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Time keeping and working memory development in early adolescence: A 4-year follow-up

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ABSTRACT

In this longitudinal study, we examined time keeping in relation to working memory (WM) development. School-aged children completed two tasks of WM updating and a time monitoring task in which they indicated the passing of time every 5 min while watching a film. Children completed these tasks first when they were 8 to 12 years old and then 4 years later when they were 12 to 16 years old. Time keeping in early adolescence showed a different pattern of outcome measures than 4 years earlier, with reduced clock checking and increased timing error. However, relative changes in WM development moderated these adverse effects. Adolescents with greater relative gains in WM development were better calibrated than participants with less developing WM functions. We discuss these findings in relation to individual and developmental differences in executive control functions and socioemotionally driven reward seeking.

Introduction

Time keeping concerns the coordination and synchronization of the subjective experience of time's passing with some type of standard and is intimately associated with complex goal-directed behavior. Time keeping often involves balancing the cost of monitoring against the cost of having inaccurate information about the environment (Atkin & Cohen, 1996; Ceci & Bronfenbrenner, 1985; Harris & Wilkins, 1982; see also Mäntylä & Carelli, 2006, for an overview). It also involves judging available resources accurately for selecting a realistic strategy. Furthermore, the monitoring strategy itself needs to be evaluated and updated. It also reasonable to assume that time keeping in complex task

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conditions (cf. multitasking or remembering multiple intentions) may reflect individual and developmental differences in executive control functions.

Mäntylä, Carelli, and Forman (2007) provided direct support for the notion that time monitoring is closely related to individual and developmental differences in executive control functions (see also Carelli, Forman, & Mäntylä, 2008; Mackinlay, Kliegel, & Mäntylä, 2009). In their study, school-aged children and young adults indicated the passing of time every 5 min while watching a DVD film. Participants also completed six experimental tasks that tapped three basic components of executive functioning: inhibition, updating, and mental shifting. 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 monitoring accuracy. 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. Individual differences in executive functioning had selective effects on time-based prospective memory performance. In both children and adults, monitoring performance was related to the working memory (WM) component (i.e., updating and inhibition), but not to the shifting component, of executive functioning.

Mäntylä and colleagues (2007) interpreted these findings to suggest that the functional role of subjective sense of time is to initiate time keeping when more specific temporal information is needed closer to the deadline. Instead of relying on absolute duration estimates, even category-level temporal information (e.g., “not yet-soon-now”) might be sufficient to minimize early clock checking and to reduce monitoring costs in most goal-directed tasks. This type of adaptive monitoring strategy might be mediated by processes related to the maintenance and updating of WM contents. Following the notion that updating and retaining dynamic event information in WM contributes to a sense of temporal continuity (Carelli et al., 2008; Jonides & Smith, 1997), individuals with efficient updating functions would be able to rely on this temporal information when monitoring deadlines. By contrast, individuals with difficulties in temporary maintenance and elaboration of WM contents may experience discontinuities in sense of time, leading to an increased dependence on external time keeping.

Following this line of reasoning, the aim of this study was to examine time keeping in relation to WM development in early adolescence. Past studies suggest a continuous increase in WM performance from early childhood to adolescence (e.g., Gathercole, Pickering, Ambridge, & Wearing, 2004; Luciana, Conklin, Hooper, & Yarger, 2005), and these functional developments have been linked to structural changes (e.g., Kwon, Reiss, & Menon, 2002; Luna, 2009; Sowell, Delis, Stiles, & Jernigan, 2001). However, knowledge about WM development in school-aged children is still limited, and the few existing studies are based on cross-sectional comparisons (see also Best, Miller, & Jones, 2009, and Garon, Bryson, & Smith, 2008, for overviews).

Taken together, past research suggests that WM and related higher order cognitive functions continue to develop even after late childhood and that individual and developmental differences in these control functions mediate complex goal-directed tasks such as time-based prospective memory. Following these observations, it is reasonable to hypothesize that both time keeping and executive functioning are more efficient (and “adult-like”) in early adolescence than in childhood. Specifically, we expected that adolescents (with better WM functions than 4 years earlier) would show more efficient monitoring behavior with less frequent monitoring (and reduced monitoring costs) while maintaining the same level of response accuracy.

