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Time monitoring and executive functioning in children and adults

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Abstract

This study examined time-based prospective memory performance in relation to individual and developmental differences in executive functioning. School-age children and young adults completed six experimental tasks that tapped three basic components of executive functioning: inhibition, updating, and mental shifting. Monitoring performance was examined in a time-based prospective memory task in which participants indicated the passing of time every 5 min while watching a movie. Separate analyses of the executive functioning data yielded a two-factor solution for both age groups, with the updating and inhibition tasks constituting a common factor and the shifting tasks constituting a separate factor. Both children and adults showed accelerating monitoring functions with low rates of clock checking during the early phase of each 5-min interval. However, compared with adults, children needed more clock checks for obtaining the same level of response accuracy. Executive functioning had selective effects on time-based prospective memory performance. In both children and adults, monitoring performance was related to the inhibition and updating components, but not to the shifting component, of executive functioning. We conclude that difficulties in temporary maintenance and updating of working memory contents may create discontinuities in sense of time, leading to an increased reliance on external cues for time keeping.

Keywords: Executive functioning; Time monitoring; Prospective memory; Updating; Inhibition; Mental shifting; School-age children; Young adults

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Introduction

Most goal-directed activities require temporal integration and monitoring of action sequences (Fuster, 1993, 2002; Luria, 1966; Norman & Shallice, 1986). In general terms, monitoring is the process by which agents assess their environments and involves activities such as assessing the progress of initiated plans, finding out what time it is, and anticipating obstacles. For example, remembering to complete an action in the future involves a monitoring phase during which the individual must monitor for the appropriate cue to execute an action. However, most everyday activities involve multiple goal-directed tasks, and efficient monitoring requires a strategy, or a scheme, for scheduling actions (i.e., when and how to monitor). In most situations, this strategy must balance the cost of monitoring against the cost of having inaccurate information about the environment, and deciding between these costs can be a complicated optimization problem (Atkin & Cohen, 1996).

Although monitoring is a necessary task for all agents, including children, insects, and robots, few studies have investigated how these agents actually behave when the goal or deadline is approaching. Yet the monitoring concept has connections to several areas, including operant conditioning (Ferster & Skinner, 1957), process control (Moray, 1986; Senders, 1983), and some areas of ethology (for a review, see Pyke, 1984). However, research on time-based prospective memory suggests certain regularities of monitoring behavior in children and adults (Ceci & Bronfenbrenner, 1985; Harris & Wilkins, 1982; for an overview, see Mäntylä & Carelli, 2006).

Ceci and Bronfenbrenner (1985) conducted a seminal study of time-based prospective memory in school-age children. In their study, 10- and 14-year-olds were instructed to remove cupcakes from an oven in exactly 30 min to avoid burning them. In another condition, the children charged a battery and were instructed to turn the charger off after 30 min to prevent overcharging. During the 30-min interval, the children played a video game in a separate room (either at home or in a laboratory setting). The clock was placed behind the children, so that the experimenter (siblings) could easily see when the children turned around to determine how much cooking or charging time remained. This checking was associated with a cost because the act of monitoring was a distraction from the game.

Ceci and Bronfenbrenner (1985; see also Ceci, Baker, & Bronfenbrenner, 1988) found that all children checked the clock frequently during the first 10 min of the waiting period and then engaged in very little clock checking until the final moments of the waiting period. Specifically, older children in both settings and younger children in the home setting reduced the frequency of monitoring actions during the middle period, from 10 to 25 min, of the task interval. When younger children were tested in the unfamiliar laboratory setting (and with an unknown experimenter), they maintained the frequency of clock checking at the same high level also during the middle phase of the task.

This study and other studies (Cicogna, Nigro, Occhionero, & Ésposito, 2005; Einstein, McDaniel, Richardson, Guynn, & Cunfer, 1995; Kerns, 2000; Maylor, Smith, DellaSala, & Logie, 2002; Park, Hertzog, Kidder, Morrell, & Mayhorn, 1997; see also Mäntylä & Carelli, 2006) suggest regularities in monitoring behavior. However, mechanisms underlying time monitoring and their relation to response accuracy (i.e., time-based prospective memory performance) are less well understood.

According to one view of prospective memory, an executive attentional system explicitly monitors the environment for target events. Following this view, retrieval occurs through the capacity-demanding attentional process of monitoring the environment for the target events. When a target event is encountered, the executive attentional system interrupts the ongoing activity and initiates the processes necessary for performing the intended action. Smith (2003) presented a strong version of this view and argued that "retrieval of an intention will never be automatic, because nonautomatic preparatory processes must be engaged during the performance interval, or the time in which the opportunity to carry out the action is likely to occur, but before the occurrence of the target event" (p. 349).

Although several studies have shown that dividing attention during retrieval decreases prospective memory performance (Einstein, Smith, McDaniel, & Shaw, 1997; Marsh & Hicks, 1998; McDaniel, Robinson-Riegler, & Einstein, 1998; Park et al., 1997), the issue concerning automatic versus controlled retrieval processes is open to debate (Einstein et al., 2005; McDaniel & Einstein, 2000; Marsh, Hicks, & Cook, 2005). It should also be noted that the contrasting views of automatic versus strategic retrieval have been examined in the context of event-based, rather than time-based, prospective memory tasks.

