclusion is that adolescents have worse distracter

suppression than adults, caused by lower availability of resources for top–down control.

Acknowledgments

References

Achenbach, T.M., 1991a. Manual for the Child Behavior Checklist/4–18 and 1991 Profile. University of Vermont Department of Psychiatry, Burlington.
Achenbach, T.M., 1991b. Manual for the Youth Self-report and 1991 Profile. University of Vermont Department of Psychiatry, Burlington.
Achenbach, T.M., Rescorla, L.A., 2003. Manual for the ASEBA Adult Forms & Profiles. University of Vermont, Research Center for Children, Youth, & Families, Burlington, VT.
Adleman, N.E., Menon, V., Blasey, C.M., White, C.D., Warsofsky, I.S., Glover, G.H., Reiss, A.L., 2002. A developmental fMRI study of the Stroop color–word task. NeuroImage 16, 61–75.
Anderson, V.A., Anderson, P., Northam, E., Jacobs, R., Catroppa, C., 2001. Development of executive functions through late childhood and adolescence in an Australian sample. Developmental Neuropsychology 20, 385–406.
Braver, T.S., Cohen, J.D., Nystrom, L.E., Jonides, J., Smith, E.E., Noll, D.C., 1997. A parametric study of prefrontal cortex involvement in human working memory. NeuroImage 5, 49–62.
Bunge, S.A., Hazeltine, E., Scanlon, M.D., Rosen, A.C., Gabrieli, J.D., 2002. Dissociable contributions of prefrontal and parietal cortices to response selection. NeuroImage 17, 1562–1571.
Bunge, S.A., Wright, S.B., 2007. Neurodevelopmental changes in working memory and cognitive control. Current Opinion in Neurobiology 17, 243–250.
Burgess, G.C., Braver, T.S., 2010. Neural mechanisms of interference control in working memory: effects of interference expectancy and fluid intelligence. PLoS One 5, e12861.
Casey, B.J., Thomas, K.M., Welsh, T.F., Badgaiyan, R.D., Eccard, C.H., Jennings, J.R., Crone, E.A., 2000. Dissociation of response conflict, attentional selection, and expectancy with functional magnetic resonance imaging. Proceedings of the National Academy of Sciences of the United States of America 97, 8728–8733.
Casey, B.J., Tottenham, N., Liston, C., Durston, S., 2005. Imaging the developing brain: what have we learned about cognitive development? Trends in Cognitive Sciences 9, 104–110.
Chen, A., Bailey, K., Tiernan, B.N., West, R., 2011. Neural correlates of stimulus and response interference in a 2–1 mapping stroop task. International Journal of Psychophysiology 80, 129–138.
Curtis, C.E., D'Esposito, M., 2003. Persistent activity in the prefrontal cortex during working memory. Trends in Cognitive Sciences 7, 415–423.
Davies, P.L., Rose, J.D., 1999. Assessment of cognitive development in adolescents by means of neuropsychological tasks. Developmental Neuropsychology 15, 227–248.
de Fockert, J.W., Rees, G., Frith, C.D., Lavie, N., 2001. The role of working memory in visual selective attention. Science 291, 1803–1806.
Demetriou, A., Christou, C., Spanoudis, G., Platsidou, M., 2002. The development of mental processing: efficiency, working memory, and thinking. Monographs of the Society for Research in Child Development 67, i–viii, 1–155; discussion 156.
Dolcos, F., Miller, B., Kragel, P., Jha, A., McCarthy, G., 2007. Regional brain differences in the effect of distraction during the delay interval of a working memory task. Brain Research 1152, 171–181.
Durston, S., Thomas, K.M., Worden, M.S., Yang, Y., Casey, B.J., 2002. The effect of preceding context on inhibition: an event-related fMRI study. NeuroImage 16, 449–453.
Egner, T., Ely, S., Grinband, J., 2010. Going, going, gone: characterizing the time-course of congruency sequence effects. Frontiers in Psychology 1, 154.
Egner, T., Hirsch, J., 2005. The neural correlates and functional integration of cognitive control in a Stroop task. NeuroImage 24, 539–547.
Engle, R.W., Kane, M.J., 2004. Executive attention, working memory capacity, and a two-factor theory of cognitive control. In: Ross, B. (Ed.), The Psychology of Learning and Motivation. Academic Press, New York, pp. 145–199.
Fruhholz, S., Fehr, T., Herrmann, M., 2009a. Early and late temporo-spatial effects of contextual interference during perception of facial affect. International Journal of Psychophysiology 74, 1–13.
Fruhholz, S., Fehr, T., Herrmann, M., 2009b. Interference control during recognition of facial affect enhances the processing of expression specific properties—an event-related fMRI study. Brain Research 1269, 143–157.
Gathercole, S.E., 1999. Cognitive approaches to the development of short-term memory. Trends in Cognitive Sciences 3, 410–419.
Giedd, J.N., 2004. Structural magnetic resonance imaging of the adolescent brain. Annals of the New York Academy of Sciences 1021, 77–85.
Grimault, S., Robitaille, N., Grova, C., Lina, J.M., Dubarry, A.S., Jolicoeur, P., 2009. Oscillatory activity in parietal and dorsolateral prefrontal cortex during retention in visual short-term memory: additive effects of spatial attention and memory load. Human Brain Mapping 30, 3378–3392.
Haxby, J.V., Hoffman, E.A., Gobbini, M.I., 2000. The distributed human neural system for face perception. Trends in Cognitive Sciences 4, 223–233.

