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Developmental Trends for Object and Spatial Working Memory: a Psychophysiological Analysis

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This study examined developmental trends in object and spatial working memory (WM) using heart rate (HR) to provide an index of covert cognitive processes. Participants in 4 age groups (6 – 7, 9 – 10, 11 – 12, 18 – 26, $n = 20$ each) performed object and spatial WM tasks, in which each trial was followed by feedback. Spatial WM task performance reached adult levels before object WM task performance. The differential developmental trends for object and spatial WM found in this study are taken to suggest that these WM components are separable. Negative performance feedback elicited HR slowing that was more pronounced for adults than for children. The development of performance monitoring as indexed by covert HR slowing following performance feedback contributes to WM performance.

Working memory (WM) comprises those functional components of cognition that allow humans to comprehend and mentally represent their immediate environment, to retain information about their immediate past experience, to support the acquisition of new knowledge, to solve problems, and to formulate, relate, and act on current goals (Baddeley & Logie, 1999). Therefore, WM is a key component of human cognition. The developmental literature has consistently shown that children's ability to maintain and manipulate information in WM develops slowly, and does not reach mature levels until late childhood (Casey, Giedd, & Thomas, 2000; Diamond, 2002; Gathercole, Pickering, Ambridge, & Wearing, 2004; Hamilton, Coates, & Heffernan, 2003; Hitch, 2002; Logie & Pearson, 1997; Pickering, 2001; Pickering, Gathercole, Hall, & Lloyd, 2001). WM is an important contributor to many abilities that are acquired during the school-age period, such as reading and mathematics (Cowan et al., 2003; Gathercole, 2004; Hitch, Towse, & Hutton, 2001), and it is often conceptualized as the driving force behind cognitive development (Case, 1992; Kail, 1990; Pascual-Leone, 1995).

One of the most generally accepted conceptualizations of WM comes from a model developed by Baddeley and Hitch (Baddeley, 1992a, 1992b; Baddeley & Hitch, 1974). This model suggests that WM is a construct consisting of multiple specialized components of cognition, including a supervisory system (the "central executive") and specialized temporary memory systems, a phonologically based store (the phonological loop), and a visuospatial store (the visuospatial sketchpad). The central executive is involved in the control and regulation of the WM system. It is considered to perform various executive functions, such as coordinating the two temporary memory systems, focusing and switching attention, and activating representations within long-term memory. Despite the fact that the unitary structure of the central executive has been called into question (e.g., Alloway, Gathercole, & Pickering, 2006; Bayliss, Jarrold, Gunn, & Baddeley, 2003; Engle, Tuholski, Laughlin, & Conway, 1999; Kane et al., 2004; Wagner, Bunge, & Badre, 2004, see also: Friedman & Miyake, 2000; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001), WM is generally agreed to consist of multiple specialized temporary memory systems.

Many studies have focused on phonological short-term memory in adults (Baddeley, 1992a, 1992b; Smith & Jonides, 1997) and in children (Alloway & Gathercole, 2005; Baddeley, Gathercole, & Papagno, 1998; Cowan, 2002; Gathercole & Hitch, 1993;

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Gathercole et al., 2004; Hitch, 2002). Visuospatial short-term memory has received less attention and is less well understood than phonological WM. Initially, visuospatial WM was assumed to be a unitary system for setting up and manipulating visuospatial images as well as storing short-term visuospatial information (Baddeley, 1992a, 1992b; Baddeley & Hitch, 1974). Numerous studies, however, have shown a double dissociation between tasks for object and spatial WM suggesting empirical evidence for the existence of separate subcomponents within the visuospatial sketchpad (Belger et al., 1998; Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999; Hecker & Mapperson, 1997; Klauer & Zhao, 2004; Logie, 1995; Mecklinger & Pfeiffer, 1996; Nystrom et al., 2000; Smith et al., 1995). Animal and human neuroimaging studies, for example, have shown that spatial and object memory are related to activation in different brain regions: the dorsal and ventral prefrontal cortex, respectively (Courtney, Ungerleider, Keil, & Haxby, 1996; Wilson, O'Scalaidhe, & Goldman-Rakic, 1993).

Recent studies that have attempted to examine the development of separate subcomponents for object and spatial WM in a single design (Hamilton et al., 2003; Logie & Pearson, 1997; Pickering et al., 2001) suggest that developmental trajectories for object and spatial WM components can be dissociated through the use of the *developmental fractionation technique* (Hitch, 1990). According to this technique, age-related changes in object WM have been observed to follow a slower trajectory than age-related changes in spatial WM. However, Hamilton et al. (2003) argued that these findings should be interpreted with caution given their observation that WM performance is influenced by age-related changes in the speed of information processing and by executive control functions. Importantly, the relative contribution of these factors to WM performance was found to differ between age groups, complicating the assessment of developmental trends in WM. Similarly, in the context of the multicomponent WM model (Baddeley & Hitch, 1974) we should take into account to what extent tasks used to assess object and spatial WM components tap control functions exercised by the central executive (Hitch et al., 2001; Klauer & Zhao, 2004). Executive control functions may well continue to develop into adolescence (Diamond, 2002; Huizinga, Dolan, & Van der Molen, 2006; Luna, Garver, Urban, Lazar, & Sweeney, 2004; Stuss, 1992; Welsh, 2002), complicating the interpretation of the results of studies of WM development.

The primary goal of the present study was to examine developmental trends in object and spatial WM while keeping procedural differences between object and spatial WM tasks minimal. Participants were presented with a series of stimuli ranging between four and eight items. They were required to respond to the stimulus using one button when the stimulus was new (object task) or presented in a new location (spatial task), and another button when the stimulus had been presented previously in the series (object task) or when it occupied a location that it had occupied previously (spatial task). The participants also performed two control tasks in which the previously presented stimuli (object task) or locations (spatial task) were cued. Memory demands were allegedly absent in the control tasks; therefore, response speed and accuracy were assumed not to discriminate between different series lengths, and between object and spatial WM control tasks. In addition, a reaction time (RT) task as a measure of basic performance speed and the random number generation (RNG) task, a task that has been demonstrated in the past to provide a reliable indicator of executive control function (Baddeley, Emslie, Kolodny, & Duncan, 1998; Miyake et al., 2000; Towse & Neil, 1998), were included to allow for an assessment of their potential contribution to developmental trends in object and spatial WM.

