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Contribution of reactive and proactive control to children's working memory performance: Insight from item recall durations in response sequence planning

Nicolas Chevalier[1], Tiffany D. James[2], Sandra A. Wiebe[3], Jennifer Mize Nelson[2] and Kimberly Andrews Espy[4,2]

[1]Department of Psychology, University of Edinburgh

[2]Department of Psychology, University of Nebraska-Lincoln

[3]Department of Psychology, University of Alberta

[4]Departments of Psychology and of Special Education & Clinical Sciences, University of Oregon

Nicolas Chevalier, Department of Psychology, University of Edinburgh; Tiffany D. James, Department of Psychology, University of Nebraska-Lincoln; Sandra A. Wiebe, Department of Psychology; University of Alberta; Jennifer Mize Nelson, Department of Psychology, University of Nebraska-Lincoln; Kimberly Andrews Espy, Departments of Psychology and of Special Education & Clinical Sciences, University of Oregon and Department of Psychology, University of Nebraska-Lincoln. This work was supported by NIH grants MH065668, DA023653, DA024769, HD038051, and HD050309. We are grateful to the participating families and everyone at the Developmental Cognitive Neuroscience Laboratory. Correspondence should be addressed to Nicolas Chevalier, Department of Psychology, 7 George Square, University of Edinburgh, Edinburgh, EH8 9JZ, UK. Phone: +44 131 650 4336. Email: nicolas.chevalier@ed.ac.uk.

Abstract

The present study addressed whether developmental improvement in working memory span task performance relies upon a growing ability to proactively plan response sequences during childhood. 213 children completed a working memory span task in which they used a touchscreen to reproduce orally presented sequences of animal names. Children were assessed longitudinally at seven time points between 3 and 10 years of age, and 21 young adults completed the same task. Proactive response sequence planning was assessed by comparing recall durations for the first item (preparatory interval) and subsequent items. At preschool age, the preparatory interval was generally shorter than subsequent item recall durations, whereas it was systematically longer during elementary school and in adults. Although children mostly approached the task reactively at preschool, they proactively planned response sequences with increasing efficiency from age 7 on, like adults. These findings clarify the nature of the changes in executive control that support working memory performance with age.

Keywords: working memory, reactive and proactive control, recall duration, response sequence planning, children.

Contribution of reactive and proactive control to preschoolers' working memory performance: Insight from item recall durations in response sequence planning

Many daily activities require children to actively process and maintain information over short periods of time. For instance, understanding a bedtime story requires remembering information about the characters and the plot and integrating new information as the story unfolds. Working memory, which is devoted to such temporary maintenance and processing of information, develops steadily during childhood (Gathercole, Pickering, Ambridge, & Wearing, 2004; McAuley & White, 2011). The present study explores to what extent proactive planning contributes to working memory development during childhood.

In most models of working memory, executive control is responsible for maintaining, processing and actively retrieving information. According to Baddeley's model (Baddeley, 2003), the central executive controls information maintainance in the phonological loop and the visuospatial sketchpad, and processing in the episodic buffer. The latter components correspond to the activated portion of long-term memory in Cowan's model (e.g., Cowan, 2010). However, this model distingusihes between two levels of activation; only the most activated information is directly accessible to consciousness, maintained in the focus of attention and operated upon by executive control. Similarly, Unsworth and Engle (2007) distinguish between information maintained in primary memory, which is readily accessible to the conscious mind, and information in secondary memory, which is no longer attended but can be easily retrieved. In this model, executive control serves both information maintenance in primary memory and information retrieval from secondary memory.

Given the prominent position of executive control in working memory models, age-related changes in executive control likely affect, perhaps even drive, working memory development during childhood. Such changes are often thought to result from a quantitative increase in processing speed (Case, 1985; Fry & Hale, 2000; Towse, Hitch, & Hutton, 1998).

For instance, according to the time-switching model (Towse et al., 1998), attention is switched between maintenance and processing episodes, with faster processing speed with advancing age shortening processing episodes and freeing up attention for longer maintenance episodes. Recent findings suggest that developing executive control allows children to alternate more strategically between processing and maintenance, with attention quickly returning to maintenance within processing episodes from 7 years on (Camos & Barrouillet, 2011). Such an age-related strategy shift points out qualitative changes in working memory during childhood, which is also consistent with the development of rehearsal strategies (e.g., Flavell, Beach, & Chinsky, 1966).

A major source of qualitative variability in executive control, which may affect working memory performance, relates to temporal dynamics. According to the "dual mechanisms of control" theory (Braver, 2012; Braver, Gray, & Burgess, 2007), executive control can be engaged proactively or reactively. Proactive control, which relies on sustained activity in the lateral prefrontal cortex (PFC), is engaged in anticipation of future cognitive demands (e.g., looking up driving directions before going to a new place), hence preventing interference with the current task before it even arises, when upcoming interference can be reliably predicted. In contrast, reactive control is transiently recruited on an as-needed basis as a function of on-the-moment demands (e.g., figuring out how to get to a new place when one is already driving). It is associated with transient lateral PFC actitivity and serves to overcome interference after it occurred, in particular when it could not be predicted (e.g., Marklund & Persson, 2012). Although young adults engage flexibly the most adaptive control mode as a function of the context, as evidenced by changes in lateral PFC activity and pupil dilation in response to experimental manipulations that encourage a specific mode (Braver, Paxton, Locke, & Barch, 2009; Chiew & Braver, 2013), they also show individual differences. Adults with higher working memory capacity engage proactive control more often than low-working

memory individuals who engage reactive control preferentially (Braver et al., 2007). Critically, control mode selection also varies developmentally (Chatham, Frank, & Munakata, 2009; Killikelly & Szűcs, 2013; Vallesi & Shallice, 2007). For instance, in a task requiring to respond to specific prime-probe combinations, more mental effort (as shown by greater pupil dilation) is observed after probe onset at 3 years of age, hence showing no anticipation of the target, whereas it is observed before probe onset at 8 years (Chatham et al., 2009); suggesting that preschoolers rely mostly on reactive control, whereas proactive control is more frequent during middle childhood.