To examine WM development and its relation to time keeping, we report a 4-year follow-up to Mäntylä and colleagues’ (2007) study. Specifically, school-aged children, who were 8 to 12 years old during the first test occasion and 12 to 16 years old during the second test occasion, completed two tasks of WM updating and a time monitoring task in which they indicated the passing of time every 5 min while watching a DVD film. The updating tasks were identical in both occasions except for differences in overall task difficulty. Specifically, because some of the children performed close to ceiling already 4 years earlier, it was necessary to use more demanding versions of the two updating tasks during the second test occasion. Consequently, instead of examining absolute changes in WM performance, our primary interest here was in relative changes. In addition to overall age effects, we hypothesized that children with more developed WM functions would show more efficient time keeping performance than children showing less development of the same. The time monitoring task was virtually identical on both occasions except that different films were used. To examine potential testing effects, an additional group of adolescents was included in the study. Specifically, because changes in monitoring strategy might also reflect participants' earlier experiences of the first test session, we included a separate group of children from 12 to 16 years of age. These participants had no earlier experience of the study, and they completed only the time monitoring task.

Method

Participants

In total, 51 children from 8 to 12 years of age completed the first (T1) session, and 42 of these 51 children completed the second (T2) session 4 years later (9 children from the original sample either declined the offer to participate in the T2 session or had moved to another part of the country). The final T2 sample was composed of 15 boys and 27 girls from 12 to 16 years of age (mean age = 14.3 - years). An additional group of 12 children (mean age = 14.3 years, range = 159–190 months) was included in the study. 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.

Task characteristics

Working memory updating

Participants completed two updating tasks, namely the word-based *n*-back task and the visuospatial matrix monitoring task. These tasks were similar during both occasions except that we attempted to avoid ceiling effects in T2 performance by increasing task complexity.

In the *n-back* task, the manual version of the 2-back task used at T1 (see *Mäntylä et al., 2007*, for details) was replaced by a computerized 3-back version. In this task, a high-frequency noun appeared for 2 s every 4 s. Participants pressed a designated computer key when they recognized a word as the same as the one three items back. The task comprised 96 words, including 24 targets.

In the *matrix monitoring* task (Salthouse, Atkinson, & Berish, 2003), a 4×4 matrix appeared on a computer screen with a black dot in one of the cells. The matrix disappeared after 2.5 s, followed by a sequence of arrows indicating 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 correct or not by pressing the "yes" or "no" key on the computer keyboard. During T1 the children monitored a sequence with two arrows in 32 trials, and during T2 they monitored 16 trials with three arrows (Block 1) and 16 trials with four arrows (Block 2). Number of incorrect responses was the dependent measure of both updating tasks.

Time monitoring

In the time monitoring task, participants indicated the passing of every 5 min while watching a DVD film. During T1 they watched a cartoon (*Garfield*), and during T2 they were shown a family comedy (*Jönssonligan och den svarta diamanten*). During both test sessions, the film 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 the participants 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 but that the green button could be used to check the clock at any time during the task. After pressing one of the buttons, the corresponding task time appeared (in red or green color) for 1 s on the computer screen. A practice phase was included at 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 any problems in understanding the task instructions.

Procedure

Children were tested in a quiet room at their school by the same female experimenter. During T2, each participant first completed two WM tasks, followed by the time monitoring task. Some participants completed additional tasks, but these data are not included in this study. For practical reasons, 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.

