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Evidencing the Developmental Shift from Reactive to Proactive Control in Early Childhood,
and its Relationship to Working Memory

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Abstract

As they age, children tend to get more effective at regulating their behavior in complex situations; this improvement in cognitive control is often interpreted as a shift from predominantly reactive control to proactive control. There are three issues with this interpretation: (1) hard evidence is lacking that younger children actually rely on reactive control; (2) the precise age range in which such a shift would occur is still unclear; and (3) the reasons for this shift have not been explored. In the present study, we tested the hypothesis that children under 5 years of age do rely on reactive control, that they progressively shift to proactive control with age, and that this shift is related to increases in working memory capacity (which is necessary for proactive control). Children aged 4 to 7 performed a cognitive control task, the AX-CPT, as well as verbal and visuo-spatial working memory tasks. Using the paradigmatic AX-CPT in this age range allowed us to observe, for the first time, an actual reactive pattern in children under 5 years of age. There was a progressive shift from reactive to proactive control, with an estimated turning point between the ages of 5 and 6. The effect of age on proactive control was essentially shared with working memory capacity, confirming that these two cognitive processes develop in tandem.

Keywords

Dual mechanisms of control (DMC); Reactive control; Proactive control; Working memory capacity; Cognitive development

Highlights

- Cognitive control is believed to shift from reactive to proactive control with age.
- A truly reactive pattern has never been directly observed in children.
- We demonstrate that children under 5 years of age do rely on reactive control.
- We provide the first empirical evidence for a true shift from reactive to proactive.
- This shift to proactive control is related to increases in working memory capacity.

As children age, they get progressively more adept at organizing their actions, inhibiting inappropriate responses, and generally controlling their behavior. This progress is defined as improvement in cognitive control, or the ability to regulate one's behavior to achieve a particular goal (e.g. Miller & Cohen, 2001). Increases in cognitive control efficiency have been widely documented throughout childhood and until adolescence (see Diamond, 2013, for a review); most of the literature has focused on the executive functions through which cognitive control is exerted, such as inhibition, shifting, and updating – and on age-related increases in the efficacy of these executive functions (e.g. Diamond, 2013; Garon, Bryson, & Smith, 2008; Morra, Panesi, Traverso, & Usai, 2018). However, developmental improvements in cognitive control can be viewed not only as quantitative, but as qualitative (Chevalier, 2015).

A number of authors have proposed that age-related increases in cognitive control ability can be described as a shift between two cognitive control strategies: reactive control, and proactive control (e.g. Brahmhatt, White, & Barch, 2010; Chatham, Frank, & Munakata, 2009; Chevalier, Martis, Curran, & Munakata, 2015; Lorscheid & Reimer, 2008; Lucenet & Blaye, 2014; Munakata, Snyder, & Chatham, 2012). In this view, younger children would rely primarily on reactive control, which consists in waiting for a control-demanding event to occur and then implementing cognitive control as a late-correction mechanism (see Braver, 2012; Braver, Gray & Burgess, 2007). Conversely, older children would tend to use proactive control, an anticipatory mechanism which consists in actively maintaining goal-relevant information in working memory so as to optimally orient behavior when the event occurs. Proactive control places more demands on working memory, but it is generally more effective, which would explain the better cognitive control performance of older children. The developmental shift from one mechanism to the other would presumably occur around 5-6 years old (e.g., Blackwell & Munakata, 2014; Chevalier, 2015; Lucenet & Blaye, 2014).

This account of development, framed within the dual mechanisms of control account (Braver, 2012; Braver et al., 2007), offers a powerful framework to interpret age-related improvements in cognitive control in that it allows for more fine-grained hypotheses than purely quantitative differences in control performance. Critically, it also offers a straightforward way to test these hypotheses by using a specific experimental paradigm, the AX-CPT (AX-Continuous Performance Task: Servan-Schreiber, Cohen, & Steingard, 1996; see also Braver et al., 2007). The AX-CPT was designed specifically to assess whether participants are actively maintaining goal-relevant information in working memory to prepare a response in advance, and has been used in the vast majority of studies on reactive and proactive control (Braver, 2012; Braver et al., 2007).