Response planning is a critical feature of proactive control (Andrews-Hanna et al., 2011; Killikelly & Szűcs, 2013; West, Bailey, Tiernan, Boonsuk, & Gilbert, 2012). Its contribution to working memory can be measured through recall item duration, that is, the time that elapses between the recall of two successive items. Unlike span length (i.e., the highest amount of information that children can recall accurately), recall durations offer direct insight on the temporal dynamic of memory search and recall processes and they correlate with academic achievement over and beyond span length (Cowan, 1992; Cowan et al., 1994, 1998, 2003; Towse, Cowan, Horton, & Whytock, 2008; Towse et al., 2008). Critically, the recall duration for the first item in the memorandum, that is, the preparatory interval, is longer than subsequent item recall durations in working memory span tasks during middle childhood and adulthood. At that age, individuals proactively retrieve and sequentially organize the to-be-recalled items before initiating their response (Cowan et al., 2003; Tehan & Lalor, 2000; Towse et al., 2008a, 2008b; Towse, Hitch, Horton, & Harvey, 2010). In contrast, it is unknown whether preschool-age children proactively plan response sequences. As preschoolers tend to exert control reactively (Chatham et al., 2009), they may not plan response sequences, but instead immediately initiate their responses and retrieve each item separately. If so, preschoolers should not show longer preparatory intervals relative to

subsequent item recall durations. In contrast, if working memory development is entirely driven by quantitative changes in processing speed or storage capacity and/or changes in executive control unrelated to response sequence planning, preschoolers should show similar preparatory intervals as school-age children and adults.

To examine whether proactive planning of the response sequence increases with age, children were assessed longitudinally on a working memory span task at seven time points between 3 and 10 years of age. In this task, children had to reproduce sequences of auditorily presented animal names by pressing buttons on a touchscreen, which required maintaining actively and processing the names to translate the auditory items into their corresponding visual items. Confirmatory factor analysis has shown that performance on this task loads onto a latent factor common to other measures of early childhood executive control, including tasks tapping working memory, resistance to distractor interference, and response inhibition tasks (Wiebe et al., 2011). Because this task departs from those used in previous reports of the preparatory interval in adults, the present study also included a group of young adults to check that adults proactively plan response sequences on this task.

We hypothesized that, as preschoolers, children would approach the task reactively, whereas by elementary school they would show proactive response sequence planning. If so, the preparatory interval should differ from subsequent item recall durations only after preschool. Further, as planning the response sequence should be more demanding for longer sequences (due to more items having to be retrieved and organized sequentially), the preparatory interval should increase across sequences at ages where response sequence planning is observed. In contrast, if working memory development is entirely driven by quantitative changes in processing speed or executive control changes unrelated to response sequence planning, the preparatory interval should be longer than subsequent item recall durations even at preschool.

Method

Participants

Study participants were 213 children (104 girls and 109 boys; 149 White non-Hispanic, 5 African American, 23 Hispanic, 1 Asian and 35 multiple race) assessed longitudinally in the preschool and elementary periods. The exact N varied across time points due to some children dropping out of the study and others being recruited. Children were recruited through birth announcements, local preschools, the local health department, and by word of mouth from a Midwestern small city. Parents completed a telephone screening before study enrollment. Children with diagnosed developmental or language delays or behavioral disorders or whose families planned to move out of the area within the study timeline were deemed ineligible and not enrolled. Children were enrolled initially in a project for which they were administered a battery of executive tasks every 9 months between the ages of 3 years 0 months and 5 years 3 months in a lagged cohort sequential design. Data from three time points were included in the present study: 3 years 9 months, 4 years 6 months, and 5 years 3 months. The data at age 3;0 were not used because most children had a maximal span length of only 1 (59%) or 2 (33%), hence strongly limiting the comparison between the preparatory interval and subsequent item recall durations. Children were tested within two weeks of the exact targeted age (mean age 3.75, *SD* = .04 and age range = 3.67-3.83; mean age 4.50, *SD* = .04 and age range = 4.42-4.58; mean age 5.24, *SD* = .04 and age range = 5.16-5.33). The same children were later enrolled in a follow-up study in which they completed another battery of executive tasks every year from grade 1 through grade 4 (Grade 1: mean age 7.22, *SD* = .32 and age range = 6.50-8.00; Grade 2: mean age 8.11, *SD* = .36 and age range = 7.33-8.99; Grade 3: mean age 9.09, *SD* = .38 and age range = 8.25-10.00; Grade 4: mean age 9.93, *SD* = .36 and age range = 9.25-10.67). Stratified sampling on social risk was used to ensure a balanced sample (36.15% were eligible for public medical assistance). The majority of

participants' mothers had completed at least some college education: 2% had less than a high school diploma/GED equivalent, 10% had a high school diploma/GED equivalent, 38% had some college education, 51% had a 4-year college degree or beyond. Parental informed consent was obtained for all children prior to participation.

A group of 21 adults (10 women and 11 men; 20 were White and one was African American, mean age = 20.21 years, *SD* = .97 year) also participated. They were undergraduate students from the major university in the same geographic area. They completed informed consent before beginning the session and received course credit in exchange for participation.

Materials and Procedure

Children were administered a battery of executive tasks at each time point (for further details, see Wiebe et al., 2011) by a trained examiner in one session (first 3 age points) or two sessions (later age points) of about 120 minutes each (including other tasks not reported here). Short breaks were used when necessary to maintain cooperation and interest. Parents were compensated for study participation, and the children received developmentally appropriate toys, stickers, and other small items. Adult participants were tested at the laboratory by a trained experimenter in a 15-min. session in which they only completed Nebraska Barnyard.