Haxby, J.V., Hoffman, E.A., Gobbini, M.I., 2002. Human neural systems for face recognition and social communication. Biological Psychiatry 51, 59–67.
Hopfinger, J.B., Buonocore, M.H., Mangun, G.R., 2000. The neural mechanisms of top–down attentional control. Nature Neuroscience 3, 284–291.
Jeyakumar, S.L.E., Warriner, E.M., Raval, V., Ahmad, S.A., 2004. Balancing the need for reliability and time efficiency: short forms of the Wechsler Adult Intelligence Scale-III. Educational and Psychological Measurement 64, 71–87.
Jongen, E.M., Jonkman, L.M., 2008. The developmental pattern of stimulus and response interference in a color–object Stroop task: an ERP study. BMC Neuroscience 9, 82.
Jongen, E.M., Jonkman, L.M., 2011. Effects of concurrent working memory load on distractor and conflict processing in a name–face Stroop task. Psychophysiology 48, 31–43.
Kane, M.J., Engle, R.W., 2003. Working-memory capacity and the control of attention: the contributions of goal neglect, response competition, and task set to Stroop interference. Journal of Experimental Psychology. General 132, 47–70.
Kim, S.Y., Kim, M.S., Chun, M.M., 2005. Concurrent working memory load can reduce distraction. Proceedings of the National Academy of Sciences of the United States of America 102, 16524–16529.
Klingberg, T., Forssberg, H., Westerberg, H., 2002. Increased brain activity in frontal and parietal cortex underlies the development of visuospatial working memory capacity during childhood. Journal of Cognitive Neuroscience 14, 1–10.
Krawczyk, D.C., Morrison, R.G., Viskontas, I., Holyoak, K.J., Chow, T.W., Mendez, M.F., Miller, B.L., Knowlton, B.J., 2008. Distraction during relational reasoning: the role of prefrontal cortex in interference control. Neuropsychologia 46, 2020–2032.
Kwon, H., Reiss, A.L., Menon, V., 2002. Neural basis of protracted developmental changes in visuo-spatial working memory. Proceedings of the National Academy of Sciences of the United States of America 99, 13336–13341.
Lansbergen, M.M., Kenemans, J.L., van Engeland, H., 2007. Stroop interference and attention-deficit/hyperactivity disorder: a review and meta-analysis. Neuropsychology 21, 251–262.
Lavie, N., De Fockert, J., 2005. The role of working memory in attentional capture. Psychonomic Bulletin and Review 12, 669–674.
Lavie, N., Hirst, A., de Fockert, J.W., Viding, E., 2004. Load theory of selective attention and cognitive control. Journal of Experimental Psychology. General 133, 339–354.
Lenroot, R.K., Giedd, J.N., 2006. Brain development in children and adolescents: insights from anatomical magnetic resonance imaging. Neuroscience and Biobehavioral Reviews 30, 718–729.
Leon-Carrion, J., Garcia-Orza, J., Perez-Santamaria, F.J., 2004. Development of the inhibitory component of the executive functions in children and adolescents. The International Journal of Neuroscience 114, 1291–1311.
Liotti, M., Woldorff, M.G., Perez, R., Mayberg, H.S., 2000. An ERP study of the temporal course of the Stroop color–word interference effect. Neuropsychologia 38, 701–711.