A secondary goal of the present study was to examine developmental trends in object and spatial WM vis-à-vis the recordings of the participants' heart rate (HR) during task performance. There is a large body of research showing a bidirectional relation between HR and information processing demands. HR decelerates during the deployment of attention in the service of detecting potentially relevant information, whereas processing and transforming that information is associated with HR speeding (Lacey & Lacey, 1974; for a review see Van der Molen, Somsen, & Orlebeke, 1985). In previous work, HR has been observed to slow when participants anticipate a target stimulus embedded in a series of nontarget stimuli, with more slowing when the number of nontarget stimuli preceding the target stimulus increased (Van der Molen, Somsen, & Jennings, 2000). This anticipatory slowing of HR became more pronounced with advancing age from middle childhood into adolescence and adulthood (Van der Molen et al., 2000). In related studies, focusing on the processing of feedback stimuli, HR was found to decelerate in anticipation of performance feedback with added deceleration when the information provided by the feedback was negative (Crone et al., 2003). The cardiac changes associated with feedback processing were less pronounced during childhood compared with adolescent and adult participants (Crone, Jennings, & Van der Molen, 2004). Finally, it has been shown that mnemonic task demands induce HR speeding, the more so when the task demands on memory processing increase (e.g., Backs & Seljos, 1994; for a review see Jennings et al., 1986).

The pattern of findings that emerged from the HR literature on information processing provides the context for a set of specific predictions regarding the relation between object and spatial WM on the one hand and cardiac changes on the other. First, preparing for the WM target stimulus is predicted to induce an anticipatory HR deceleration that returns to baseline at the time of the initiation of the response (e.g., Somsen, Van der Molen, Jennings, & Orlebeke, 1985). Second, increasing demands on WM should elicit an acceleratory HR trend reducing the peak of anticipatory deceleration (e.g., Backs & Seljos, 1994). Assuming that WM demands are similar for object and spatial WM tasks, anticipatory HR changes should not differentiate between tasks. Third, the anticipation of performance feedback was assumed to induce added deceleration that is larger for negative feedback compared with positive feedback (e.g., Crone et al., 2003). The cardiac changes associated with feedback processing were predicted to be smaller in children compared with adults (Crone et al., 2004; Van der Molen et al., 2000). Finally, it was assumed that the magnitude of the cardiac changes associated with feedback processing is proportional to the ability to detect that an error has been made in response to the target stimulus. This ability should decrease with increasing WM load and should be less pronounced for children compared with adults. In sum, this study aimed at investigating developmental trends in object and spatial WM using HR changes as converging measures of processing demands on WM and performance monitoring.

Method

Participants

Three groups of children and one group of young adults participated in the study; twenty 6- to 7-year-olds (11 girls, $M = 6.6$, $SE = 0.68$), twenty 9- to 10-year-olds (11 girls, $M = 9.7$, $SE = 0.72$), twenty 11- to 12-year-olds (11 girls, $M = 11.9$, $SE = 0.70$), and twenty 18- to 26-year-olds (10 females, $M = 21.9$, $SE = 2.09$). The young adults were students at the University of Amsterdam who received course credit for participating. The children were recruited through a local school, and were selected with the help of their teachers and with their parents' consent. Children who participated in the study had average or above-average IQ according to teacher reports. Participants with learning disorders, behavioral disorders, or a history of neurological impairments were excluded from the study. No detailed information regarding parental income, parental education level, or family size of the participants was collected. However, participants were mostly Caucasian, and tended to come from middle-class families.

Experimental Tasks

Stimulus displays. For the object tasks, two displays were presented on each trial; a stimulus display and an outcome display. The object WM task stimulus display consisted of a square box at the center of the screen in which different abstract symbols were presented in sequential order. Abstract figures (www.cog.brown.edu/~tarr/stimuli.html#pw) were used to minimize the possibility that participants would use verbal strategies. In the spatial WM task 4, 6, or 8 square boxes were presented in a vertical row at the center of the screen. On each trial, a happy face was presented on one of the square boxes. Participants were told that the square boxes in both the object task and the spatial task each contained a reward, and were instructed to collect as many rewards as possible. To this end, they were required to press one of two keys (''Z'' or ''/'') with their left or right index finger, respectively. The keys corresponded to the options ''open the box'' and ''do not open the box.'' The assignment of keys was counterbalanced across participants and held fixed across the experiment. Participants were not instructed to respond as fast as possible. A representation of the stimulus displays used in the object and spatial WM tasks and an example of a trial are presented in Figure 1. Participants were instructed that in the object WM task, a box should be opened every time a *new figure* was presented, but should be kept closed when an earlier displayed figure was presented. In the spatial WM task participants were instructed to open a box every time the happy face was presented in a *new location*, and not when it appeared in one of the locations it was presented in before. This manipulation required participants to keep track of the figures that were already seen within the sequence and the locations that had already been occupied. Upon pressing one of the keys, the stimulus display was replaced by the outcome display showing a square containing a ''$'' sign, indicating that the box was opened correctly, or an ''X'' sign, indicating that the box was opened incorrectly. If the participant decided not to open the

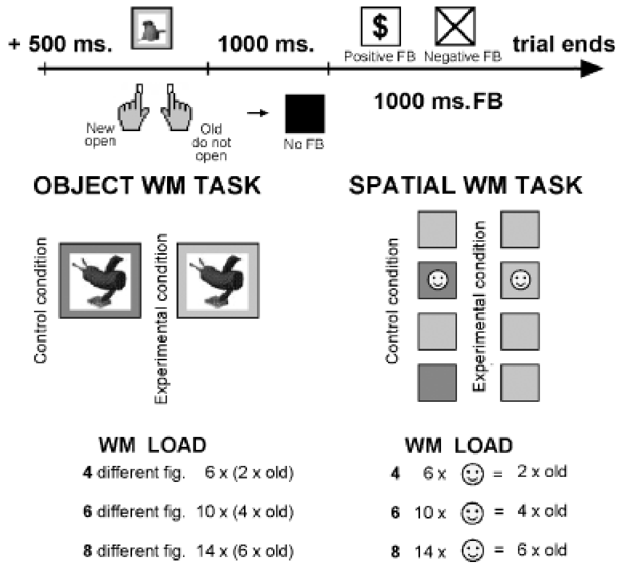

Figure 1. Object working memory (WM) task trial with examples of positive ($), negative (x), and noninformative (■) feedback displays. The bottom half of the figure shows the task design and stimulus displays for the experimental and control conditions of the WM tasks. See text for details about stimulus presentation.

box, it turned black irrespective of the accuracy of the participant's decision.