Working memory was assessed using *Nebraska Barnyard* (adapted from the Noisy Book, Hughes, Dunn, & White, 1998). The task required actively maintaining animal names and matching them with their corresponding colored squares on the touchscreen before recalling them by pressing the colored squares in the correct order. The version administered at ages 3;9, 4;6 and 5;3 was presented using Perl v5.8.8 (ActiveState Software, Vancouver, BC), whereas the version administered at later ages was presented using E-prime 2.0 (Psychology Software Tools, Pittsburgh, PA, USA). Children were introduced to a set of 9 pictures, each representing a different animal on a differently colored background and

arranged in a 3 × 3 grid (Figure 1). Children were asked to get their "pointy finger ready" by positioning it below the grid of pictures. In the familiarization phase, children pressed each animal picture and the computer produced the corresponding sound. Then, the animal pictures were removed (but box colors remained the same) and children completed a set of 9 practice trials during which the examiner named each animal individually, and the child was required to press the colored square corresponding to that animal. Finally, trials with sequences of animals were administered, beginning with sequences of 2 animals and increasing progressively until the child's performance met the discontinuation criterion. Items were presented at a pace of one per second. Voice inflection on the last animal name in each sequence signalled sequence end and served as a cue for participants to start recalling. Up to 3 trials were administered at each span length: if the first 2 trials for a span were correct, participants were automatically given credit for the third trial, which was omitted, and if all 3 trials for a span were incorrect, the task was discontinued. For the version of the task presented in Perl, accuracy and recall duration for each item were coded from videos by trained undergraduate students using Noldus Observer 5.12 (Noldus Information Technology, Wageningen, Netherlands). Two cameras with different angles were used so as to capture precisely the time frame when children pressed each button. 20% of the videos were double coded to assess inter-rater agreement (M = 94.6%). Children who were enrolled in the first year of the follow-up study completed this version of the task, using Eprime, for the first year only. Assessments completed in any of the other 4 years of the follow-up study and among the adults included an Eprime version in which animal names sequences were not read by the experimenter but pre-recorded and presented through the E-Prime interface.

Three measures were computed: preparatory interval, item recall duration, and span length. *Preparatory interval* was the time that elapsed between the end of the auditory item sequence and the first picture press. *Item recall duration* was scored as the time that elapsed

between the prior picture press and the subsequent picture press for a given item. Item recall durations were computed for correct trials only (i.e., trials for which all items were pressed in the correct order) and averaged across items (excluding the first one). *Span length* was scored as the highest sequence of animals that the participant correctly reproduced in the right order.

The data were analyzed separately for adults and children because of the substantial difference in sample size and the longitudinal nature of the child data. The longitudinal analysis for the child data was achieved with multilevel modeling (MLM), which allows modeling the dependency over time and levels (e.g. participants and button presses nested within sequence) (see Hoffman & Rovine, 2007; Quene, 2004), hence capitalizing in the longitudinal and repeated measures design of the present study. The temporal position of a given item within a sequence was referred as the "item temporal order". Given that our hypothesis focused on response sequence planning, we contrasted the recall duration of the first item (i.e., preparatory interval) with the mean recall duration of subsequent items within each sequence. Recall times were log-transformed to correct for non-normal distributions and minimize the influence of age-related differences in baseline recall durations. Because the maximal sequence length reached at each age varied, sequence length could not be entered as a predictor along with age. Instead, separate models were computed for each sequence length in order to examine the effect of age. A specific age point was entered for a sequence length if at least 15% of the participants contributed data. All age points were included in the analyses of 2- and 3-item sequences. For 4-items sequences, 4;6 and later age points were included. The analysis for 5-item sequences included ages 7 through 10, and finally the one for 6-item sequences included ages 8 through 10. Item temporal order, age and their interaction were used as predictors. Importantly, recall durations in Nebraska Barnyard necessarily vary as a function of both cognitive processes and spatial distance among buttons because children responded with one finger of one hand and had to move across space as they pressed buttons.

Response execution time necessarily varied as a function of the spatial distance between buttons. For instance, going from the left bottom button to right top button necessitates a bigger finger move and thus more time than going from the left bottom button to the middle bottom button. Therefore, the spatial distance in cm in between buttons, or between the start position below the grid and the first correct button, was entered as a predictor in the models. Its main effect was estimated to allow us to control for it while examining the effects of the other predictors. Similarly, we entered the method of administration (i.e., sequences read by the examiner vs. pre-recorded sequences) as a predictor so as to control for its potential effect. To probe whether sequence significantly affected the difference between the preparatory intervals and subsequent item recall durations at each age point, we ran a second series of models for each age point separately, including the sequence length as a predictor.

For the adult sample, a single model allowed us to examine both whether the preparatory interval was longer than subsequent item recall durations and whether this difference increased with the sequence length. Therefore, the multilevel model was comprised of buttons nested within sequence.

All study analyses were run using the PROC MIXED component of the SAS 9.3 statistical package (SAS Institute, Cary, NC, USA).

Results

Table 1 shows the maximal span length and the proportion of correct trials at each time point and for each sequence length. The maximal span length significantly increased with age, $F(6, 899) = 430.91$, $p < .0001$, $\eta_p^2 = .74$. Mean item recall durations were computed based on the correct trials and are shown in Figure 2.