Results

Time monitoring data

Time monitoring performance was examined in terms of monitoring frequency (mean number of "green" responses) and response accuracy (mean absolute error of "red" responses). Table 1 summarizes these data as a function of group, including the corresponding adult data reported in Mäntylä and colleagues' (2007) study. These data show a clear change in the children's monitoring strategy in that they reduced the rate of monitoring from approximately nine clock checks to less than two clock checks during a 5-min task interval, $F(1, 41) = 79.09$, $MSe = 12.96$, $\eta_p^2 = .66$, $p < .01$. As shown in Table 1, children's monitoring frequency at T2 was even lower than that of adults, $F(1, 88) = 31.16$, $MSe = 2.15$, $\eta_p^2 = .26$, $p < .01$. However, this result did not reflect repetition effects given that the T2 control group, whose members completed the time monitoring task for the first time, showed a similar pattern of clock checking behavior as the T2 child group. An analysis of variance (ANOVA) on these data showed a significant effect of group, $F(2, 98) = 17.06$, $MSe = 2.07$, $\eta_p^2 = .26$, $p < .01$, and Tukey's post hoc tests indicated that the mean of the T1 adults was significantly greater than that of the T2 children ($p < .01$) and that of the T2 control group ($p < .02$). The mean difference of these latter two groups (T2 children and T2 control) was not significant.

Table 1 also shows that this age-related change in monitoring strategy had a striking effect on the children's response accuracy. At T1, children and adults showed the same level of accuracy, but reduced clock checking at T2 was now associated with large timing errors, $F(1, 41) = 18.39$, $MSe = 259.02$, $\eta_p^2 = .31$, $p < .01$. A separate ANOVA with group (T2 children, T2 control, or T1 adults) as a between-participants factor showed a significant main effect of group, $F(2, 98) = 11.88$, $MSe = 215{,}49$, $\eta_p^2 = .20$, $p < .01$. Post hoc comparison indicated that the mean of the T2 children was significantly greater than that of the T1 adults ($p < .01$). No other effects were observed.

Fig. 1 shows the frequency data as a function of group and task duration collapsed across the four 5-min intervals. Apart from differences in the overall rate of monitoring, children at T2 showed a flatter monitoring function than at T1. As shown in Fig. 1, all three age groups increased the rate of monitoring linearly during the first 4 min of each interval. Furthermore, both adults and children at T1 maximized the rate of clock checking during the last minute of each 5-min interval. By contrast, children at T2 did not show the same accelerating monitoring when the deadline was approaching. Fig. 2 also shows virtually identical monitoring functions for the T2 control and T2 child groups.

Working memory and time keeping

The updating data of both sessions were first submitted to separate principal component analyses, and the resulting factor scores were used as an index to examine differences in WM development and their relation to time keeping. Table 2 summarizes simple correlations for age, WM, and time monitoring separately for the T1 and T2 data. These analyses show a highly significant correlation between

Table 1
Monitoring performance as a function of group.

	Monitoring frequency	Response errors
T1 children	9.03 (4.93)	6.92 (10.70)
T2 children	1.83 (1.10)	22.21 (19.26)
T2 controls	2.16 (1.15)	14.53 (18.38)
T1 adults	3.62 (1.68)	6.99 (9.78)

Note. Standard deviations are in parentheses.

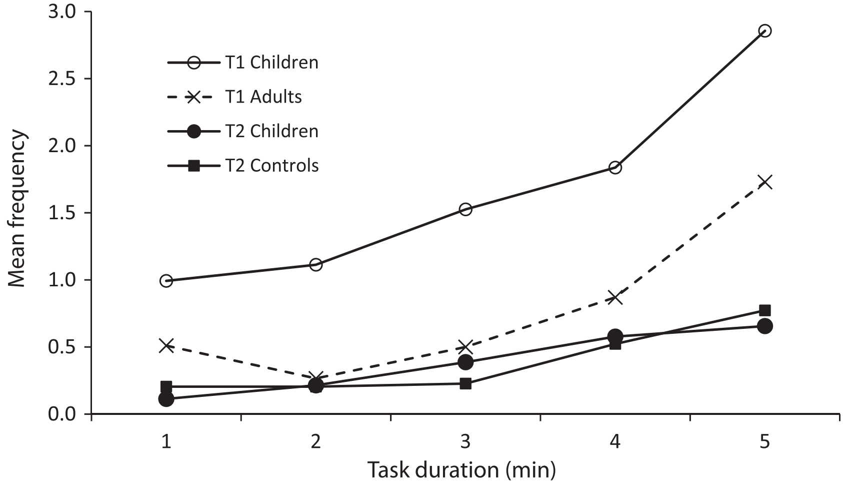

Fig. 1. Monitoring frequency as a function of group and task duration collapsed across four 5-min intervals.