The task consisted of two separate conditions. In the experimental condition, the edge of the square box was always green in the object WM task, and the square boxes were always green in the spatial WM task; therefore, the participants needed to remember whether a figure had been seen before, or whether a happy face had previously appeared in a location. In the control condition, all performance requirements were the same, except that in this condition in the object task the edge of the square box turned red when a previously seen figure was presented, and in the spatial task the square box in which the happy face appeared turned red when it was a location where it had appeared before. The order of experimental and control conditions was counterbalanced across participants. The presentation time of the target stimulus was response-terminated. A response resulted in a 1,000 ms blank screen, followed by a 1,000 ms outcome display. The intertrial interval varied between 500, 1,000, 1,500, or 2,000 ms.

Task design. In each block, three series of trials consisting of 4, 6, or 8 different abstract symbols or spatial locations were presented. Thus, both the object and spatial WM tasks consisted of load 4, 6, and 8 trials. Symbols and locations were presented 6, 10, or 14 times, requiring participants to open the box 4, 6, and 8 times and keeping it closed 2, 4, and 6 times, respectively (see Figure 1). Which stimuli were repeated was pseudorandomized to ensure that two consecutive trials were never identical and that the stimulus associated with the final trial in a series had not been previously seen. Participants had to keep stimuli active in memory throughout the series. During both WM tasks, the load 4, 6, and 8 trial series were presented 4 times in the control condition and 4 times in the experimental condition. Consequently, a total of 24 load 4 trials, 40 load 6 trials, and 56 load 8 trials were presented in both the experimental and control condition, resulting in 120 trials for the control condition and 120 trials for the experimental condition in total. To familiarize participants with the stimuli and procedure, they received a block of practice trials consisting of two series of 6 and 8 experimental and control trials at the beginning of each task.

Speed of processing (SP) task. The SP task was based on a 2-choice RT task adopted from Van den Wildenberg (2003). In the SP task, an arrow was presented in the center of the screen, pointing to the left or to the right. Participants had to respond to this arrow as quickly and accurately as possible by pressing the "Z" or "/" key with their left or right index finger, corresponding to the direction of the arrow. The response-to-stimulus interval was set at 1,000 ms. Participants received a block of 15 practice trials at the beginning of the task. The task consisted of a series of 75 trials.

RNG task. The RNG task was a computer version of the RNG task (Huizinga et al., 2006) developed by Towse and Neil (1998). Participants were required to generate numbers randomly by pressing keys, labeled 1–10, on a computer keyboard. A brightly colored star was shown for 1,000 ms on each trial, after which it was replaced by a question mark indicating that participants should respond as fast as possible. The response-to-stimulus interval was set at 1,000 ms. Participants received a block of 15 practice trials at the beginning of the task. The RNG task consisted of a block of 75 trials.

Exit interview. Upon completing the experiment, all participants were asked whether they had used any particular strategy when performing the WM tasks. Special attention was given to any kind of verbal strategies participants might have used. These strategies were probed by questions like: "How did you remember which box you should open or how did you remember which object was old or new?" All answers were quantified, using two categories. Participants who reported they were "naming the abstract figures" were coded as having used a verbal strategy. Participants reporting, for example, to have "just looked at the pictures" were coded as using a nonverbal strategy.

Psychophysiological measures. During the WM tasks, the electrocardiogram (ECG) and respiration were continuously recorded. The ECG was recorded from three electrodes, attached via the modified lead-2 placement. Respiration was recorded through a sensor situated across the abdomen. The signals were sampled and recorded by a computer at a rate of 400 Hz. The recorded interbeat intervals (IBIs) were screened for physiologically impossible readings and artifacts. These were corrected by adjusting specific parameters in the program that extracted the IBIs from the digitized ECGs. The respiration signal was used only to eliminate HR changes associated with gross respiratory changes (Jennings et al., 1981).

Procedure. All participants were tested individually in a quiet laboratory or classroom. All participants completed all tasks. Each session began with attaching the physiological equipment and ended with the exit-interview. The tasks were presented in two possible orders: RNG, spatial WM, object WM and RT, or vice versa. Stimuli were presented in color against a white background on a 15-in. computer screen placed at a distance of 70 cm from the participant. Preceding each task participants were given written instructions, which were shown on the screen. To make sure that even the youngest children understood the instructions, these were also read to the participants and care was taken that all participants understood the instructions after practice. The two WM tasks took approximately 25 min each to complete. The other tasks lasted approximately 5 min each. There were short breaks between all tasks, and children were given a drink and a cookie halfway through the experiment. Including instructions and breaks, participants spent approximately 90 min in the laboratory or classroom.

Results

Results will be presented in two major sections. The performance results will be presented first, followed by the presentation of the HR findings.

Behavioral Data

The performance of participants was examined by computing accuracy and median RT. The data were then submitted to repeated measures analyses of variance (ANOVAs) with age group (4), as a between-subjects factor and task (object/spatial) and condition (experimental/control), and load (4, 6, or 8) as within-subjects factors.

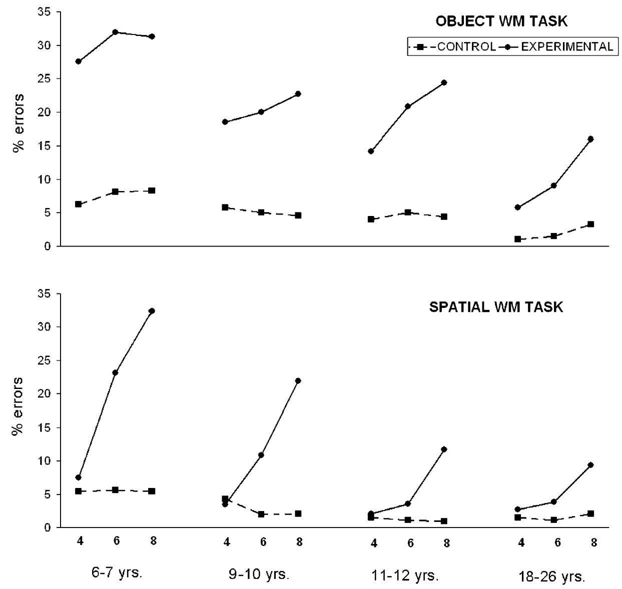

Figure 2. Average percentage of errors in the experimental and control condition as a function of increasing working memory (WM) load for each age group and both WM tasks separately. Age differences are observed in the experimental condition for both the spatial and object WM tasks.