Adults

The effects of item temporal order[1], sequence length, and button spatial distance on recall durations were significant, $F(1, 651) = 102.33$, $p < .001$, $\eta_p^2 = .14$; $F(4, 653) = 22.86$, $p < .001$, $\eta_p^2 = .12$; $F(1, 651) = 10.77$, $p = .001$, $\eta_p^2 = .02$. Critically, item temporal order and sequence length interacted, $F(4, 651) = 4.45$, $p = .001$, $\eta_p^2 = .03$ (Figure 2). The preparatory interval was longer than the mean recall times for subsequent items for all sequence lengths (Table 2). Further, the preparatory intervals significantly increased from 2- and 3-item sequences to 5-item sequences, $t(651) = -2.32$, $p = .020$, $d = -.18$ and $t(651) = -2.95$, $p = .003$, $d = -.23$, respectively, and 6-item sequences, $t(651) = -2.84$, $p = .004$, $d = -.22$ and $t(651) = -3.42$, $p < .001$, $d = -.27$. It also significantly increased from 4- to 6-item sequences, $t(651) = -2.36$, $p = .018$, $d = -.18$. These findings confirm that the preparatory interval reflects response sequence planning and that adults proactively planned their response sequence on the Nebraska Barnyard, consistent with previous studies (e.g., Towse et al., 2008a, 2008b).

Children

For the 2-item sequence length, age had a significant effect on recall durations, $F(1, 3914) = 93.29$, $p < .001$, $\eta_p^2 = .02$, which was qualified by a significant interaction with item temporal order, $F(6, 3879) = 21.40$, $p < .001$, $\eta_p^2 = .03$. Table 2 shows the pairwise comparisons between the preparatory interval and the average of subsequent item recall durations. The preparatory interval was shorter than the recall duration of the second item from ages 3;9 to 5;3, whereas it was longer than the recall duration of the second item at later age points. As shown in Figure 3, the reactive pattern observed at preschool surprisingly was more pronounced at age 5;3 than 4;6, $t(3881) = 3.49$, $p < .001$, $d = .11$. The switch from reactive to proactive patterns between 5;3 and 7 was significant, $t(3881) = -7.73$, $p < .001$, $d = -.25$, whereas the proactive pattern did not change later on, all ps $> .342$. There was also significant main effects of age, $F(6, 3914) = 93.29$, $p < .001$, $\eta_p^2 = .13$, and button spatial

[1] We also ran the same analyses separating all items in each sequence. These analyses revealed the same significant effects.

distance, $F(1, 3916) = 33.14$, $p < .001$, $\eta_p^2 = .01$, indicating that recall durations increased as a function of the button spatial distance between two presses. The effect of method was not significant, $p = .330$.

For the 3-item sequence length, the main effects of item temporal order, $F(1, 4957) = 4.00$, $p = .045$, $\eta_p^2 = .001$, and age, $F(6, 4999) = 123.48$, $p < .001$, $\eta_p^2 = .13$, significantly interacted, $F(6, 4956) = 69.46$, $p < .001$, $\eta_p^2 = .08$. The preparatory interval was shorter than the average recall duration of subsequent items at all three preschool age points, whereas the reverse pattern was observed between ages 7 and 10. Between ages 4;6 and 5;3, recall durations on subsequent items became even longer relative to the first items, t (4957) = 3.90, $p < .001$, $d = .11$. In addition to the significant difference between ages 5;3 and 7, t (4957) = 3.90, $p < .001$, $d = .11$, the proactive pattern increased in magnitude between ages 8 and 9, t (4957) = -3.66, $p < .001$, $d = -.10$ (Figure 3). Both button spatial distance and method were significant, $F(1, 5014) = 10.37$, $p < .001$, $\eta_p^2 = .002$, and $F(1, 4800) = 8.31$, $p < .001$, $\eta_p^2 = .002$, respectively.

For the 4-item sequence length, the effect of age, item temporal order, and their interaction were again significant, $F(5, 5165) = 102.38$, $p < .001$, $\eta_p^2 = .09$, $F(1, 5263) = 41.96$, $p < .001$, $\eta_p^2 = .01$, and $F(5, 5254) = 27.80$, $p < .001$, $\eta_p^2 = .03$, respectively. Surprisingly, there was no difference between the preparatory interval and subsequent item recall durations at age 4;6, whereas children took longer to recall subsequent items than the first item at age 5;3. During elementary school, children took longer to recall the first item, suggesting that they planned their response sequence. The difference between the preparatory interval and subsequent item recall durations became more pronounced between 4;6 and 5;3, t (5255) = 2.91, $p = .003$, $d = .08$, changed in direction between 5;3 and 7, t (5255) = -5.85, $p < .001$, $d = -.16$, and the magnitude of the proactive pattern increased between 7 and 8, t (5255) = -2.74, $p = .006$, $d = -.08$. Both button spatial distance and method were significant, $F(1,$

5302) = 105.70, $p < .001$, $\eta_p^2 = .02$ and $F(1, 4409) = 7.05$, $p = .008$, $\eta_p^2 = .002$, respectively.

For 5-item sequence length, the main effect of age fell short of significant, $F(3, 3111) = 2.54$, $p = .054$, $\eta_p^2 = .002$, while item temporal order had a significant effect, $F(1, 3116) = 246.58$, $p < .001$, $\eta_p^2 = .07$, that interacted with age, $F(3, 3115) = 15.22$, $p < .001$, $\eta_p^2 = .01$. From ages 7 through 10, children showed longer preparatory intervals than subsequent item recall durations. The proactive pattern increased in magnitude from ages 7 to 8, t (3116) = -3.74, $p < .001$, $d = -.13$, and 9 to 10, t (3116) = -3.54, $p < .001$, $d = -.13$. The effect of button spatial distance was significant, $F(1, 3137) = 47.72$, $p < .001$, $\eta_p^2 = .01$, whereas the effect of method was not, $p = .840$

For 6-item sequence length, there was a significant effect of item temporal order, $F(1, 1001) = 321.50$, $p < .001$, $\eta_p^2 = .24$, whereas its interaction with age was not significant, p = .609. Children showed longer preparatory intervals than subsequent item recall durations from ages 8 through 10. There was a significant effect of button spatial distance, $F(1, 1013) = 18.43$, $p < .001$, $\eta_p^2 = .02$, whereas the effects of age and method were not significant, ps > .405. Taken together, these findings suggest a change from a reactive approach to Nebraska Barnyard at preschool age to proactive response sequence planning during elementary school.