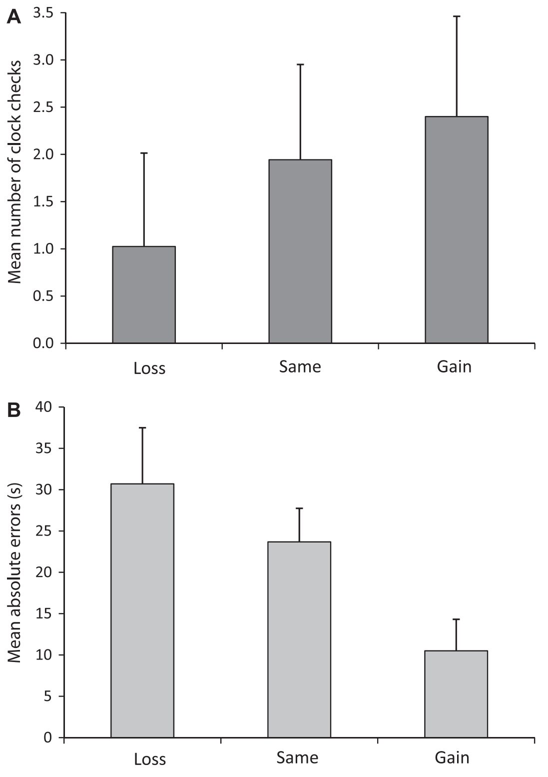

Fig. 2. Monitoring performance as a function of WM change group for frequency (A) and response accuracy (B). Standard errors are in parentheses.

WM updating and age at T2. Separate analyses on the absolute updating data (rather than standardized scores) replicated these findings by showing larger age effects at T2 than at T1. Specifically, both the n-back ($r = -.44$, $p < .01$) and matrix monitoring ($r = -.38$, $p < .02$) errors showed significant

Table 2
Pearson correlations for age, working memory, and time monitoring at T1 (above diagonal) and T2 (below diagonal).

Measure	1	2	3	4
1. Age	–	−.37*	−.31*	−.12
2. Working memory	−.50**	–	.38*	.07
3. Monitoring frequency	−.01	−.16	–	−.43**
4. Monitoring accuracy	−.08	.21	−.70**	–

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

correlations with age at T2, whereas these correlations were only marginally significant at T1. Similarly, as shown in Table 2, monitoring frequency and response accuracy showed an even stronger negative correlation than 4 years earlier. However, in contrast to the T1 data, the correlation between monitoring frequency and WM was not significant at T2. We also examined age-related differences by dividing the T2 sample into two age groups (12 and 13 years vs. 14 and 15 years). As in the T1 data reported in Mäntylä and colleagues' (2007) study, the two age groups showed similar monitoring patterns at T2, with somewhat higher monitoring frequency in the younger group than in the older group. However, there were no significant age differences in T2 monitoring frequency or response accuracy.

In the second step of the analysis, we examined monitoring performance in relation to WM development. To obtain a relative measure[1] of WM development, we calculated a difference score between T1 and T2 factor scores for each participant. In this index, a positive difference score indicates increased performance (in standardized factor scores) and a negative difference score indicates reduced performance (relative to the group mean at T1 and T2).

Descriptive analyses of these data indicated that 22 (53%) of the participants (referred to as the Same group) had the same relative position at T1 and T2 (defined as ±0.5 SD in difference scores). Of the remaining participants, 10 children (referred to as the Gain group) had improved their relative performance (defined as >0.5 SD) and 10 children (referred to as the Loss group) had a lower rank at T2 than at T1 (defined as <−0.5 SD). There were no significant group differences in age ($F = 1.02$), and the gender distributions of the Same and Gain groups were rather balanced. However, the gender distributions of the Loss group were biased in that a large majority (9 of 10) were girls.