Response accuracy on the WM tasks. The accuracy scores for each age group are presented in Figure 2. Main effects for age group, task, condition, and load were significant (all $ps < .001$, all $\eta_p^2 > .521$) and these effects were qualified by a significant four-way interaction between age group, load, condition, and task, $F(6, 152) = 8.04$, $p < .001$, η_p^2 .241. The four-way interaction was followed up by separate ANOVAs for the experimental and control conditions. The ANOVA on the data from the control condition did not result in any significant effects, $ps > .05$. In contrast, the ANOVA for the experimental condition yielded a Load $\times$ Task Type interaction, $F(2, 152) = 16.34$, $p < .001$, η_p^2 .177, that showed a larger increase in the percentage of errors with an increase in WM load for the spatial WM task (15%) than for the object WM task (7%). This interaction was qualified by a three-way interaction between age group, load, and task type, $F(6, 152) = 9.34$, $p < .05$, η_p^2 .269. Separate analyses revealed a significant interaction between age group and task demands for the spatial WM task, $F(6, 152) = 13.28$, $p < .001$, η_p^2 .344. Comparisons between age groups indicated that the effect of spatial WM load was significantly larger in the 6- to 7-year-olds compared with the 9- to 10-year-olds, $F(2, 76) = 4.63$ $p < .05$, η_p^2 .109, the 11- to 12-year-olds, $F(2, 76) = 22.16$ $p < .001$, η_p^2 .368, and the 18- to 26-year-olds, $F(2, 76) = 29.78$ $p < .001$, η_p^2 .439. The 9- to 10-year-olds showed a larger effect of increasing WM load than the 11- to 12-year-olds, $F(2,76) = 6.74$, $p < .01$, η^2_p .151, and the 18- to 26-year-olds, $F(2,76) = 12.24$, $p < .001$, η^2_p .244. Finally, the 11- to 12-year-olds and 18- to 26-year-olds did not differ significantly from each other, $p = .28$, η^2_p .033.

Similar analyses carried out on the performance data generated by the object task revealed only a main effect of age group, $p < .001$, η^2_p .463, but no Load × Group interaction, $p > .05$, η^2_p .067. Thus, in the object task, the effect of WM load did not differ between age groups. However, a repeated measures ANOVA on the object task data with age Group (4) as a between-subjects factor and condition (experimental/control) and load (4, 6, or 8) as within-subjects factors did result in a Condition × Age Group interaction, $F(3,76) = 12.09$, $p < .001$, η^2_p .323. The decrease in accuracy in the experimental condition, relative to the control condition, was smaller in older participants.

Comparisons between age groups showed that the increase in the percentage of errors as a function of WM load was significantly larger for 6- to 7-year-olds (22%) than for 9- to 10-year-olds (15%), $F(1,38) = 9.80$, $p < .01$, η^2_p .205, 11- to 12-year-olds (16%), $F(1,38) = 7.71$, $p < .01$, η^2_p .169, and 18- to 25-year-olds (8%), $F(1,38) = 42.20$, $p < .001$, η^2_p .526. The 9- to 10-year-olds did not differ from the 11- to 12-year-olds, $p = .98$, η^2_p .000, but the 9- to 10-year-olds and the 11- to 12-year-olds performed significantly worse than the 18- to 25-year-olds, $F(1,38) = 11.05$, $p < .01$, η^2_p .225 and $F(1,38) = 8.53$, $p < .001$, η^2_p .183, respectively. Thus, spatial WM performance, as indexed by accuracy, reached adult levels earlier (at age 11–12) than object WM performance (beyond age 11–12).

Response speed on the WM tasks. The median RT for each age group, WM task, condition, and WM load are presented in Table 1. A similar ANOVA as for accuracy was performed on the speed of responding and the RT results generally parallel the accuracy results. Again, all main effects were significant (all ps $< .001$, all $\eta^2_p > .121$). These effects were qualified by a four-way interaction between age group, load, condition, and task type, $F(6,152) = 3.50$, $p < .01$, η^2_p .121. A follow-up ANOVA on the RTs that emerged from the control task did not result in significant effects (all ps $> .05$, all $\eta^2_p < .556$). Subsequent analyses for the experimental condition resulted in a significant Task × Load × Group interaction, $F(6,152) = 2.85$, $p < .05$, η^2_p .101. The analyses carried out on the data from the spatial WM task yielded a significant Load × Group interaction, $F(6,152) = 3.19$, $p < .01$, η^2_p .112. This interaction revealed that the effect of an increase in WM load in 6- to 7-year-olds differed significantly from the effect in 9- to 10-year-olds, $F(2,76) = 3.82$, $p < .05$, η^2_p .091, in the 11- to 12-year-olds, $F(2,76) = 4.02$, $p < .05$, η^2_p .096, and in the 18- to 26-year-olds $F(2,76) = 4.30$, $p < .05$, η^2_p .102. RT increased with WM load in all age groups but reached a plateau for the 6- to 7-year-olds when WM load increased from 6 to 8 locations; $M = 1{,}533$, $SE = 138.1$ and $M = 1{,}488$, $SE = 114.7$, respectively.

A similar analysis on the data from the object WM task yielded only a main effect of age group,

Table 1
Median Reaction Time for Each Age Group, Task, Condition, and WM Load

	Spatial						Object					
	Control			Experimental			Control			Experimental		
Task condition WM load	4	6	8	4	6	8	4	6	8	4	6	8
Age group 6- to 7-year-olds (*n* = 20)												
RT	1,256	1,210	1,253	1,252	1,533	1,488	1,473	1,456	1,438	1,861	1,853	1,901
SE	73.7	53.2	52.6	58.2	77.5	72.8	74.1	67	69.6	106.7	91.6	105.2
9- to 10-year-olds (*n* = 20)												
RT	793	806	823	827	887	995	1,142	1,069	1,141	1,326	1,341	1,375
SE	73.7	53.2	52.6	58.2	77.5	72.8	74.1	67	69.6	106.7	91.6	105.2
11- to 12-year-olds (*n* = 20)												
RT	690	722	726	734	810	956	943	901	921	1,113	1,189	1,150
SE	73.7	53.2	52.6	58.2	77.5	72.8	74.1	67	69.6	106.7	91.6	105.2
18- to 26-year-olds (*n* = 20)												
RT	548	564	572	585	651	776	743	704	709	985	1,050	1,027
SE	73.7	53.2	52.6	58.2	77.5	72.8	74.1	67	69.6	106.7	91.61	105.2

Note. RT = reaction time in ms; WM = working memory.