Finally, we examined whether the time difference between the preparatory intervals and subsequent item recall durations was influenced by sequence length at each age point. At age 3;9, there was no interaction between item temporal order and sequence, $p = .184$, further suggesting that children that young did not plan their response sequences. At age 4;6, there was a significant Item temporal order × Sequence interaction, $F(2, 1278) = 3.79$, $p = .022$, $\eta_p^2 = .01$, due to a shorter difference for 4-item sequences than 2- and 3-item sequences, t (1278) = -2.27, $p = .023$, $d = -.13$ and t (1278) = -2.72, $p = .006$, $d = -.15$ respectively. The exact same pattern was observed at age 5;3, $F(2, 2378) = 8.60$, $p < .001$, $\eta_p^2 = .01$, with a smaller difference for 4-item sequences than 2- and 3-item sequences, t (2377) = -3.20, $p = .001$, d = -

.13 and t (2378) = -4.00, $p < .001$, d = -.16, respectively. These findings suggest that the reactive pattern became less pronounced as the sequence to be recalled was more challenging at ages 4;6 and 5;3. Surprisingly, there was no interaction between item temporal order and sequence at age 7, $p = .983$. In contrast, Item temporal order and Sequence significantly interacted at ages 8, 9 and 10, $F(4, 3865) = 12.64$, $p < .001$, $\eta_p^2 = .01$, $F(4, 4420) = 16.82$, $p < .001$, $\eta_p^2 = .01$, and $F(4, 3098) = 18.39$, $p < .001$, $\eta_p^2 = .02$, respectively. At 8, the difference between the preparatory interval and recall durations of subsequent items significantly increased from 2- to 4-item sequences, t (3665) = -2.05, $p = .040$, d = -.07, 4- to 5-item sequences, t (3665) = -3.18, $p = .001$, d = -.11, and 5- to 6-item sequences, t (3665) = -2.58, $p = .010$, d = -.09. At 9, the difference increased significantly between 2- and 3-item sequences, t (4420) = -4.50, $p < .001$, d = -.14, and between 5- and 6-item sequences, t (4420) = -4.08, $p < .001$, d = -.12. At 10, the pairwise comparisons were significant between 2- and 3-item, and 4- and 5-item sequences, t (3098) = -4.00, $p < .001$, d = -.14, t (3098) = -3.19, $p < .001$, d = -.11. As expected, once children have switched to a proactive profile (except at 7 years), response sequence planning takes more time as the number of items increase.

Discussion

The present study used item recall durations to examine whether the temporal dynamic of working memory processes shows a reactive to proactive shift during childhood. At ages 3;9, 4;6 and 5;3, preschoolers generally approached the working memory span task reactively, not planning the response sequence, as suggested by shorter preparatory intervals than subsequent item recall durations. Preschoolers likely encoded items passively and retrieved and translated into a specific button each item only after recalling the previous one in an "as-needed" fashion. In contrast, children from 7 through 10 years of age and adults proactively planned their response sequences, as suggested by longer preparatory intervals than subsequent item recall durations. During elementary school, children, like adults, delayed

responding in order to proactively plan the response sequence, which likely required retrieving and translating most items before starting to respond, although additional retrieval likely took place in between presses as well. Further, proactive sequence planning changed during elementary school, becoming more sensitive to the number of items to be organized. These findings reveal that children shift from reactive to proactive control with age in the context of a working memory span task and show that this shift in control mode affects response sequence planning.

Working memory development during childhood cannot be fully explained by quantitative changes in processing speed and executive control efficiency. Our findings clearly point out qualitative changes in the control strategies that children use over time (see also Camos et al., 2011; Chevalier, Huber, Wiebe, & Espy, 2013). They clarify the nature of the executive changes that drive growing working memory during childhood, by revealing that a shift in the temporal dynamic of control helps children proactively plan response sequences. These findings are consistent with previous evidence for a reactive to proactive transition in executive control during childhood (Andrews-Hanna et al., 2011; Chatham et al., 2009; Killikelly & Szűcs, 2013). Furthermore, the observed transition between 5 and 7 years of age converges with prior findings showing important changes in children's working memory performance around that time. Specifically, children start switching attention between maintenance and processing in a finer way around 7 years of age (Camos et al., 2011), and the structural components of working memory (central executive, phonological loop, visuospatial sketchpad) can be observed from 6 years of age onward (Gathercole et al., 2004).

Such a change in proactive response sequence planning may shed light on the interplay between active maintenance in primary memory and active retrieval in secondary memory, as defined by Unsworth and Engle (2007). Because preschoolers do not plan the

response sequence, they may maintain actively in primary memory the first item only whereas subsequent items have to be retrieved from secondary memory while responding. If true, it would explain why the preparatory interval was not just equivalent to subsequent item recall durations, but actually shorter at preschool. Consistently, unlike adults, young children have recently been found to rely mostly on primary memory and not to use secondary memory to support primary memory when it is saturated (Roome & Towse, 2013). One open question is whether school-age children and adults maintained all animal names in primary memory during encoding and then started planning the response sequence right after the last item was encoded, or if they started planning the response sequence during item encoding by translating each item into its corresponding button and virtually constructing the spatial trajectory as each new item was heard. If the latter is true, then perhaps younger children could be more likely to adopt a similar strategy if animal names were easier to associate with their corresponding buttons (e.g., by displaying the animal pictures on the buttons during the test phase), encouraging them to construct the spatial trajectory during encoding. Indeed, recent findings suggest that preschoolers can be encouraged to engage proactive control through environmental manipulations (Chevalier, Martis, Curran, & Munakata, submitted).