Even if one assumes that a variety of cognitive processes can be recruited to support prospective memory retrieval (McDaniel & Einstein, 2000), it is reasonable to argue that time-based tasks rely more heavily on executive control processes than do event-based tasks (Craik, 1986; Einstein & McDaniel, 1996). In most time-based tasks of prospective memory, intentions are triggered by time-related cues that can be mediated by external factors (e.g., noticing a clock on the wall) or internal factors (e.g., time-related associations, internal clock). Compared with event-based tasks, these cues are more implicit, and self-initiated thoughts and monitoring are critical to successful performance in most time-based tasks of prospective memory.

A number of studies provide direct evidence for the notion that prospective memory performance is mediated by executive functioning (Burgess, Veitch, de Lacy Costello, & Shallice, 2000; Glisky, 1996; Kerns, 2000; Mäntylä, 2003; Mäntylä & Nilsson, 1997; Martin, Kliegel, & McDaniel, 2003; McDaniel, Glisky, Rubin, Guynn, & Routhieaux, 1999; see also Salthouse, Atkinson, & Berish, 2003). However, few studies have examined the relation between monitoring frequency and executive functioning (Cayenberghs, DeBruycker, Helsen, & d'Ydewalle, 2005; Kerns, 2000; Kerns & Price, 2001). These studies suggest that response accuracy, but not monitoring frequency per se, is related to individual and developmental differences in executive control functions.

For example, in Kerns's (2000) study, 6- to 12-year-olds played a computer game, *CyberCruiser,* which involved driving a vehicle on a road. In addition to the primary task of driving (and earning points when not hitting other vehicles), children were instructed to monitor the level of available fuel. Using two different buttons on the joystick, they could check the fuel level and refuel when the tank was less than one quarter full. The duration of the game was 5 min, with the car running out of gas after 1 min of play without filling. If participants ran out of gas, the gas gauge was automatically refilled and the game restarted with zero points. Participants also completed four tasks of executive functioning: two tasks of visuospatial working memory (the delayed alternation–nonalternation and self-ordered pointing tasks) and two measures of inhibitory capacity (the Stroop and go–no go tasks).

Kerns (2000) found age-related differences in prospective memory performance in that younger children ran out gas more frequently than did older children. Regarding monitoring behavior, both younger and older children showed similar patterns of gas checks.

Specifically, children demonstrated a J-shaped, rather than a U-shaped, distribution of monitoring actions. Furthermore, the prospective memory measure (number of times ran out of gas) correlated significantly with three of the six executive function measures. Monitoring frequency in terms of number of gas checks correlated with one measure of executive functioning (omissions on the go–no go task), with more gas checks being related to a higher number of omission errors. However, when age was controlled, there were no significant correlations between the number of checks and the measures of executive function, suggesting that "a failure of prospective memory (running out of gas), but not the frequency of checking per se, is related to other indicators of executive control" (p. 68; for similar findings with younger adults, see also Cayenberghs et al., 2005).

Kerns and Price (2001) used the same *CyberCruiser* task as did Kerns (2000) and found that children with attention deficit hyperactivity disorder (ADHD) ran out of gas more frequently than did children without ADHD. The two groups also showed different distributions of checks in that children with ADHD repeatedly checked the gas immediately after they had run out of gas. However, there were no group differences in number of gas checks, suggesting that ADHD-related problems in executive functions are not related to monitoring frequency.

These findings are somewhat paradoxical considering that a number of studies suggest a close relation between response accuracy and executive functioning, so that participants with problems in executive functioning show impaired prospective memory performance. Most relevant studies also show significant (negative) correlations between monitoring frequency and accuracy; that is, participants who check the clock frequently also show improved performance. One possible reason for this inconsistency is that few studies have examined both monitoring frequency and response accuracy in relation to individual (and developmental) differences in executive functioning. It should also be noted that Kerns (2000), Kerns and Price (2001), and Cayenberghs and colleagues (2005) all used similar computer games (*CyberCruiser* and *Space Raider*) with specific task demands. Furthermore, the minimal effects of executive functioning on monitoring performance in these studies might be related to measurement problems (Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Miyake et al., 2000; Rabbitt, 1997; Salthouse, 2005).

In this study, we used a latent variables approach to examine time-based prospective memory performance in relation to developmental and individual differences in executive functioning. Following the studies of Miyake and colleagues (2000) and Salthouse (2005; see also Salthouse et al., 2003), our basic strategy was to statistically extract what is common among the tasks selected to tap a putative executive function and then use that ("purer") latent variable factor to examine how different executive functions relate to monitoring frequency and accuracy in children and adults. Specifically, participants completed six experimental tasks that were assumed to reflect one of the three target executive functions of shifting, updating, or inhibition. In the time monitoring task, both children (8- to 12-year-olds) and young adults (university students) were instructed to indicate the passing of time every 5 min while watching a short movie.

Our primary hypothesis was that individual and developmental differences in executive functioning would be related to time monitoring performance, so that participants with low performance in the executive functioning tasks would show less efficient monitoring performance than would participants with better cognitive control functions. It should be noted that monitoring efficiency was assumed to reflect multiple parameters, including monitoring frequency (number of clock checks) and response accuracy (timing error) and their relation to secondary task demands (monitoring costs). In this study, efficient monitoring was defined as a combination of monitoring frequency (i.e., few clock checks), distribution of clock checks (i.e., few early checks), and response accuracy (i.e., close to the deadline).