$F(3, 76) = 15.60$, $p < .001$, η_p^2 .381. Post hoc Tukey tests revealed that the 6- to 7-year-olds responded slower ($M = 1{,}872$, $SE = 94.8$) than the 9- to 10-year-olds ($M = 1{,}347$, $SE = 94.8$), the 11- to 12-year-olds ($M = 1{,}151$, $SE = 94.8$), and the 18- to 25-year-olds ($M = 1{,}021$, $SE = 94.8$). Load did not alter the preceding effects. In broad outline, these results are consistent with the accuracy results reported previously. That is, performance reached an adult level for the spatial WM task earlier than for the object WM task.

Response speed on the SP task. Performance on the SP task was evaluated by computing accuracy and median RT for each participant. The SP data were then submitted to a one way-ANOVA with group (4) as the between-subjects factor. The ANOVA for accuracy showed a main effect of group, $F(3, 76) = 18.56$, $p < .001$. Post hoc Tukey tests revealed that 6- to 7-year-olds were less accurate ($M = 15.9\%$, $SE = 8.2$) than the 9- to 10-year-olds ($M = 7.7\%$, $SE = 6.1$), the 11- to 12-year-olds ($M = 3.6\%$, $SE = 3.0$), and the 18- to 26-year-olds ($M = 3.9\%$, $SE = 5.4$). The three oldest groups did not differ significantly from each other. The ANOVA carried out on the speed of responding showed a main effect of group as well, $F(3, 76) = 36.20$, $p < .001$. Post hoc Tukey tests indicated that the 6- to 7-year-olds ($M = 588.67$, $SE = 91.4$) responded slower than the 9- to 10-year-olds ($M = 511.66$, $SE = 86.3$), the 11- to 12-year-olds ($M = 457.71$, $SE = 54$), and the 18- to 26-year-olds ($M = 362.37$, $SE = 35.8$). The mean SP did not differ between the 9- to 10-year-olds and 11- to 12-year-olds, but the oldest group responded faster than all three younger groups (all ps $< .05$). Finally, correlations between speed and accuracy were not significant.

RNG. Performance on the RNG task was assessed using Towse and Neil's (1998) RgCalc program, which produces several different indices of "randomness." The RNG index was used for our purposes. The RNG index provides the frequency of response pairs, and this frequency value may vary between 0 (*fully random*) and 1 (*fully predictable*). The RNG frequency index was submitted to a one-way ANOVA with age group (4) as a between-subjects factor and RNG as a within-subjects factor. The ANOVA failed to reveal significant differences between age groups, $p = .46$.

SP and RNG predictors. SP scores were submitted as covariates in an analysis of covariance (ANCOVA) on the WM data with age group (4) as a between-subjects factor and task (object, spatial), condition (experimental, control), and load (4, 6, or 8) as within-subjects factors. Importantly, the previously observed four-way interaction between Task $\times$ Load $\times$ Condition $\times$ Group remained significant, $F(6, 150) = 3.75$, $p < .01$, η_p^2 .131, when SP was added as a covariate. The ANCOVA revealed a significant interaction between SP and condition, $F(1, 75) = 6.93$, $p < .01$, η_p^2 .085. An additional correlation analysis was performed to examine this interaction. The correlation analysis showed that the difference in accuracy between the experimental and control condition correlated significantly with SP, $r = .63$, $n = 80$, $p < .001$. The partial correlation, corrected for age group, was also significant, $r = .29$, $n = 77$, $p < .01$. This positive relation indicated that accuracy on WM tasks increased as participants responded faster on the SP task. This association was consistent across all age groups.

RNG scores were submitted as covariates in a similar ANCOVA on the WM data. Again, the previously observed four-way interaction between Task $\times$ Load $\times$ Condition $\times$ Group remained significant, $F(6, 150) = 8.14$, $p < .001$, η_p^2 .246. However, correlation analyses for difference scores between the experimental and control conditions did not show a significant correlation with RNG for the object ($p > .05$) and spatial ($p > .05$) WM tasks.

Verbal strategies. The exit interview showed that several participants used a verbal strategy in the WM tasks. For the spatial WM task 10% of 6- to 7-year-olds, 15% of 9- to 10-year-olds, 35% of 11- to 12-year–olds, and 20% of 18- to 26-year-olds reported to have used a verbal strategy. However, for the object task, respectively, 10%, 35%, 55%, and 100% of participants reported using a verbal strategy. To determine whether verbal strategy use influenced WM task performance, the data were submitted to repeated measures ANOVAs with age group (2) and Strategy (verbal, nonverbal) as between-subjects factors and condition (experimental, control) and load (4, 6, or 8) as within-subjects factors. The data of the 6- to 7-year-olds and 18- to 26-year-olds were not included in this analysis, as only 10% of participants in the youngest group and all participants in the oldest group indicated that they used a naming strategy when performing the object WM task. Consequently, the age group factor had only two levels (9–10 vs. 11–12 years). The ANOVAs were performed on the data of each WM task, separately.

The ANOVA carried out on the spatial WM task data yielded a significant Condition $\times$ Strategy interaction, $F(1, 36) = 6.43$, $p < .05$, η_p^2 .152. Post hoc analyses showed that participants who used a verbal strategy were more accurate in the experimental condition than participants who did not ($M = 9.77$, $SE = 0.95$ vs. $M = 5.57$, $SE = 1.78$, respectively), $F(1, 36) = 4.33$, $p < .05$, η_p^2 .107, but not in the control condition, $p > .05$, η_p^2 .010. Likewise, the ANOVA carried out on the object WM task data showed that participants who used a verbal strategy were more accurate than participants who did not use a verbal strategy when performing the experimental task ($M = 23.86$, $SE = 1.56$ vs. $M = 16.35$, $SE = 1.74$), $F(1, 36) = 10.30$, $p < .01$. η_p^2 .223. Age group did not alter any of these effects.

HR Changes

The HR analyses are presented in two separate sections. The first set of analyses focused on the HR changes associated with the processing of the target stimulus and the second set of analyses focused on cardiac responses associated with the processing of the feedback stimulus.

Cardiac response associated with target processing. The cardiac response associated with the processing of the target stimulus in the control and experimental condition for the object and spatial WM tasks is presented in Figure 3. In this figure, the cardiac response is plotted in terms of IBIs. Thus, a lengthening of IBI indicates a slowing of HR. The cardiac response is plotted around the presentation of the target stimulus. That is, the target stimulus occurred during the IBI indicated as IBI-0 in the figure. The preceding IBI (IBI-1) and subsequent IBI's (IBI1, IBI2, IBI3, and IBI4) are plotted around the IBI of the target stimulus (IBI0). The IBI response is plotted relative to a pretarget stimulus baseline (IBI-2; i.e., two IBIs preceding the IBI of the target stimulus).