Interestingly, the reactive pattern observed early in childhood, with preparatory intervals shorter than subsequent item recall durations, became more pronounced over the preschool period. This surprising tendency may reflect strengthening or more consistent use of the strategy consisting in prioritizing (i.e., maintaining in primary memory) the first item in the series over time. More consistent use of this strategy may lead children to build a better representation of its advantages and limitations, which helps them to search for or select alternative strategies, hence potentially explaining why the reactive pattern became more pronounced before the switch to the proactive pattern. Indeed, such meta-cognitive representations have been hypothesized to drive the development of executive control

(Zelazo, 2004) and influence children's use of proactive and reactive control (Chevalier et al., submitted). Nevertheless, the reactive pattern was less marked for 4-item sequences, especially at age 4;6. This attenuation of the observed reactive pattern may be due to a subsample of preschoolers (potentially the most cognitively advanced) starting to plan their response sequence when the task is sufficiently challenging. This is all the more plausible since 4-item sequences are more challenging at age 4;6 than 5;3 and 4-year-olds passing this sequence length represent a more selected sample (44 out of 146 at 4;6 and 107 out of 176 at 5;3) of potentially more cognitively advanced children.

During elementary school, children more systematically planned their response sequences. Consistently, the difference between the preparatory intervals and subsequent item recall durations increased with the sequence length from ages 8 through 10 and during adulthood, hence confirming that response sequence planning took more time with more items to organize sequentially. Interestingly, at 7 years of age, the sequence length did not affect this difference, suggesting that children that age did not plan their response sequence as effectively as they did later in childhood. Response sequence planning continued to develop after 7 as shown by increasing differences between the preparatory intervals and subsequent item recall durations with advancing age, especially for the longest sequences. Consistent with these findings, although children start to engage proactive control from about 6 years of age, proactive control continues to increase through early adulthood on other executive control measures (Andrews-Hanna et al., 2011; Waxer & Morton, 2011).

Although the difference between the preparatory intervals and subsequent item recall durations changed with advancing age, these differences seem to be driven in part by shorter recall durations of subsequent items, hence raising the possibility that children improved at retrieving later items in the sequence, perhaps in spite of similar response planning across ages. However, this interpretation cannot account straightforwardly for increasing differences

between preparatory intervals and subsequent item recall durations as a function of sequence length. Most importantly, it holds only if one assumes that response sequence planning and retrieval are independent processes. Yet, they are more likely to be intrinsically related because better initial planning should yield faster recall durations for subsequent items.

In conclusion, the present study clarified the nature of executive control changes that drive changes in working memory performance during childhood. Specifically, they showed that children mostly adopt a reactive approach until 5 years of age whereas response sequence planning emerges around 7 years and increases in efficiency through age 10. Of course, it remains possible that processes other than proactive response planning may also contribute to the present results; therefore this question should be further investigated through experimental manipulations in future studies. Of particular interest will be whether variables that affect the developmental trajectory of executive control, such as sex or socio-economic status (e.g., Clark et al., 2013), also influence the developmental course of response sequence planning. Finally, the two-year gap between ages 5 and 7 did not allow us to examine precisely how this shift occurs during that period; therefore research is needed to determine whether it changes sharply or steadily and the extent to which this trajectory varies across children.

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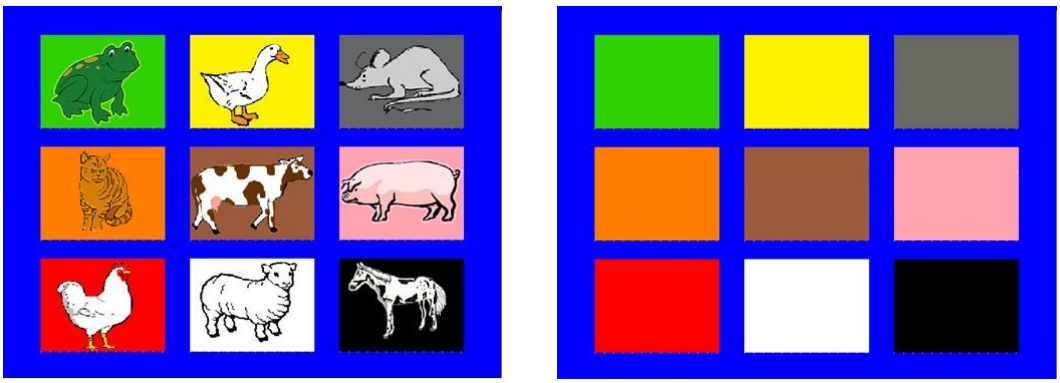

Figure 1. Illustration of the grid of colored squares with the animals (as used during the familiarization phase) and without the animals (as used during the practice and test trials). Participants had to reproduce sequences of animal names by pressing the colored squares on a touchscreen. Colors from top to bottom, left to right: green, yellow, gray, orange, brown, pink, red, white, and black. The background color is blue.