We expected selective effects of executive functioning in that individual differences in the updating component of executive functioning were expected to play a central role in time monitoring performance. Specifically, due to the dual-task nature of most prospective memory tasks (e.g., remembering a deadline while being involved in a continuous everyday activity such as attending a meeting or watching television), the individual's task is to maintain and update working memory representations of the ongoing activity while occasionally paying attention to the approaching deadline. This updating function requires monitoring and encoding task-relevant information and then revising the items held in working memory by replacing less relevant information with newer, more relevant information (Jonides & Smith, 1997). The updating process is assumed to involve "temporal tagging" (Jonides & Smith, 1997; Smith & Jonides, 1999), so that old information that is no longer relevant may be identified and discarded. This kind of management of the retained sequence of events in working memory is assumed to provide a sense of temporal continuity. Consistent with this notion, difficulties in temporary maintenance and elaboration of working memory contents may create distortions and discontinuities in subjective experience of time (Brown, 1990; Michon & Jackson, 1984), which in turn can be expected to increase reliance on external support for time keeping.

We also hypothesized that not only updating but also inhibitory processes would mediate time-based prospective memory performance. First, the updating function goes beyond the simple maintenance of task-relevant information by requiring a dynamic manipulation of the content of working memory and thus implies active suppression of old irrelevant information (Carretti, Cornoldi, DeBeni, & Romanó, 2005; Engle & Kane, 2004; Hasher, Zacks, & May, 1999; Miyake et al., 2000; Ruiz, Elosua, & Lechuga, 2005; Smith & Jonides, 1999). Second, although there is some support for a distinction between the updating and inhibition components, the issue concerning the diversity and unity of the executive functioning construct is open to debate (Baddeley, 1996; Duncan, Johnson, Swales, & Freer, 1997; Lehto et al., 2003; Miyake et al., 2000; Royall et al., 2002; Salthouse, 2005; Sluis, van der Dolan, & Stoel, 2005; Smith & Jonides, 1999; Teuber, 1972).

Method

Participants

Participants were 51 children and 62 young adults. The children, who were recruited from an elementary public school, were 8–12 years of age (mean = 10.3), with an equal number of boys and girls at each grade level. All children spoke Swedish as a first language and had no obvious behavioral or educational problems. Parental consent for participation was obtained for all children. The adult participants were Umeå University undergraduates who were 20–29 years of age (mean = 24.3 years), with an equal number of men and women. None of the participants had experience with similar experiments.

Task characteristics

Executive functioning

All participants completed the six tasks hypothesized to tap one of the three target executive functions of shifting, updating, or inhibition. Task administration either was computerized or used a paper-and-pencil format. The computerized tasks were written in Visual Basic (E-Prime), and the stimuli were displayed on a 15-inch PC monitor. Apart from some procedural differences (discussed later), child and adult participants completed the same set of executive functioning tasks. It should also be noted that our primary focus was on time control in school-age children, and the adult sample was included in the study to increase the generality of findings rather than to make direct comparisons between children and adults.

Inhibition of prepotent responses was assessed with the *stop signal* and *Stroop* tasks. In the stop signal task, the letter X or O appeared on the computer screen, and participants indicated the identity of the stimulus letter by pressing a specific key as quickly as possible. The task consisted of 48 trials, and participants were instructed not to respond (i.e., to inhibit the response) when they heard a computer-emitted tone on 10 randomly selected trials, but otherwise to keep performing the same categorization task as before. A fixation point appeared on the screen 1000 ms before target presentation, and the stop signal appeared 400–600 ms after the target (see also Logan, 1994; Salthouse et al., 2003).

In the Stroop task (Stroop, 1935), participants were instructed to name the color of a set of stimuli as quickly as possible. The neutral condition consisted of 36 rectangles printed in one of six colors: blue, brown, green, red, white, or yellow. In the incongruent condition, 36 color words were printed in a different color (e.g., "blue" printed in red color). In both conditions, the stimuli were presented on a single page. To identify children with potential reading problems, the neutral and incongruent conditions were preceded by a reading condition in which each child read a list of color words printed in black. All of the children were relatively proficient readers (mean reading time = 17.5 s) except for one child (mean reading time = 30.7 s), who was not included in the subsequent analysis. For the final sample ($n = 50$), the correlation between age and reading time was not significant, $r = -.23$, $p > .10$.

Task *shifting* was based on two experimental tasks referred to as the *connections* and *category fluency* tasks, respectively. The connections task is based on the Trail Making test, with the difference being that the length of the path-connecting successive items in the different conditions are controlled, and the same conditions include both alphabetic and numeric versions (Salthouse et al., 2000). Children completed a simplified version of the connections task. In this *color connection* task, the target items were numbers and colors rather than numbers and letters (as in the connections task). Both tasks consisted of three pages with 49 circles containing letters and numbers or two colors (pink and yellow) and numbers, respectively. In the same condition, participants drew lines between items from the same category (i.e., only between numbers, between letters, or between colors) as quickly as possible. In the different condition, they connected the items by alternating between two sequences (e.g., A–1–B–2–C–3 . . ., 1–yellow–2–pink–3–yellow . . .).

In the category fluency task (see also Parkin, Hunkin, & Walter, 1995), participants first generated instances for two separate categories ("animals" and "things to eat or drink") during a 1-min period, followed by a combined condition in which they generated instances by alternating between the two categories (e.g., cat, pizza, horse, milk, ...). Participants provided verbal responses that were recorded for subsequent analyses.