To examine the relation between WM development and time keeping, we first calculated simple correlations for age, WM difference score, monitoring frequency, and response accuracy. These data are summarized in Table 3. A most striking finding here is that relative WM change was highly correlated with monitoring performance. Children with more developing updating functions (as indexed by positive WM change scores) checked the clock more frequently and were more accurate than children with less development. As already indicated by the descriptive analysis, WM change was not related to participants' age.

The correlation data summarized in Table 3 suggest that participants who improved their relative WM performance (i.e., the Gain group) also had a better calibrated monitoring strategy than participants with less relative development (i.e., the Loss group). This pattern of results is illustrated in Fig. 2.

As shown in Fig. 2A, monitoring frequency was minimized in the Loss group and maximized in the Gain group. An ANOVA on the frequency data showed a significant main effect of group, $F(2, 39) = 4.84$, $MSe = 1.03$, $\eta_p^2 = .20$, $p < .01$. Post hoc tests showed that the mean of the Loss group was significantly lower than the means of the Same ($p < .05$) and Gain ($p < .01$) groups. The means of the latter two groups were not significantly different. As suggested by the significant correlation between frequency and accuracy, Fig. 2B shows large group differences in response accuracy. An ANOVA on these data showed a significant main effect of group, $F(2, 39) = 3.16$, $MSe = 0.47$, $\eta_p^2 = .14$, $p < .05$. Post hoc tests showed that the mean of the Loss group was significantly greater than that of

[1] We also used a related index of WM change that was based on T1 − T2 differences in standardized (z) scores calculated separately for the n-back and matrix monitoring tasks. These data showed a similar pattern of results as the one-component factor scores reported here, namely that monitoring frequency correlated significantly with the n-back ($r = .35$, $p < .05$) and matrix monitoring ($r = .35$, $p < .05$) difference scores. Similarly, the correlation between response accuracy and matrix monitoring was reliable ($r = -.37$, $p < .02$). The corresponding correlation with n-back was also negative but not significant ($r = -.26$, $p < .10$).

Table 3
Pearson correlations for age, working memory change, and time monitoring.

Measure	1	2	3	4
1. Age	–	.14	−.01	−.08
2. Working memory change		–	.45**	−.39*
3. Monitoring frequency			–	−.70**
4. Monitoring accuracy				–

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

the Gain group ($p < .02$) but not that of the Same group. The difference between the Gain and Same groups was marginally significant ($p = .06$). It should be noted that the analyses of the T1 data did not show significant group differences in monitoring frequency or in response accuracy (Fs < 1).

Fig. 3 provides a more detailed description of monitoring behavior in these groups. As can be seen, the Gain group showed a more strategic (and adult-like) clock checking pattern than the Loss group in that its members accelerated monitoring when the 5-min deadline was approaching. (The Same group was not included here, but its monitoring function paralleled that of the Gain group at a somewhat lower level.) Furthermore, although the Loss group also showed signs of accelerating monitoring functions, its members also showed the largest discrepancy with the adults' functions during the critical deadline periods.

The monitoring data of the three WM change groups were submitted to a 3 (Group) × 5 (Duration) × 4 (Block) mixed ANOVA, with group (Loss, Same, or Gain) as a between-participants factor. These analyses showed a significant main effect of duration, $F(4, 156) = 8.84$, $MSe = 0.33$, $\eta_p^2 = .20$, $p < .01$, and its interaction with group, $F(1, 98) = 1.99$, $MSe = 0.20$, $\eta_p^2 = .09$, $p < .05$. No other effects were observed. Contrast tests indicated that only the linear component of the Group × Duration interaction was significant, $F(1, 39) = 3.58$, $MSe = 0.47$, $\eta_p^2 = .16$, $p < .05$. As shown in Fig. 4, these data suggest that the difference between the Gain and Loss groups was accentuated in the 5-min duration condition (during the 5th and last minute of the block).