In the AX-CPT, participants are confronted with sequences of cue and probe letters; they are required to respond positively to the probe letter only if it is an X and if the preceding cue was an A (AX sequence). Due to the large proportion of AX trials, participants who use proactive control tend to prepare a target response when the cue is an A, which elicits high error rates and very slow response times when the probe letter happens to be something other than an X (AY trials). Conversely, these participants can answer quickly and accurately by preparing a non-target response on trials where the cue is a letter other than A, even if it is followed by an X (BX trials). The opposite pattern is observed for participants who use reactive control: not preparing a target response in advance elicits relatively fast response times and few errors on AY trials, but the X probe tends to lure them into incorrectly making a target response on BX trials. The AX-CPT has been used in many studies, repeatedly showing that young adults rely on proactive control (Braver et al., 2007), whereas healthy older adults demonstrate a typical reactive pattern with higher error rates on BX than AY trials (Braver et al., 2001; Braver, Satpute, Rush, Racine, & Barch, 2005; Paxton, Barch, Storandt, & Braver, 2006; Paxton, Barch, Racine, & Braver, 2008).

Because it is usually considered that "young children rely exclusively on reactive control" (Chevalier, 2015, p. 240; see Barker & Munakata, 2015, Blackwell & Munakata, 2014, or Munakata et al., 2012, for similar statements), and because the AX-CPT paradigm allows for a clear dissociation between the two mechanisms – as demonstrated in the context of normal aging –, it seems like the literature should abound with examples of studies showing a transition from a reactive pattern in preschoolers to a proactive pattern in middle childhood. It is therefore especially surprising that no true shift from reactive to proactive control has ever been observed directly.

To be clear, proactive control has been convincingly shown to increase with age during childhood, with older children demonstrating more and more advantage for BX trials over AY trials. However, evidence that younger children actually rely on reactive control – implementing cognitive control as a late-correction mechanism – is remarkably scarce. Based on available data, it could equivalently be the case that young children try to use proactive control but do so less effectively, or that young children do not control their behavior at all (see Braver et al., 2007). If an actual shift from reactive to proactive control does take place, there is also precious little empirical evidence to estimate at what age children cease using reactive control.

The seminal study on this topic compared 3.5-year-olds and 8-year-olds with a modified version of the AX-CPT (Chatham et al., 2009). This study successfully demonstrated an unambiguous age-related increase in the use of proactive control. Critically, however, even the 3.5-year-old group did not demonstrate a clearly reactive pattern of performance. The difference between AY and BX error rates was not tested for significance, but given their extremely high overall error rates (close to chance level, around 50% errors on both AY and BX trials), it is unclear whether these children exerted reactive control, or no control at all. Children in the 3.5-year-old group were slower on AY trials than on BX trials

to the same extent as 8-year-olds, and pupillometric data indicated that on average, they exerted descriptively more effort during the delay between the cue and the probe letter than after the probe had occurred, suggesting proactive control. While complementary analyses, such as an examination of pupillometric data restricted to BX trials, provided clues compatible with use of reactive control in 3.5-year-old children, the results never showed the reactive profile observed in older adults with a clear-cut pattern of advantage for AY trials (Braver et al., 2001, 2005; Paxton et al., 2006, 2008).

The few subsequent studies that used the AX-CPT with children faced similar issues, observing increases in the use of proactive control but never a truly reactive profile. Two studies by Lorschach and Reimer (2008, 2010) compared 9-year-old children, 12-year-old children, and adults, and found a proactive pattern with better BX performance in both groups of children – unsurprisingly given their age. Lucenet and Blaye (2014) compared 5-year-olds and 6-year-olds and found that both groups displayed, on average, a proactive pattern of performance. A common limitation of these studies is the difficulty in pinpointing the precise developmental timecourse of increase in the use of proactive control, due to large gaps between age groups (e.g., 3.5-year-olds and 8-year-olds in Chatham et al., 2009), sampling of older children (Lorschach & Reimer, 2008, 2010), or too restricted an age range (Lucenet & Blaye, 2014). In fact, a single study sampled children under 5 years of age (Chatham et al., 2009).