The *updating* component of executive functioning was assessed with the *n-back* and *matrix monitoring* tasks. The *n*-back task was a manual (children) or computerized (adults) version of a two-back task. In the manual version of the task, the experimenter presented a capital consonant, with one item on each page of a booklet. The pages were turned at an even pace at the rate of 2–3 s per item. The children tapped the page when they recognized a letter as the same as the letter two items back. The task consisted of four sequences of 25 letters, with seven targets in each sequence. Adult participants viewed the same set of letters presented on a computer screen at the rate of 2 s per item.

In the matrix monitoring task (Salthouse et al., 2003), a matrix appeared on a computer screen with a black dot in one of the cells. The matrix disappeared after 3 s, followed by a sequence of three arrows that indicated the movement of the dot in the (imaginary) matrix. Finally, the matrix reappeared on the computer screen with the dot in one of the cells. Participants were instructed to decide whether the position of the dot was the same as or different from the final position indicated by the arrow. Participants responded by pressing a specific key on the computer keyboard. On each of the 12 trials, children monitored one 3×3 matrix, whereas adults were presented with two 4×4 matrices, followed by two parallel sequences of arrows.

Time monitoring

In the *time monitoring* task, participants were instructed to indicate the passing of every 5 min while watching a video. They were not informed about the duration of the monitoring task (20 min for children and 30 min for adults). Children watched an animated movie (*Garfield*), and adult participants were shown another animated movie (*Spirited Away*). For each group, the video was presented on a computer monitor, and a response box with a green button and a red button was placed next to the monitor. The experimenter instructed each participant that the red button should be pressed when the clock on the monitor showed 05:00, 10:00, 15:00, and so on without informing the participant about the duration of the task. The experimenter also clarified that the red button should be used only for indicating the passing of every 5 min, whereas the green button could be used to check the clock anytime during the task. After pressing one of the buttons, the corresponding task time appeared (in red or green color) on the computer screen for 2 s. A practice phase was included in the beginning of the task to clarify the instructions and to familiarize participants with the task. The experimenter also demonstrated that the clock would start at 00:00 and that, for example, 10:00 would mean 10 min. None of the participants indicated problems in understanding the task instructions. All children were familiar with *Garfield,* but none of them reported seeing the specific episode. Six adult participants reported that they had seen the *Spirited Away* movie previously, and the monitoring data for these participants were examined separately.

Procedure

Each participant was tested individually during two 45-min sessions. Children were tested in a quiet room at their elementary school, and adult participants were tested in a similar room at the university campus. During the first session, each participant completed three executive functioning tasks: Stroop, *n*-back, and color connections. During the second session 7–10 days later, they completed the remaining three executive functioning tasks—stop signal, matrix monitoring, and category fluency—followed by the time monitoring task. Some participants also completed a *psychophysical judgment* task, but these data are not included in this article. The order of task completion was the same for all participants. For each task, the experimenter verified that the participant understood the instructions, and all of the tasks included a practice phase during which the experimenter illustrated the task instructions. Children were tested by the same female experimenter, whereas adult participants were tested by either a female or male experimenter.

Results

Executive functioning

Descriptive statistics for the six executive functioning tasks are summarized in Table 1. Both age groups show reasonable distributions, and the subsequent analyses were based on nontransformed data. For all six measures, a large value refers to poor task performance. Specifically, the difference in reading times between the neutral and incongruent conditions was the primary measure of the Stroop task. For the stop signal task, responses faster than 400 ms (i.e., before the stop signal was presented) were not included in the analysis (<5% for adults and <8% for children). Task performance was examined in terms of three measures: stop signal reaction time, omission errors, and comission errors. Omission errors refer to the number of times a participant was not able to stop responding (i.e., pressed the key when a stop stimulus was presented), and comission errors refer to the number of incorrect or failed responses (i.e., responded with the incorrect key or failed to respond to a go stimulus). Typically, the stop signal reaction time is the primary measure derived from this task, but we used a combined error (omission plus comission) as the dependent variable (see also Miyake et al., 2000; Salthouse et al., 2003). However, it should be noted that the response time and error data were highly correlated for both age groups ($r > .80$). As shown in Table 1, the mean error rate for children was 9.1 (6.2 omissions and 2.9 comissions), and adult participants averaged 3.7 errors (2.6 omissions and 1.1 comissions). In the *n*-back task, the primary dependent measure was obtained by combining the number of missed targets (maximum of 28 omissions) and the total of

Table 1
Descriptive statistics for the executive functioning tasks in children and adults

Task	Children ($n = 50$)		Adults ($n = 62$)	
	M (*SD*)	Skewness	*M* (*SD*)	Skewness
Stroop	30.44 (11.15)	0.74	12.99 (5.45)	0.76
Stop signal	9.13 (7.02)	0.88	3.72 (3.23)	1.23
Matrix	1.12 (1.31)	1.38	4.13 (1.54)	0.22
N-back	5.62 (3.59)	1.22	1.48 (1.60)	1.41
Connections	2.86 (3.81)	–0.12	9.41 (4.68)	−0.14
Category fluency	2.81 (3.79)	−0.10	4.28 (6.87)	−0.28

Note. Standard deviations are in parentheses.

number of false responses (maximum of 72 comissions). The number of incorrect responses was the dependent measure of the matrix monitoring task. As shown Table 1, both groups made relatively few errors in the matrix monitoring task, with children showing a lower level of error rate than adult participants. However, as noted earlier, children and adults completed different versions of the task (one 3×3 matrix vs. two 4×4 matrices), and so a direct comparison between the age groups level is not meaningful. Finally, following earlier studies, the two shifting tasks were based on the difference in number of responses between the same and mixed conditions. Also here, the apparent superior performance of children is related to differences in task demands and overall levels of performance.