Discussion

This longitudinal study examined time keeping in relation to WM development in early adolescence. We hypothesized that adolescent children would show more efficient WM updating than

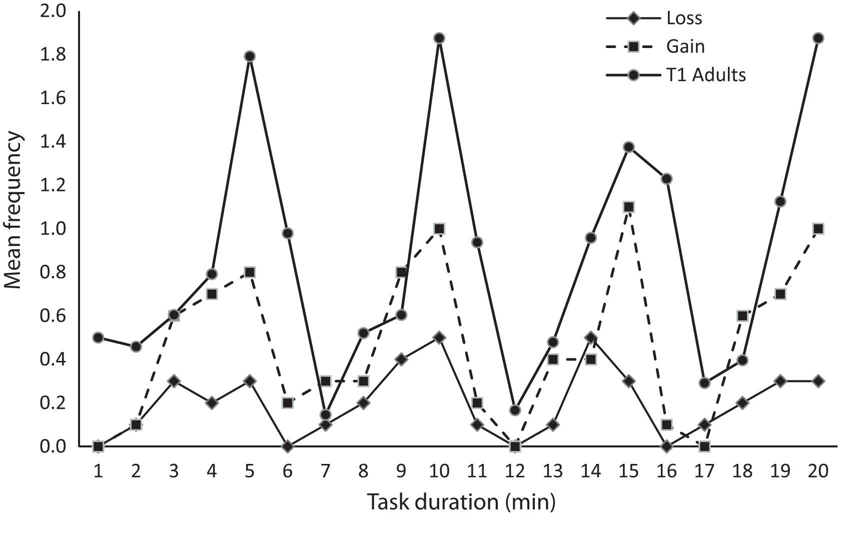

Fig. 3. Monitoring frequency as a function of group and task duration.

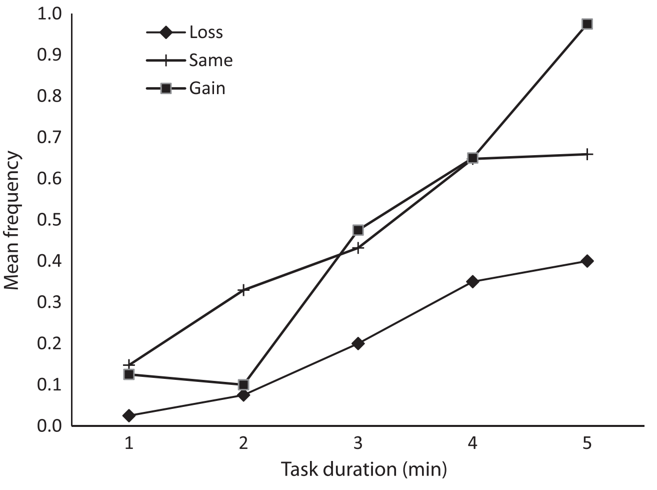

Fig. 4. Monitoring frequency as a function of WM change group and task duration collapsed across four 5-min intervals.

4 years earlier and that these age-related changes in WM functioning would be associated with more efficient time keeping. As reported in Mäntylä and colleagues' (2007) study, children at T1 showed the same level of response accuracy as adults, but they needed more frequent clock checks to reach the same level of accuracy. Extending these findings, we expected that adolescents would show a more adult-like monitoring strategy with fewer clock checks while maintaining response accuracy.

The findings of this study supported our hypothesis in that monitoring frequency was significantly reduced between T1 and T2 and even lower than that of adults. Furthermore, adolescents' infrequent clock checking was associated with large timing errors at T2. This pattern of results suggests that adolescents overestimated their time keeping capacity in that the reduced monitoring had a large cost in timing accuracy.

Mäntylä, Del Missier, and Nilsson (2009) observed a similar pattern of task costs in adult participants. In their study, young, middle-aged, and older adults indicated the passing of time every 5-min interval while listening to a short story (low task demands) or completing a series of cognitive tasks (high task demands). Consistent with our findings, older adults needed more clock checks than younger adults to obtain the same level of response accuracy. However, when task demands were increased, older adults changed their monitoring strategy by reducing their clock checking frequency to the same level as younger adults. As a result, age differences in time-based prospective memory shifted from monitoring frequency to response accuracy. This pattern of results is similar to our findings with a capacity-related shift in the two outcome measures. However, in older adults this strategy shift was related to age-related decrements in executive functions (which were measured with separate tasks), whereas in adolescents these effects might reflect differences in both cognitive and socioemotional development.