The plots presented in Figure 3 show the cardiac response that is typically observed when participants prepare for a significant stimulus, that is, an IBI lengthening (i.e., cardiac slowing) preceding the stimulus and a return to baseline (acceleratory recovery) upon the initiation of the response to the stimulus. In addition, it can be seen that cardiac slowing is considerably less pronounced in the object WM task compared with the spatial WM task. Quite unexpectedly, the plots presented in Figure 3 show that the difference between object and spatial tasks occurred both for the experimental and control conditions. Finally, Figure 4 shows that WM load exerted only minimal effects in the object WM task in contrast to a pronounced effect that the highest WM load has in the spatial WM task. The visual impressions created by Figures 3 and 4 were verified statistically by a repeated measures ANOVA carried out on IBI1, with Group (4), as a between-subjects factor, and task (object, spatial), condition (experimental,

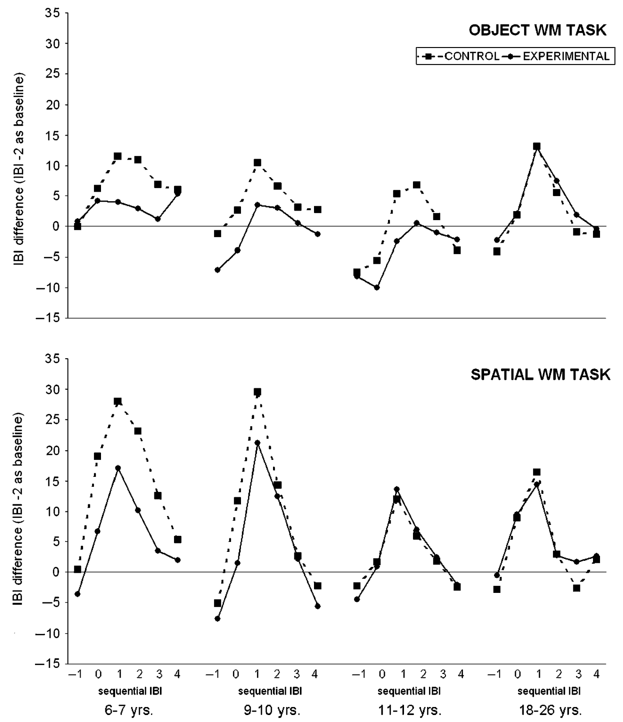

Figure 3. Six interbeat intervals (IBIs) are plotted around the presentation of the stimulus (IBI0). Average IBI length is plotted for the control and experimental condition for both working memory (WM) tasks and for each age group separately. Heart rate slows during stimulus presentation, but the relative slowing is reduced in the object WM task.

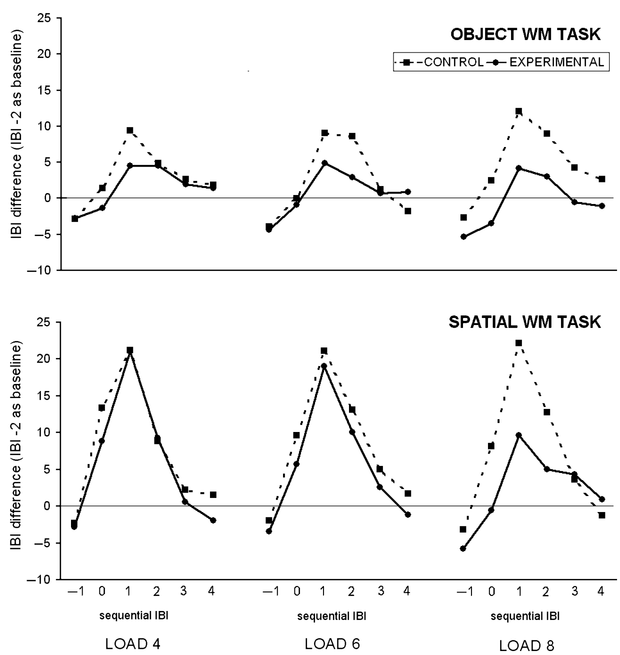

Figure 4. Six interbeat intervals (IBIs) are plotted around the presentation of the stimulus (IBI0). Average IBI length is plotted for working memeory (WM) loads 4, 6, and 8, in the control and experimental conditions for both WM tasks. Heart rate shows anticipatory slowing before stimulus presentation, and an overall relative acceleration in relation to high memory demands.

control), and load (4, 6, or 8), as within-subjects factors. The analysis focuses on the IBI following the presentation of the stimulus (IBI1), as previous studies showed that IBI1 shows the most pronounced effects of the experimental manipulation for both stimulus processing (Somsen et al., 1985) and feedback processing (Crone et al., 2003, 2004)

The ANOVA yielded a significant main effect of task, $F(1,76) = 37.87$, $p < .001$, η_p^2 .333, that was qualified by an interaction between task and load, $F(2,152) = 4.46$, $p < .05$, η_p^2 .055. This interaction was not altered by the effect of condition, $p > .05$, η_p^2 .028. Follow-up analyses performed on the data of the experimental condition revealed a significant Task × Load interaction, $F(2,152) = 6.37$, $p < .001$, η_p^2 .077. Load altered the cardiac response in the spatial WM task, $F(2,152) = 11.40$, $p < .001$, η_p^2 .130, but did not in the object WM task, $p > .10$, η_p^2 .000 (see Figure 4). Importantly, age group effects were absent, with the exception of an interaction between condition and age group that approached significance, $F(3,76) = 2.29$, $p = .085$, η_p^2 .083. This interaction is plotted in Figure 3. This figure shows that the difference between experimental and control conditions is much more pronounced in the child groups compared with adult participants. A post hoc analysis, collapsing data across the two youngest groups and the two oldest groups, indicated that the IBI shortening (i.e., cardiac speeding) induced by the mnemonic task demands was more pronounced in the younger compared with the older participants, $F(1,78) = 6.50$, $p < .02$, η_p^2 .077. Finally, correlations between IBI1 and performance measures were all nonsignificant.