The executive functioning data were submitted to separate principal components analyses (promax rotation). As shown in Table 2, these analyses yielded a two-component solution for both age groups. Specifically, the two inhibition tasks and the two updating tasks constituted Factor 1 (referred to as the *supervision* component) (see also Oberauer, Süß, Wilhelm, & Wittman, 2003), and the two shifting tasks constituted Factor 2 (referred to as the *shifting* component). For both age groups, these two factors were the only ones with eigenvalues greater than 1. The correlations between the two factors were .06 and −.14 for children and adults, respectively. It should be noted that positive factor scores (i.e., individual *z* scores) reflected low task performance for both constructs.

Monitoring performance

Monitoring frequency

Time monitoring performance was examined in terms of monitoring frequency (i.e., "green" clock-checking responses) and timing error (i.e., "red" target time responses). As noted earlier, the durations of the monitoring task were 20 min for children and 30 min for adults. We analyzed the adult data for the whole 30-min interval, and these data were virtually identically to those for the 20-min interval.

Fig. 1 shows the frequency data as a function of age and task duration. As can be seen, the younger children (8- and 9-year-olds) and older children (10- to 12-year-olds) checked the clock more frequently than did the adults, but the three age groups showed similar patterns of monitoring behavior. Specifically, both the children and the adults checked the clock infrequently during the early phase of the task (i.e., first 2 min), followed by an accelerating clock-checking frequency when the 5-min deadline was approaching. Curve

Table 2
Factor loadings for the principal factor analysis of the inhibition, updating, and shifting tasks of executive functioning in children and adults

Construct	Task	Adults		Children	
		Factor 1	Factor 2	Factor 1	Factor 2
Inhibition	Stroop	.73	.38	.67	.20
	Stop signal	.74	−.03	.68	−.30
Updating	Matrix monitoring	.59	.07	.71	−.04
	N-back	.56	−.17	.71	.05
Shifting	Connections	−.03	.83	.07	.77
	Category fluency	.09	.64	−.07	.76

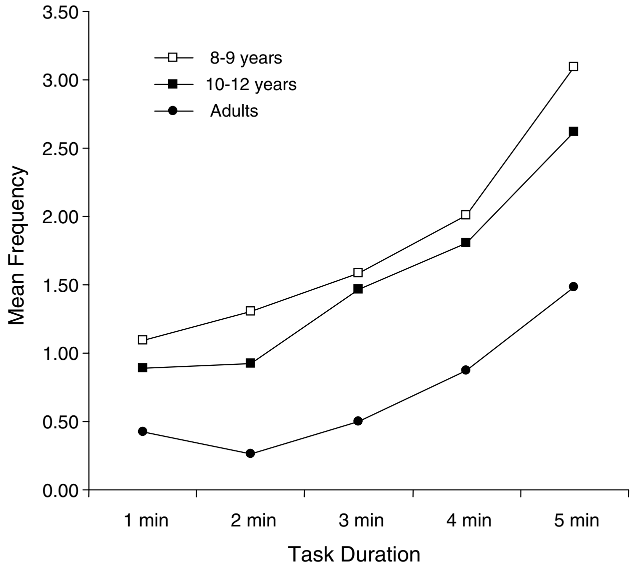

Fig. 1. Monitoring frequency as a functions of age, collapsed across four 5-min task intervals.

estimations of these data indicated that a quadratic, rather than a linear, function provided the best fit for both the children's frequency data ($Y = 1.17 - 0.27t + 0.12t^2$, $R^2 = .98$) and the adults' frequency data ($Y = 0.55 - 0.35t + 0.11t^2$, $R^2 = .99$). It should also be noted that the two age groups showed comparable estimates of the $b2$ parameter (i.e., .12 and .11), suggesting similarly accelerating rates of clock checking. For the sake of comparison, these curve estimations were based on four 5-min blocks for both age groups, but the adult data showed a virtually identical pattern for the complete (6×5 min) data set.

Fig. 2 provides a more detailed description of the clock-checking data. Apart from differences in the overall rate of monitoring, the three age groups showed rather similar functions across the four 5-min blocks. Fig. 2 also shows that the rate of clock checking was

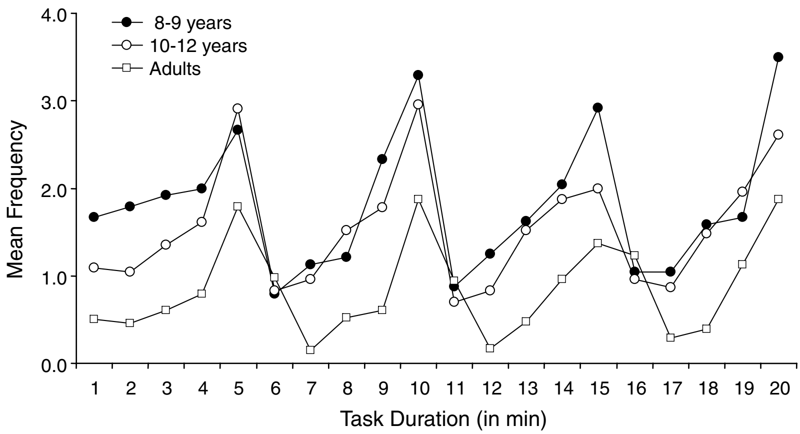

Fig. 2. Monitoring frequency as a function of age.

minimized immediately after each 5-min deadline, producing a sawtooth-like monitoring function for all three age groups.