Consistent with this notion, another central finding of this study was that differences in adolescents' monitoring strategy were *not* associated with individual differences in WM updating per se. In contrast to the T1 data (in which these differences were observed [see Mäntylä et al., 2007]), monitoring frequency at T2 was not related to WM performance, possibly due to the low variability in the frequency data. Instead, a more informative finding of this study was that time keeping in early adolescence was systematically related to *relative changes* in WM development, as indexed by the WM difference score. Both correlation and group-level analyses indicated that participants who showed an improvement in WM updating (i.e., a gain in their relative position between T1 and T2) also showed less risky time keeping behavior than participants who showed less developing updating functions.

One interpretation of these striking changes in preadolescents' monitoring strategy is that they reflect socioemotional development with an increased tendency to reward seeking and risk taking. Although cognitive control functions continue to develop after late childhood (see Best et al., 2009 and Garon et al., 2008, for overviews), changes in socioemotional development might have an even stronger effect on adolescents' strategies in complex goal-directed tasks.

Compared with their "childhood" behavior 4 years earlier, adolescents might have considered themselves as more mature and "cool" and approached the same task with a different attitude and metacognitive strategy. Due to changes in social and emotional development, adolescent participants might have preferred a more risky strategy in which infrequent clock checking (i.e., getting close the deadline without checking too often) was considered as more challenging, and thus potentially more rewarding, than their earlier approach. This strategy was also associated with a secondary task reward (i.e., watching the ongoing video without interruptions). However, as discussed earlier, a backside of this approach was that it produced very large timing errors.

This striking change in adolescents' monitoring behavior might reflect age-related changes in decision-making competence. As noted earlier, monitoring in most goal-directed tasks can be seen as a decision-making problem in which the individual must decide when to ask for the task-relevant information while balancing between the cost of monitoring against the cost of having inaccurate information. Thus, the observed changes in monitoring behavior strategies might reflect developmental differences in affective decision making and their interactions with more analytic decision processes (Fischhoff, 2008; Rivers, Reyna, & Mills, 2008).

Recent advances in developmental neuroscience provide some support for this view. With the advent of advanced brain imaging techniques, it has become possible to characterize changes in brain activity during cognitive development. This work has shown that cognitive and brain maturational changes continue throughout late childhood and adolescence and that efficient top-down modulation of reflexive acts might not be fully developed until adulthood (see, e.g., Luna, Padmanabhan, & O'Hearn, 2010 and Paus, 2010, for overviews). In particular, a growing body of work suggests that increased risk taking and reward seeking in adolescence is related to a temporal disjunction between the heightened arousal of neural networks implicated in affective and motivational regulation and the slower maturation of executive control functions and their underlying neural mechanisms (Casey, Getz, & Galvan, 2008; Steinberg, 2008). According to this view, the temporal gap between puberty, which impels adolescents toward thrill seeking, and the slow maturation of the cognitive control system, which regulates these impulses, makes adolescence a time of heightened vulnerability for risky behavior (see also Casey et al., 2008; Ernst et al., 2005; Galvan et al., 2006; Rivers et al., 2008; Steinberg, 2005).

Our findings are consistent with this view in that risk taking in the sense of infrequent monitoring and low accuracy was accentuated in adolescents with less WM development. Although this result should be interpreted with caution, it might suggest that the participants of the Loss group showed the greatest *discrepancy* between their "hot" affective regulation and the slower maturation of "cool" executive control functions and their underlying neural mechanisms. By contrast, adolescents with greater gains in WM development (i.e., the Gain group) showed a better balance between cognitive and affective regulation, possibly due to earlier maturation of the prefrontally mediated executive functions.

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