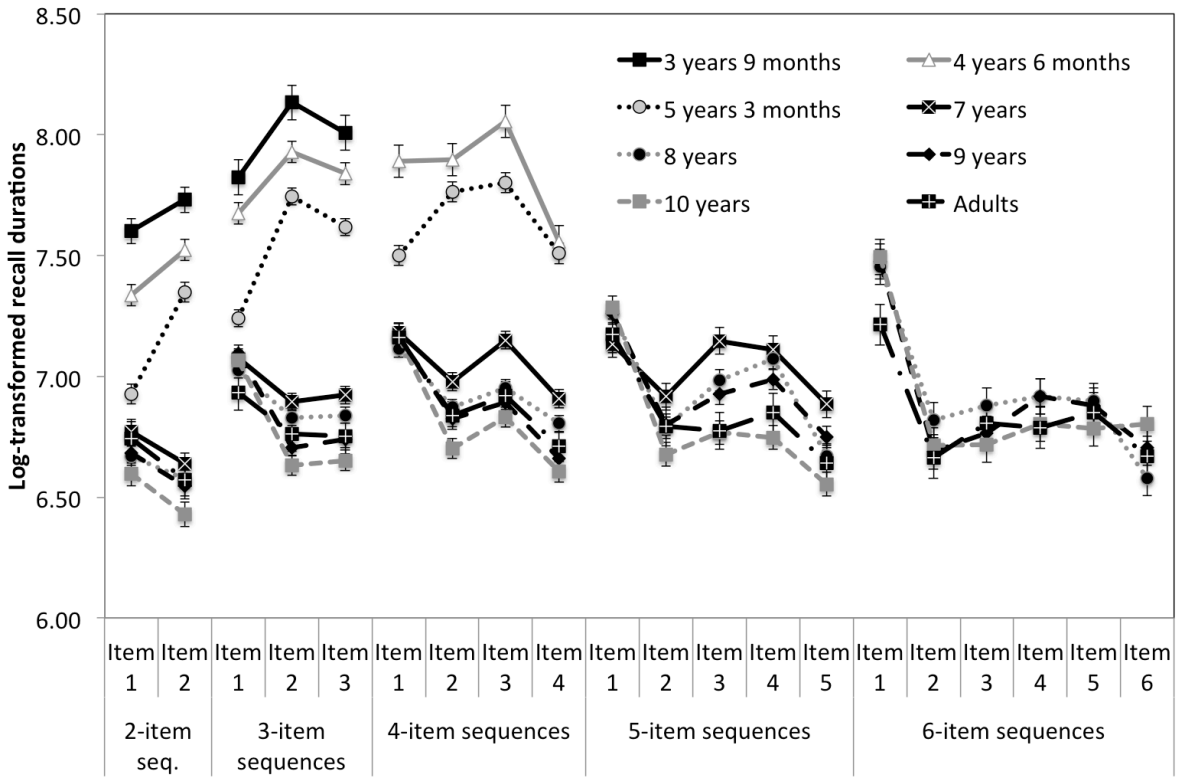

Figure 2. Mean log-transformed preparatory interval and item recall durations in seconds for each sequence length as a function of the button serial position and age, controlling for button spatial distance. Vertical bars indicate standard errors. At preschool age, children adopted a reactive approach whereas they proactively planned their response sequence during elementary school.

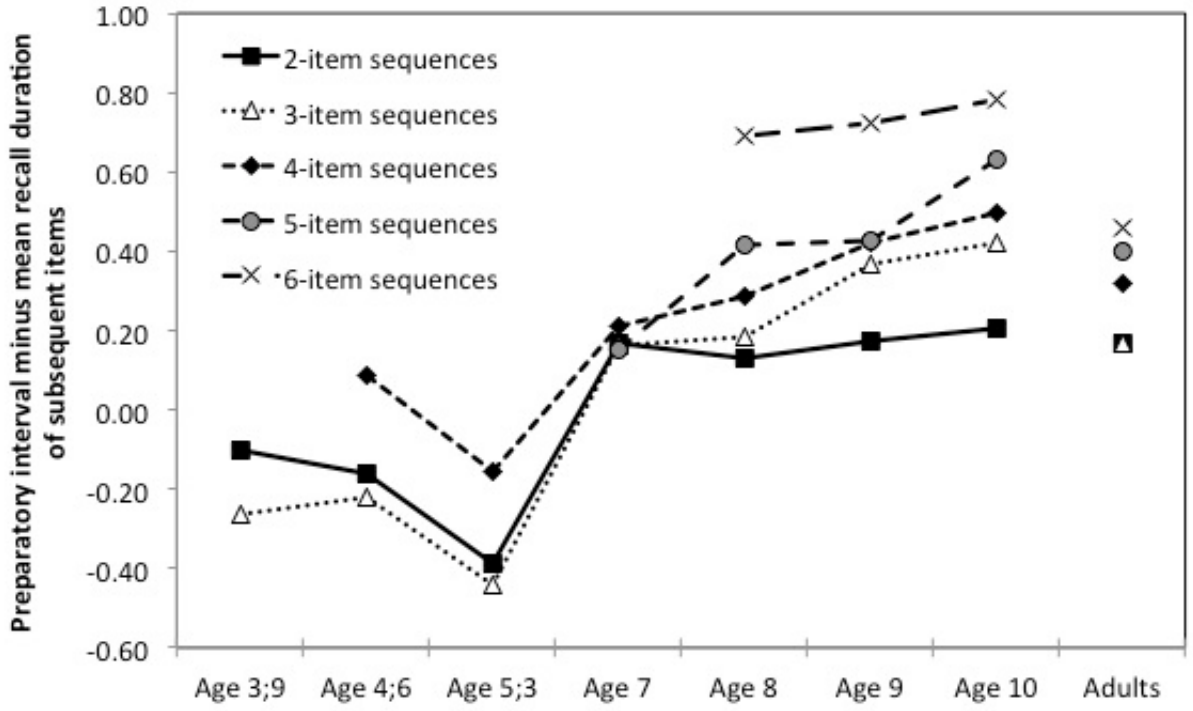

Figure 3. Differences between log-transformed preparatory intervals and the mean of log-transformed recall durations of subsequent items as a function of the sequence length and age. Proactive response sequence planning increased with age, especially for the longer sequences.

Table 1.

Proportion of correct trials for each sequence length and age point, and mean maximal span length (and standard deviations).