The frequency data were submitted to two analyses. The first analysis of variance (ANOVA) examined overall age differences in monitoring frequency by contrasting children and adults. In the second analysis, we examined age-related differences in children's monitoring frequency. Both analyses were based on a 2 (Age) × 4 (Block) × 5 (Task Duration) mixed ANOVA, with the last two factors as within-subjects variables. Concerning the first analysis, the ANOVA yielded significant main effects of age, $F(1,94) = 53.88$, $MSe = 452.50$, $\eta_p^2 = .37$, $p < .01$, and task duration, $F(4,376) = 103.88$, $MSe = 151.62$, $\eta_p^2 = .53$, $p < .01$. As can be expected, the children showed a higher rate of clock checking ($M = 1.67$/min) than did the adults ($M = 0.70$/min). Contrast tests indicated that the main effect of task duration was mediated by a significant quadratic trend, $F(1,94) = 51.48$, $MSe = 71.04$, $p < .01$. The ANOVA also showed a significant interaction effect among age, block, and task duration, $F(12,1116) = 2.45$, $MSe = 1279.00$, $\eta_p^2 = .04$, $p < .01$. Contrast tests indicated that the age difference in frequency was mediated by an interaction between the quadratic component of the task duration factor and the cubic component of the block factor, $F(1,93) = 4.80$, $MSe = 2.50$, $\eta_p^2 = .03$, $p < .05$. This interaction is not considered in more detail due to its small effect size and because contrasting children and adults was not our primary interest.

In the second analysis, we examined age-related differences in monitoring frequency within the sample of school-age children. This ANOVA yielded a significant main effect of task duration, $F(4,188) = 47.24$, $MSe = 108.94$, $\eta_p^2 = .50$, $p < .01$. Contrast tests indicated that the main effect of task duration was mediated by a significant linear trend, $F(1,47) = 60.44.48$, $MSe = 312.94$, $\eta_p^2 = .56$, $p < .01$, and a significant quadratic trend, $F(1,48) = 50.37$, $MSe = 116.94$, $\eta_p^2 = .52$, $p < .01$. Although the younger children checked the clock somewhat more frequently than did the older children (Table 3), neither the main effect of age, $F(1,49) = 1.77$, $p > .15$, nor its interaction with task duration, $F < 1$, was significant. However, a significant three-way interaction among age, task duration, and block, $F(2,564) = 2.40$, $MSe = 1.94$, $\eta_p^2 = .04$, $p < .01$, suggested that the four blocks produced different monitoring functions for the younger and older children. As can be seen in Fig. 2, the two age groups produced very similar monitoring functions except for the first 3–4 min of the task. Although both age groups accelerated monitoring when the 5-min deadline was approaching, the younger children maintained a higher rate of clock checking during the initial phase of the first block. However, the younger children also reduced their clock checking during the first minutes of the following blocks, producing similar monitoring functions for both age groups. Contrast tests confirmed this observation by showing that the age effect was mediated by a significant interaction between the linear

Table 3
Monitoring performance as a function of age

Measure	Age group		
	Younger children	Older children	Adults
Monitoring frequency	9.95 (4.83)	8.11 (5.07)	3.62 (1.68)
Absolute discrepancy	7.48 (11.59)	6.38 (11.59)	6.99 (9.78)
Accuracy coefficient	1.01 (0.05)	1.01 (0.04)	1.02 (0.04)
Prospective memory	0.83 (0.23)	0.84 (0.24)	0.82 (0.21)

Note. Standard deviations are in parentheses.

components of block and task duration, $F(1,47) = 5.83$, $MSe = 6.06$, $\eta_p^2 = .11$, $p < .05$. No other effects were observed.

Timing error

Timing performance was measured in terms of absolute and relative errors. The former measure, referred to as the *absolute discrepancy score,* reflects timing errors regardless of their direction. The latter measure, referred to as the *accuracy coefficient score*, was obtained by dividing each participant's response by the corresponding target time, with coefficients greater than 1.0 reflecting overproductions and coefficients less than 1.0 reflecting underproductions. Furthermore, we obtained a measure of prospective memory performance by calculating the proportion of responses with a maximum delay of 10 s. These data are summarized in Table 3 and suggest similar patterns of performance for children and adults. Separate 3 (Age) × 4 (Block) ANOVAs on the three measures of timing error yielded no significant main effects or interactions. Taken together, the monitoring data suggest that the children checked the clock more frequently than did the adults but that timing error was not related to age.