Studies based on paradigms other than the AX-CPT have been invaluable in providing converging evidence that the use of proactive control increases with age, but have not resolved these core issues. A series of experiments with cued task-switching paradigms showed that children younger than 8-10 years old devote less attention to the cue displayed prior to the target (Chevalier, Dauvier, & Blaye, 2018), tend to exert less effort during the delay prior to target onset (Chevalier et al., 2015), and prepare their response less efficiently

during this delay (Chevalier & Blaye, 2016), indicating reduced use of proactive control. On the other hand, children as young as 5 years old do prepare their response in advance based on the cue during the delay before the target appears (Chevalier & Blaye, 2016; Chevalier, Blaye, Dufau, & Lucenet, 2010; Karbach & Kray, 2007), especially when this strategy is the most efficient (Chevalier et al., 2015), again suggesting a reduced tendency to use proactive control but not a strictly reactive profile per se.

Other studies used attentional tasks and memory tasks; while not designed to measure cognitive control, these paradigms led to similar conclusions. One study based on a sustained attention task allowing for anticipation showed that performance increases with age in 4- and 5-year-old children, which may reflect increased proactive control (Doebel, Dickerson, Hoover, & Munakata, 2018); but indexing cognitive control exclusively based on total performance only makes it possible to determine that efficacy increases with age, not whether participants of a given age are using reactive control or proactive control. Another study showed that children over 7 years of age tend to spend more time preparing their response prior to recalling a series of items, which might indicate more proactive control, but this pattern was only apparent for short to-be-remembered sequences (Chevalier, James, Wiebe, Nelson, & Espy, 2014). One study using a *n*-back task indicated reduced sustained activity in the dorsolateral prefrontal cortex in 9-to-13-year-old children when compared to adults, corresponding to reduced proactive control, but not more transient activity at the time of the probe in either the prefrontal cortex or other areas underlying reactive control (Brahmbhatt et al., 2010), again suggesting that these children did not actually use reactive control to a greater extent than adults.

Rationale for the Present Study

In summary, it is commonly accepted that younger children exclusively use reactive control, but no published study has ever observed a truly reactive profile in these children – especially using the paradigmatic task for the dual mechanisms of control framework, the AX-CPT. This is highly surprising, given that a reactive pattern has often been reported in older adults (Braver et al., 2001, 2005; Paxton et al., 2006, 2008). Prior studies have also yielded relatively imprecise estimates of the timecourse for a shift from reactive to proactive control. Our two primary objectives were to test whether children can actually be observed to use predominant reactive control, and if so, at what age.

To this end, we tested children in a continuous age range between 4 years old and 7.5 years old (compatible with prior hypotheses of a shift around 5-6 years; Blackwell & Munakata, 2014; Chevalier, 2015; Lucenet & Blaye, 2014). The ambiguous pattern observed by Chatham and colleagues (2009) might be partly attributable to a modified version of the AX-CPT, with the use of only four different stimuli allowing participants to rely on associative learning (see Lucenet & Blaye, 2014, for a discussion of this point); for this reason, we used an adaptation of the AX-CPT closer to the adult version with 14 different cue and probe stimuli. We also directly contrasted the use of reactive and proactive control with a summary measure, the proactive behavioral index (PBI; Braver, Paxton, Locke, & Barch, 2009), which reflects the balance between the two mechanisms.

A third objective of the present study was to examine the concurrent development of a possible determinant of the shift towards proactive control. No empirical studies have directly investigated the underpinnings of this shift: it is often assumed that maturation of the dorsolateral prefrontal cortex is the source of cognitive control improvements, but this does not explain what happens mechanistically. If younger children are capable of using either

cognitive control strategy, as prior studies have suggested (Chevalier et al., 2010, 2015; Chevalier & Blaye, 2016), why would they prefer one type of control over the other? The literature puts one possible answer forward: working memory capacity. WMC is often hypothesized to be involved in the development of cognitive control (e.g. Roberts & Pennington, 1996). In particular, working memory is thought to be critical for the active maintenance of goal-related information to orient behavior (Miller & Cohen, 2001). As such, it holds a central role in the dual mechanisms of control framework: to engage in proactive control, it is necessary to actively hold contextual information in working memory (Braver et al., 2007).