	Proportion of correct trials					Mean maximal span length
	2 items	3 items	4 items	5 items	6 items	
Age 3;9	52.2% (*N*=146)	17.8% (*N*=117)	6.0% (*N*=44)	0% (*N*=7)	--	2.4 (.6)
Age 4;6	74.9% (*N*=176)	41.9% (*N*=169)	23.2% (*N*=107)	3.4% (*N*=49)	0% (*N*=5)	2.9 (.9)
Age 5;3	85.4% (*N*=207)	65.1% (*N*=207)	39.5% (*N*=182)	4.5% (*N*=133)	2.1% (*N*=16)	3.6 (.8)
Age 7	98.0% (N=125)	95.0% (N=124)	79.7% (N=125)	29.6% (N=124)	9.7% (N=70)	4.7 (.7)
Age 8	98.5% (N=168)	94.9% (N=168)	83.3% (N=168)	37.9% (N=165)	14.3% (N=116)	4.9 (.8)
Age 9	98.6% (N=178)	67.7% (N=178)	87.6% (N=178)	46.8% (N=176)	18.8% (N=134)	5.1 (.9)
Age 10	99.6% (N=114)	97.0% (N=114)	88.3% (N=114)	58.5% (N=113)	21.6% (N=100)	5.4 (.8)
Adults	100% (*N*=21)	93.3% (*N*=21)	92.5% (*N*=21)	66.7% (*N*=20)	43.6% (*N*=15)	6.1 (1.11)

Table 2.

Mean log-transformed recall durations for the first item (preparatory interval) and subsequent items (averaged across items) as a function of item sequence length and age. Standard errors appear in parentheses. Significant pairwise comparisons and the longer duration are shown in bold.

Sequence Length	Age	Preparatory interval	Subsequent Item Recall duration (average)	Comparison
2 items	3;9	7.60 (0.05)	**7.73 (0.05)**	***t* (3881) = -2.05, *p* = .040, *d* = -.07**
	4;6	7.34 (0.04)	**7.52 (0.04)**	***t* (3881) = -3.72, *p* < .001, *d* = -.12**
	5;3	6.93 (0.04)	**7.35 (0.04)**	***t* (3881) = -9.42, *p* < .001, *d* = -.30**
	7	**6.77 (0.04)**	6.64 (0.04)	***t* (3881) = 2.32, *p* = .020, *d* = .07**
	8	**6.67 (0.04)**	6.57 (0.04)	***t* (3881) = 1.97, *p* = .048, *d* = .06**
	9	**6.68 (0.04)**	6.55 (0.04)	***t* (3881) = 2.89, *p* = .003, *d* = .09**
	10	**6.60 (0.05)**	6.43 (0.05)	***t* (3881) = 2.86, *p* = .004, *d* = .09**
	Adults	**6.74 (0.08)**	6.57 (0.08)	***t* (651) = 2.86, *p* = .004, *d* = .22**
3 items	3;9	7.82 (0.07)	**8.07 (0.05)**	***t* (4957) = -2.96, *p* = .003, *d* = -.08**
	4;6	7.67 (0.04)	**7.88 (0.04)**	***t* (4958) = -4.39, *p* < .001, *d* = -.12**
	5;3	7.24 (0.04)	**7.68 (0.03)**	***t* (4958) = -12.32, *p* < .001, *d* = -.35**
	7	**7.08 (0.04)**	6.91 (0.03)	***t* (4957) = 4.06, *p* < .001, *d* = .12**
	8	**7.03 (0.03)**	6.83 (0.03)	***t* (4958) = 5.40, *p* < .001, *d* = .15**
	9	**7.10 (0.03)**	6.72 (0.03)	***t* (4958) = 10.75, *p* < .001, *d* = .31**
	10	**7.07 (0.04)**	6.64 (0.03)	***t* (4957) = 9.92, *p* < .001, *d* = .28**
	Adults	**6.93 (0.07)**	6.76 (0.06)	***t* (651) = 2.70, *p* = .007, *d* = .21**
4 items	4;6	7.87 (0.07)	7.86 (0.04)	*t* (5256) = 0.25, *p* = .799, *d* = .01
	5;3	7.48 (0.04)	**7.71 (0.03)**	***t* (5256) = -5.22, *p* < .001, *d* = -.14**
	7	**7.14 (0.04)**	7.02 (0.02)	***t* (5258) = 2.86, *p* = .004, *d* = .08**
	8	**7.07 (0.03)**	6.89 (0.02)	***t* (5259) = 5.12, *p* < .001, *d* = .14**
	9	**7.12 (0.04)**	6.80 (0.02)	***t* (5259) = 9.05, *p* < .001, *d* = .25**
	10	**7.12 (0.04)**	6.72 (0.03)	***t* (5258) = 9.07, *p* < .001, *d* = .25**
	Adults	**7.14 (0.06)**	6.82 (0.04)	***t* (651) = 4.10, *p* < .001, *d* = .32**
5 items	7	**7.13 (0.06)**	7.01 (0.03)	***t* (3116) = 2.05, *p* = .040, *d* = .07**
	8	**7.26 (0.05)**	6.88 (0.03)	***t* (3116) = 8.71, *p* < .001, *d* = .31**
	9	**7.26 (0.04)**	6.87 (0.03)	***t* (3116) = 9.97, *p* < .001, *d* = .36**
	10	**7.28 (0.05)**	6.69 (0.04)	***t* (3116) = 13.59, *p* < .001, *d* = .49**
	Adults	**7.17 (0.08)**	6.77 (0.06)	***t* (651) = 6.91, *p* < .001, *d* = .54**
6 items	8	**7.46 (0.07)**	6.82 (0.04)	***t* (1003) = 8.91, *p* < .001, *d* = .56**
	9	**7.48 (0.07)**	6.79 (0.05)	***t* (1003) = 11.77, *p* < .001, *d* = .74**
	10	**7.50 (0.07)**	6.76 (0.05)	***t* (1003) = 11.54, *p* < .001, *d* = .73**
	Adults	**7.22 (0.08)**	6.76 (0.06)	***t* (651) = 6.73, *p* < .001, *d* = .53**