Time control in children and adults

To examine individual and developmental differences in executive functioning in relation to time-based prospective memory performance, each participant's factor scores were related to monitoring frequency and timing error. In these analyses, timing error was based on the absolute discrepancy scores. Table 4 summarizes the zero-order correlations of both age groups. For the children's data (below the diagonal in Table 4), the supervision component of executive functioning correlated significantly with age and monitoring frequency, suggesting that the younger children showed greater problems in the inhibition and updating tasks and that they checked the clock more frequently than did the older children. However, the partial correlation between monitoring frequency and supervision was significant even after controlling for age, $r = .41$, $p < .01$. Table 4 also shows that shifting was not related to age or monitoring performance. Consistent with earlier studies, monitoring frequency and timing error were negatively related, although the correlation was only marginally significant ($p < .06$). Considering that our major hypothesis focused on the updating component of executive functioning, we also examined the association between monitoring performance and the two measures of the construct. These additional

Table 4
Pearson correlation coefficients for age, executive functioning, and time monitoring in children (below diagonal) and adults (above diagonal)

Measure	1	2	3	4	5
1. Age	—	.22	−.03	−.16	.19
2. Supervision	−.50**	—	.07	.12	.38**
3. Shifting	.05	−.06	—	.12	.22
4. Monitoring frequency	−.31*	.48**	.01	—	−.44**
5. Timing error	−.09	.14	−.19	−.26	—

* $p < .05$.
** $p < .01$.

analyses indicated that the two updating tasks were also related to frequency of monitoring; the correlations for the *n*-back and monitoring tasks were .39, $p < .01$, and .28, $p < .06$, respectively.

A separate analysis of the adult data showed a similar pattern of zero-order correlations in that only the supervision component was related to monitoring performance. As shown in Table 4, timing error, but not monitoring frequency, correlated significantly with the supervision component. However, monitoring frequency was negatively correlated with timing error, which in turn was related to the supervision component of executive functioning.

Fig. 3 shows a path-analytic model of influences of age and components of executive functioning on timing error and monitoring frequency in children (note that large values of these three measures indicate inefficient performance). These data suggest that the supervision component of executive functioning predicted children's timing errors directly ($p < .06$) and indirectly via monitoring frequency. In other words, children with low performance in the updating and inhibition tasks (i.e., high supervision scores) showed more inefficient monitoring performance (i.e., more frequent clock checking and somewhat greater timing errors) than did children with better performance in the updating and inhibition tasks. Age was not related to timing error or monitoring frequency, but as can be seen in Fig. 3, age and supervision were significantly correlated. Finally, as already suggested by the zero-order correlations in Table 4, shifting was not related to monitoring frequency or timing error.

Fig. 4 shows a corresponding path-analytic model of the adult data. Again, timing error, but not frequency, was mediated by the supervision component of executive

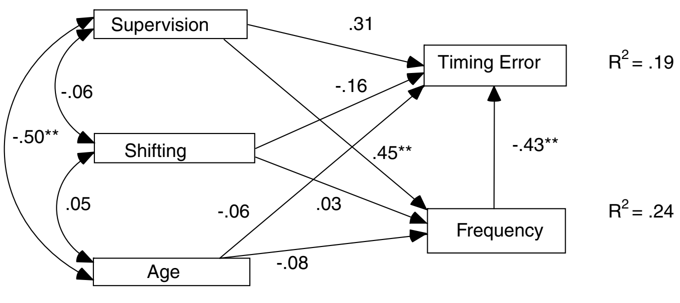

Fig. 3. A path-analytic model of influences of age and components of executive functioning on monitoring frequency and timing error in children. $^{**}p < .01$.

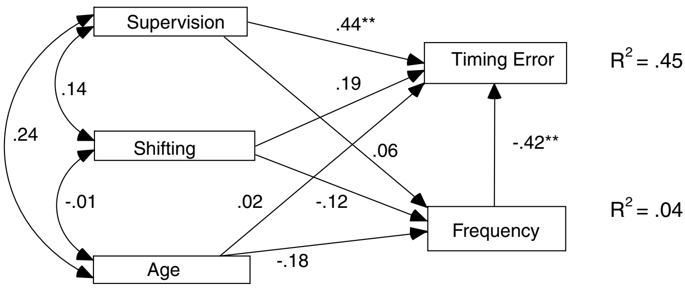

Fig. 4. A path-analytic model of influences of age and components of executive functioning on monitoring frequency and timing error in adults. $^{**}p < .01$.

functioning. In other words, adult participants with good performance in the inhibition and updating tasks showed better time-based prospective memory performance than did less efficient individuals. Furthermore, the adult participants checked the clock relatively infrequently ($M = 3.6$ per 5 min), and variability in monitoring frequency was not related to individual differences in executive functioning. Finally, and consistent with the children's data, shifting was not related to monitoring frequency or timing error.

Discussion

The aim of this study was to examine time-based prospective memory performance in children and adults by relating monitoring frequency and timing error to individual differences in executive functioning. Although past research suggests that executive functioning is closely related to prospective memory performance (i.e., timing error), the few studies that have examined monitoring behavior in children and adults suggest that efficient time monitoring is not related to individual differences in executive control functions. In this study, we attempted to relate time-based prospective memory performance (i.e., both monitoring frequency and timing error) to tasks that were assumed to reflect three basic components of executive functioning. Our primary hypothesis was that tasks assumed to tap the updating component of executive functioning would mediate time monitoring performance due to its dynamic demands on monitoring and revising task-relevant working memory representations. In the absence of strong support for a componential model of executive functioning, we also assumed that updating and inhibition are correlated, rather than distinct, components of executive functioning and that time monitoring performance would be related to individual differences in both components.

Consistent with earlier studies (Ceci & Bronfenbrenner, 1985; Kerns, 2000), our findings suggest that school-age children also monitor strategically by increasing the rate of clock checking when the deadline is approaching. In contrast to Ceci and Bronfenbrenner's (1985) U-shaped monitoring functions, we observed low levels of early clock checking during the first 5-min interval. The overall shape of a monitoring function probably is mediated by a number of task-related factors (see also Mäntylä & Carelli, 2006), but in the current study even the youngest children showed increasing clock checking during the first 5-min interval.