Luciana, M., Conklin, H.M., Hooper, C.J., Yarger, R.S., 2005. The development of nonverbal working memory and executive control processes in adolescents. Child Development 76, 697–712.
Luna, B., Garver, K.E., Urban, T.A., Lazar, N.A., Sweeney, J.A., 2004. Maturation of cognitive processes from late childhood to adulthood. Child Development 75, 1357–1372.
Luna, B., Padmanabhan, A., O'Hearn, K., 2010. What has fMRI told us about the development of cognitive control through adolescence? Brain and Cognition 72, 101–113.
Luna, B., Thulborn, K.R., Munoz, D.P., Merriam, E.P., Garver, K.E., Minshew, N.J., Keshavan, M.S., Genovese, C.R., Eddy, W.F., Sweeney, J.A., 2001. Maturation of widely distributed brain function subserves cognitive development. NeuroImage 13, 786–793.
Lundqvist, D., Flykt, A., Öhmann, A., 1998. The Karolinska Directed Emotional Faces (KDEF). Karolinska Institute, Stockholm.
Markela-Lerenc, J., Ille, N., Kaiser, S., Fiedler, P., Mundt, C., Weisbrod, M., 2004. Prefrontal-cingulate activation during executive control: which comes first? Brain Research. Cognitive Brain Research 18, 278–287.
McNab, F., Klingberg, T., 2008. Prefrontal cortex and basal ganglia control access to working memory. Nature Neuroscience 11, 103–107.
Osaka, M., Osaka, N., Kondo, H., Morishita, M., Fukuyama, H., Aso, T., Shibasaki, H., 2003. The neural basis of individual differences in working memory capacity: an fMRI study. NeuroImage 18, 789–797.
Padmala, S., Bauer, A., Pessoa, L., 2011. Negative emotion impairs conflict-driven executive control. Frontiers in Psychology 2, 192.
Park, S., Kim, M.S., Chun, M.M., 2007. Concurrent working memory load can facilitate selective attention: evidence for specialized load. Journal of Experimental Psychology. Human Perception and Performance 33, 1062–1075.
Passolunghi, M.C., Cornoldi, C., De Liberto, S., 1999. Working memory and intrusions of irrelevant information in a group of specific poor problem solvers. Memory and Cognition 27, 779–790.
Pecchinenda, A., Heil, M., 2007. Role of working memory load on selective attention to affectively valent information. European Journal of Cognitive Psychology 19, 898–909.
Qiu, J., Luo, Y., Wang, Q., Zhang, F., Zhang, Q., 2006. Brain mechanism of Stroop interference effect in Chinese characters. Brain Research 1072, 186–193.
Rossion, B., Joyce, C.A., Cottrell, G.W., Tarr, M.J., 2003. Early lateralization and orientation tuning for face, word, and object processing in the visual cortex. NeuroImage 20, 1609–1624.
Rubia, K., Overmeyer, S., Taylor, E., Brammer, M., Williams, S.C., Simmons, A., Andrew, C., Bullmore, E.T., 2000. Functional frontalisation with age: mapping neurodevelopmental trajectories with fMRI. Neuroscience and Biobehavioral Reviews 24, 13–19.
Rubia, K., Smith, A.B., Woolley, J., Nosarti, C., Heyman, I., Taylor, E., Brammer, M., 2006. Progressive increase of frontostriatal brain activation from childhood to adulthood during event-related tasks of cognitive control. Human Brain Mapping 27, 973–993.