Cardiac response associated with feedback processing. The IBI response associated with the feedback stimulus is plotted in Figure 5. The feedback stimulus is presented during IBI0 and the preceding (IBI-1) and subsequent IBIs (IBI1 and IBI2) are plotted as well. The cardiac response is plotted relative to a prestimulus baseline (IBI-2). The left panel of Figure 5 presents the IBI response associated with positive or negative feedback following the participant's decision to open a box (i.e., when it was judged that a stimulus was new or a location occupied for the first time). It can be seen that positive feedback is followed by a prompt return to baseline. In contrast, negative feedback is associated with added cardiac slowing (i.e., a lengthening of the IBIs subsequent to the feedback IBI). The right panel of Figure 5 displays the IBI response associated with the stimulus following the decision not to open the box (i.e., when it was judged that a stimulus had been seen previously or a location occupied before).

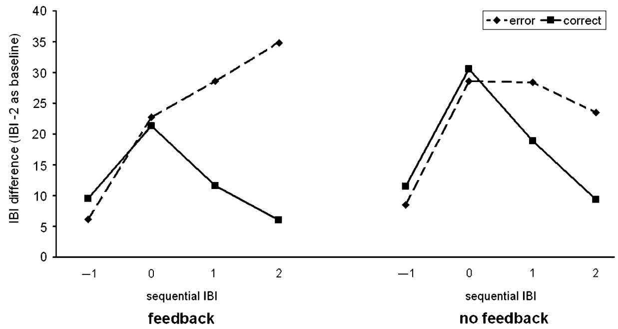

Figure 5. Four interbeat intervals (IBIs) are plotted around the presentation of the feedback (IBI0). IBI length is plotted for errors and correct responses and for the feedback and no-feedback conditions separately. Heart rate slows following erroneous responses, in both feedback conditions.

Note that in this case the stimulus was always the same (a black screen) and did not provide feedback concerning the correctness of the participant's decision. Thus, in the right panel, "correct" and "error" refer to the response, not to information that is provided by the feedback. Yet, it can be seen that acceleratory recovery is postponed on error trials relative to correct trials.

The analysis will again focus on IBI1 (the IBI following the presentation of the feedback), as this IBI was previously found to show the most pronounced effects of the experimental manipulation for feedback processing (Crone et al., 2003, 2004). The cardiac response associated with feedback processing was statistically examined by performing a repeated measures ANOVA on IBI1 with age group (4) as a between-subjects factor and task (object/spatial), feedback (informative/uninformative) and accuracy (correct/incorrect) as within-subjects factors. The factor "feedback" refers to informative stimuli indicating that the decision to open the box was correct or incorrect versus uninformative stimuli keeping participants uncertain about the correctness of their decision to leave the box closed. In the latter case, participants had to rely on their own ability to register errors. The ANOVA yielded a significant main effect of accuracy, $F(1,73) = 21.52$, $p < .001$, η_p^2 .228. Stimuli following an error delayed acceleratory recovery relative to stimuli following correct decisions. The interaction between accuracy and feedback just failed to reach an acceptable level of significance, $F(1,73) = 3.69$, $p = .059$, η_p^2 .048. This interaction was not altered by task, $p > .05$, η_p^2 .024, or age group, $p > .05$, η_p^2 .058.

There was a significant interaction between task and feedback, $F(1,73) = 4.25$, $p < .05$, η_p^2 .055, showing more pronounced cardiac slowing when feedback

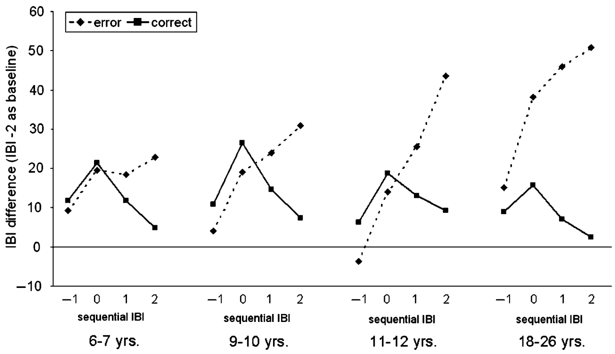

Figure 6. Four interbeat intervals (IBIs) are plotted around the presentation of the feedback (IBI0). IBI length is plotted for errors and correct responses for each age groups separately. Heart rate slows following performance errors, but this slowing is larger for older age groups.

was informative compared with when it was uninformative but this interaction is difficult to interpret as the higher order interaction with accuracy was lacking, $p > .05$, η_p^2 .024.

More important, the Age Group × Accuracy interaction reached significance, $F(3, 73) = 4.37$, $p < .01$, η_p^2 .152. This interaction is plotted in Figure 6. All age groups exhibit the cardiac slowing associated with the stimulus presented following an incorrect response but the slowing increased with advancing age. More specifically, the IBI1 difference between correct and error trials failed to attain significance in the two younger age groups, ps > .15, η_p^2s < .065, but reached significance in the 11- to 12-year-olds, $F(1, 19) = 4.57$, $p < .05$, η_p^2 .194, and it was significant in adult participants, $F(1, 16) = 14.65$, $p < .001$, η_p^2 .478. Interestingly, the higher order interaction between the effects of age group, accuracy, and feedback fell short of significance, $p = .22$, η_p^2 .058, suggesting that children's performance-monitoring ability develops slowly for both internal (uninformative feedback) and external (feedback) error detection.

Discussion

The primary goal of the present study was to examine developmental trends in object and spatial WM while avoiding procedural differences between tasks and using control tasks, with zero memory demands as a baseline. Age groups performed equally well on the object and spatial control tasks with error rates below 10% for all three series lengths. These data suggest that the assessment of object and spatial WM performance is not confounded by unwanted procedural differences between WM tasks. The patterns of results observed in the experimental conditions of the object and spatial WM tasks show clear differences. The results of the spatial WM task show that all age groups performed equally accurately when the series length was short (i.e., four items). Using a WM load of only four items the performance of all age groups equaled the performance on the spatial control task (i.e., error rate < 10%). However, in all age groups, performance declined when WM load increased, while remaining above chance level. Interestingly, this decline was more pronounced for younger age groups. All age groups differed significantly from each other, with the exception of the 11- to 12-year-olds and the adult participants. This finding indicates that spatial WM memory reached mature levels by the end of middle childhood.

The results that emerged from the object WM task show adult error rates for the lowest WM load that were similar to the results obtained for the spatial task (below 10%). However, in children error rates were higher, the more so when children were younger (in the youngest age group error rates approached 30%). The difference in error rates between the 11- and 12-year-olds and adults suggests that object WM continues to develop into adolescence.