Furthermore, children and adults not only used the same general strategy for monitoring deadlines (i.e., interval reduction) but also showed comparable levels of time-based prospective memory performance. Both the 8-year-old schoolchildren and the 20-year-old undergraduates provided more than 80% of the target responses within 10 s. However, to obtain an equally high level of time-based prospective memory performance, the children relied on external time keeping more frequently than did the adult participants.

The analysis of the executive functioning data yielded a two-factor solution for both age groups, with a high degree of commonality between the updating and inhibiting tasks. Although the primary aim of this study was not to test alternative models of executive functioning (i.e., exploratory factor analysis rather than confirmatory factor analysis), the current findings are consistent with the notion that mental shifting is a distinct component of executive functioning (Baddeley, 1996; Lehto et al., 2003; Miyake et al., 2000). Our findings are also consistent with neuropsychological studies (Gehring &

Knight, 2002) and neuroimaging studies (for a review, see Collette & Van der Linden, 2002) suggesting that parietal areas play a more basic role in shifting processes than do prefrontal areas.

However, the current findings are inconsistent with those multicomponent models of executive functioning in which updating and inhibition are considered as separate components (Dempster, 1992; Diamond, 1990; Lehto et al., 2003; Miyake et al., 2000; Nigg, 2000; Russell, 1999). For example, the findings of Miyake and colleagues (2000) supported a three-component model of executive functioning, but it should be noted that the correlation between their updating and inhibition constructs was .63 (for similar correlations for school-age children, see also Lehto et al., 2003). Although large correlations between latent factors are not necessarily a problem, this pattern of results may suggest that updating and inhibition should be considered as a single construct of executive functioning (Bunting & Conway, 2002; Pennington, 1994; Sluis et al., 2005).

Miyake and colleagues (2000) tested the hypothesis that the updating and inhibition factors were perfectly correlated by allowing two correlations among the three factors to vary freely and constraining the third correlation to equal 1. Based on this test, they concluded that the three factors are correlated but distinct. However, as noted by Sluis and colleagues (2005), constraining the correlation between two factors to equal 1 is not sufficient. Instead, the correlation between these factors with the third factor should also restricted to be identical. They reanalyzed the results of Miyake and colleagues and concluded that "a model in which updating and inhibition are perfectly correlated is tenable" (Sluis et al., 2005, p. 559).

Whether updating and inhibition are considered as a unitary construct or as distinct factors of executive functioning, the current findings suggest that monitoring performance is related to individual and developmental differences in tasks that were assumed to tap these processes. For both children and adults, supervision was directly related to timing error. Furthermore, children, but not adults, with low performance in the updating and inhibition tasks (i.e., high supervision scores) checked the clock more frequently than did children with more efficient updating and inhibition functions. These children attempted to compensate for their difficulties in the updating and inhibition functions by relying on external time keeping more frequently than did children with more efficient supervision functions. Yet these compensatory activities were inefficient in that children with poor supervision performance not only checked more frequently than did better performing children but also were less accurate time monitors than were better performing children.

Another interesting implication of this pattern of compensatory behavior is that increased demands on external time keeping should have indirect effects on secondary task performance. In other words, external time keeping facilitates prospective memory performance, but these actions are associated with a monitoring cost in that attention is distracted from the primary task (e.g., watching a movie). Thus, although increased monitoring may compensate for differences in goal-directed task performance, problems in executive control functions may impair other aspects of everyday functioning.

In contrast to the children's data, the adults' data suggested that individual differences in the supervision component were not related to monitoring frequency. That is, adult participants with low levels of performance in the updating and inhibition tasks showed a lower level of prospective memory performance than did better performing participants, but monitoring frequency was not related to individual differences in updating and inhibition functions. This pattern of results may reflect a variety of developmental effects, including differences in response bias and overall working memory capacity. Concerning the former hypothesis, adults with low supervision performance may have experienced discontinuities in sense of time but were more reluctant to rely on external time keeping. Developmental differences in updating functions may also have contributed to different patterns of data in children and adults; that is, the low-performing adults were less dependent on external support than were the low-performing children. Taken together, these findings may suggest that inefficient monitoring performance in children reflected a combined effect of individual and developmental differences in updating functions.

Another central finding was that tasks assumed to tap the shifting component of executive functioning were not related to monitoring frequency or timing error. In other words, participants with low performance in the shifting tasks did not check the clock more frequently or produce more late responses in the monitoring task than did participants with better shifting performance. Consistent with our hypothesis, these selective effects of executive functioning may reflect task-specific differences in demands on temporal maintenance of information. Compared with shifting tasks, most updating tasks require maintenance of dynamic event information, which provides a temporal coherence for the observed event. The functional role of subjective sense of time is to reduce monitoring costs by initiating monitoring actions when more specific temporal information is needed closer to the deadline. In that context, even category-level temporal information (e.g., "not yet—soon—now") might be sufficient to minimize early clock checking and to reduce monitoring costs. This type of cognitively constructed, but functional, time might be mediated by processes related to the maintenance and updating of working memory contents. Following the notion that updating and retaining dynamic event information in working memory contributes to a sense of temporal continuity, individuals with efficient updating and inhibition functions would be able to rely on this temporal information when monitoring deadlines. In contrast, an individual with difficulties in temporary maintenance and elaboration of working memory contents may experience discontinuities in sense of time, leading to an earlier and more frequent reliance on external time keeping.

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