Rushworth, M.F., Paus, T., Sipila, P.K., 2001. Attention systems and the organization of the human parietal cortex. The Journal of Neuroscience 21, 5262–5271.

Rypma, B., Berger, J.S., D'Esposito, M., 2002. The influence of working-memory demand and subject performance on prefrontal cortical activity. Journal of Cognitive Neuroscience 14, 721–731.

Schleepen, T.M., Jonkman, L.M., 2010. The development of non-spatial working memory capacity during childhood and adolescence and the role of interference control: an N-Back task study. Developmental Neuropsychology 35, 37–56.

Schweinberger, S.R., Pickering, E.C., Jentzsch, I., Burton, A.M., Kaufmann, J.M., 2002. Event-related brain potential evidence for a response of inferior temporal cortex to familiar face repetitions. Brain Research. Cognitive Brain Research 14, 398–409.

Segalowitz, S.J., Santesso, D.L., Jetha, M.K., 2010. Electrophysiological changes during adolescence: a review. Brain and Cognition 72, 86–100.

Semlitsch, H.V., Anderer, P., Schuster, P., Presslich, O., 1986. A solution for reliable and valid reduction of ocular artifacts, applied to the P300 ERP. Psychophysiology 23, 695–703.

Sowell, E.R., Thompson, P.M., Holmes, C.J., Jernigan, T.L., Toga, A.W., 1999. In vivo evidence for post-adolescent brain maturation in frontal and striatal regions. Nature Neuroscience 2, 859–861.

Spreen, O., Strauss, E., 1998. A Compendium of Neuropsychological tests, Second Edition. Oxford University Press, New York, NY.

St. Clair-Thompson, H.J., 2010. Backwards digit recall: a measure of short-term memory or working memory. European Journal of Cognitive Psychology 22, 286–296.

Stroop, J.R., 1935. Studies of interference in serial verbal reactions. Journal of Experimental Psychology 18, 643–662.

Sun, Y., Gao, X., Han, S., 2010. Sex differences in face gender recognition: an event-related potential study. Brain Research 1327, 69–76.

Thomason, M.E., Race, E., Burrows, B., Whitfield-Gabrieli, S., Glover, G.H., Gabrieli, J.D., 2009. Development of spatial and verbal working memory capacity in the human brain. Journal of Cognitive Neuroscience 21, 316–332.

Tillman, C.M., Wiens, S., 2011. Behavioral and ERP indices of response conflict in Stroop and flanker tasks. Psychophysiology 48, 1405–1411.

Wechsler, D., 1991. Wechsler Intelligence Scale for Children, 3rd ed. Psychological Corporation, New York.

Wechsler, D., 1997. Wechsler Adult Intelligence Scale, 3rd ed. The Psychological Corporation, San Antonio, TX.

West, R., 2003. Neural correlates of cognitive control and conflict detection in the Stroop and digit-location tasks. Neuropsychologia 41, 1122–1135.

West, R., 2004. The effects of aging on controlled attention and conflict processing in the Stroop task. Journal of Cognitive Neuroscience 16, 103–113.

West, R., Alain, C., 2000. Effects of task context and fluctuations of attention on neural activity supporting performance of the Stroop task. Brain Research 873, 102–111.

West, R., Jakubek, K., Wymbs, N., Perry, M., Moore, K., 2005. Neural correlates of conflict processing. Experimental Brain Research 167, 38–48.

Woodman, G.F., Vogel, E.K., Luck, S.J., 2001. Visual search remains efficient when visual working memory is full. Psychological Science 12, 219–224.