Why did imposing a WM load demand in the experimental condition of the object WM task have such a detrimental effect on children's performance compared with the effect that a similar manipulation had on their performance in the experimental condition of the spatial WM task, while the performance difference between memory tasks was considerably less pronounced for the adult participants? The data suggest that the object WM task is more difficult than the spatial WM task; adults may have compensated for this difficulty by adopting a verbal strategy. All adults reported to have used a verbal stimulus-coding strategy when performing the object WM task whereas only 10% of the youngest childen did, and this finding is consistent with studies on the use of verbal strategies (Palmer, 2000; Pickering, 2001). The analysis aiming at the potential influence of verbal strategy use indicated that participants who used a verbal strategy were more accurate in performing the object WM task than those who did not (84% vs. 76%, respectively). Therefore, the differences in performance between age groups are likely to be due to differences in the way participants approached the task, rather than differences in WM capacity per se.

Previously, Hamilton et al. (2003) reported that developmental trends in object and spatial WM may be obscured by concurrent changes in basic processing speed and/or executive control function (see also: Gathercole et al., 2004; Hitch, 2002; Kail, 1992; Kail & Park, 1994; Logie & Pearson, 1997;

Pickering, 2001). In order to assess the potentially compromising effect of developmental change in basic processing speed, a standard choice reaction task was adopted from the literature (Van den Wildenberg & Van der Molen, 2004) and included in the present study. This task yielded the typical age-related increase in the speed and accuracy of responding, consistent with prior studies (Case, Kurland, & Goldberg, 1982; Fry & Hale, 2000; Luna et al., 2004; Salthouse, 1992). When basic processing speed was included as a covariate in the analysis examining the speed of responding on the object and spatial WM task all significant effects continued to exist. The pattern of significant effects that was obtained for the speed of responding on the WM tasks showed a relatively more protracted development of object WM relative to spatial WM, paralleling the findings observed for accuracy. Interestingly, correlation analyses revealed in all age groups that as participants were faster on the standard choice reaction task, they responded more accurately on the WM tasks. This finding is consistent with the hypothesis of basic processing speed as a cognitive primitive (e.g., Baltes, Staudinger, & Lindenberger, 1999) and the notion that basic processing speed provides a major dimension of individual differences in intelligence rather than developmental change in cognitive capacities (e.g., Anderson, 2001; but see Cerella & Hale, 1994).

Hamilton et al. (2003) observed that developmental differences in executive control function may compromise WM development. Executive control function is a multifacetted concept that may have several indicators (Diamond, 2002; Huizinga et al., 2006; Miyake et al., 2000; Welsh, Pennington, & Groisser, 1991; Welsh, 2002). In the present study, a single indicator, derived from the RNG task, was used that has been demonstrated in the past to provide a reliable indicator of executive control function (Baddeley et al., 1998; Miyake et al., 2000; Towse & Neil, 1998). Prior studies administering this task to children reported a mild developmental improvement in random generation between 7 years of age and adulthood (Rabinowitz, Dunlap, Grant, & Campione, 1989; Towse & Mclachlan, 1999). In the current study, however, the performance on the RNG task failed to discriminate between age groups. Moreover, correlating the RNG index of executive control function with the performance measures derived from the WM tasks failed to reveal any significant associations. However, a single index of executive control function probably does not provide sufficient insight. Therefore, these findings do not speak to the issue of a potential confound between developmental trends in WM and executive control function.

A particular feature of the present study was the use of HR changes in order to provide a convergent measure of WM load and to assess developmental change in feedback and error processing vis-à-vis the WM task demands. The advantage of this measure is that phasic IBIs allow the study of time-specific processing (stimulus vs. feedback monitoring) that cannot be observed on the basis of behavior only. The cardiac response showed the typical response associated with the preparation for a significant stimulus and the speeded response to it—anticipatory HR slowing with added deceleration upon the detection and processing of the target stimulus, which is then followed by acceleratory recovery associated with the initiation of the motor response (e.g., Somsen et al., 1985; for a review: Van der Molen et al., 1985). We expected that imposing a demand on WM would induce an acceleratory trend, thereby reducing the maximum deceleratory amplitude of the cardiac response. In general, the cardiac results were consistent with this expectation. That is, maximum HR slowing was depressed considerably when WM demands were added to the object task and to the spatial task but, in the latter task, only for the highest WM load. The cardiac response did not differentiate between the control and the experimental spatial tasks for low WM loads. The object WM task induced a much stronger acceleratory trend compared with the spatial WM task. This differential effect was the smallest for the adult participants. The latter finding could be due to qualitative changes in task performance with advancing age. Future work should examine this possibility by manipulating WM demands across a larger range.

The cardiac response associated with error and feedback processing yielded a particularly interesting finding. As predicted, negative feedback induced added cardiac slowing that was more pronounced with advancing age (e.g., Crone et al., 2003, 2004). The cardiac slowing to negative feedback has been interpreted to signal a monitoring mechanism that enables improvement of performance on subsequent trials (e.g., Crone et al., 2004). The increase in cardiac slowing to negative performance feedback with advancing age has been taken to suggest that the monitoring mechanism does not reach mature levels until adolescence or even young adulthood (Crone et al., 2004). The current findings extend the results reported previously by showing that cardiac slowing also occurs following uninformative feedback after an erroneous response. This finding indicates that cardiac slowing is a manifestation of a monitoring mechanism signaling that performance needs to be adjusted, based on the processing of external feedback or on the internal detection that an error has occurred. In this regard, the cardiac response is similar to the error-related negativity that can be recorded over central brain regions (e.g., Holroyd & Coles, 2002; Miltner, Braun, & Coles, 1997).

In conclusion, the main finding that emerged from the present study is the separability of developmental trends for object and spatial WM. This finding is consistent with a host of studies suggesting a fractionation of visuospatial WM into separate visual and spatial components (for a recent review, see Klauer & Zhao, 2004). This finding is also consistent with the developmental literature suggesting that object and spatial WM mature along different trajectories (Hamilton et al., 2003; Logie & Pearson, 1997; Pickering et al., 2001). The current HR analysis provided converging evidence by showing that object WM demands contribute to the acceleratory trend of the cardiac response to a greater extent compared with spatial WM demands thereby mirroring and supporting the behavioral findings. Moreover, not only processing demands during the presentation of WM items but also the subsequent monitoring of performance is related to overall WM performance, and both processes are sensitive to developmental change. These results demonstrate that stimulus processing and outcome monitoring should be studied in parallel and that psychophysiological measures contribute to our understanding of monitoring processes important for WM functioning that cannot be studied on the basis of behavior alone.

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