Because working memory increases with age during childhood, lower WMC in younger children could explain why they use less proactive control. Two studies have attempted to explore this possibility by manipulating the delay between cue and probe (i.e., working memory demands) in the AX-CPT, with contradictory conclusions. One study suggested that shortening the delay between cue and probe reduces age-related differences in performance (Lorsbach & Reimer, 2010), whereas the other study concluded that the effect of age was independent of delay (Lucenet & Blaye, 2014). A more direct way to test the involvement of working memory would be to measure individual differences in WMC: several studies in adults have suggested that WMC can predict the use of proactive control in the AX-CPT (Redick, 2014; Redick & Engle, 2011; Richmond, Redick, & Braver, 2015; but see Cooper, Gonthier, Barch, & Braver, 2017). In the present study, we investigated the role of working memory by measuring individual differences, using both verbal and visual WMC tasks so as to obtain a domain-general estimate of WMC (in line with the dominant conception of working memory capacity as primarily aspecific: Kane et al., 2004; see also Arsalidou, 2013; Halford, Cowan, & Andrews, 2007; Pascual-Leone, 1970). We then tested the relations between WMC, age and proactive control.

Method

Participants

A sample of 69 children (54% male) completed the experiment¹. These children were recruited in three consecutive school grades: pre-kindergarten ($n = 25$, mean age = 4.41 years), kindergarten ($n = 21$, mean age = 5.72 years), and 1st grade ($n = 23$, mean age = 6.68 years). The resulting sample had an approximately continuous age range (mean age = 5.63 years, $SD = 0.99$, range = 4.17 to 7.25 years).

Participants were predominantly White and of average socioeconomic status, reflecting the characteristics of the local community. All participants spoke French as their first language and attended the class corresponding to their age group. All children within a class were invited to complete the experiment. Informed written consent was obtained from the children's parents and all children provided verbal assent.

Materials

Cognitive control task: the AX-CPT.

Task. Participants performed a child-adapted version of the AX-CPT (see Lucenet & Blaye, 2014), similar to the adult version except that the letters were replaced by animals. The task was presented as a series of races between two animals (cue and probe). Children were instructed to press the green response button with their dominant index finger when they saw a hen (A) followed by a cat (X), and to press the red response button with their other index finger in all other cases. Other possible animals were a horse, a crocodile, a snail, an elephant, a giraffe, a rabbit, a lion, a sheep, a snake, a mouse, a turtle and a cow. Children's knowledge of all these animal names was verified before the introduction of the task itself.

¹ No *a priori* power analysis could be performed, as the absence of prior data made it impossible to estimate the size of the expected effect of age on proactive control. Data collection was planned based on prior studies using the same task and a similar design (Chatham et al., 2009; Lorschbach & Reimer, 2008, 2010; Lucenet & Blaye, 2014), which had a maximal sample size of $N = 68$ in Chatham et al. (2009).

Probe animal pictures were displayed along with two red- and green-colored circles at the bottom of the screen representing the two response buttons, so as to help the child keep track of which animals were cues and which were probes.

Participants first completed 8 demonstration trials, which could be repeated if needed, to get acquainted with the task. They then performed 16 practice trials, followed by three test blocks of 30 trials (18 AX, 4 AY, 4 BX, 4 BY; i.e. 60% AX, 13.3% AY, 13.3% BX, 13.3% BY)². Trials within each block were presented in semi-random order to control for trial sequences (see Chatham et al., 2009): a task block always started with two AX trials, there were never more than three consecutive trials requiring the same response, sequences of one AX / two AX / three AX trials occurred three times each, and AX trials were followed equally often by AY and BY trials, as were BX trials.

Each trial started with a fixation cross displayed for 500ms. A cue animal picture was then displayed at the center of the screen for 1000ms, followed by a 1500ms inter-stimulus interval. Lastly, a target animal picture was presented until the participant responded or until a response deadline. This response deadline was adjusted on an individual basis so that the task kept an appropriate pace for children of all ages and ability levels: during the practice trials the maximal time to respond was set to 6000ms, and during the actual task it was computed as the child's average response time over the preceding blocks plus one standard deviation. Participants received audio feedback after each trial, with different sounds corresponding to correct, incorrect and too-slow responses.

Data processing. The first trial of each task block (always an AX trial due to the semi-random order) was excluded from the analyses. Trials with response times faster than 200ms

² The proportion of AX trials was slightly decreased from the classic paradigm with 70% AX trials, so as to obtain more precise estimates for the critical AY and BX trials. This is a minor change, as the proportion of trials varies from one study to the next – with recent studies leaning towards 40% AX trials (e.g. Gonthier, MacNamara, Chow, Conway, & Braver, 2016; Richmond et al., 2015).

and trials where the child did not respond within the deadline were also excluded; this represented between 7% and 15% of trials for all trial types. Average error rates were computed without taking these trials into account. Response times were computed on trials with correct answers only. To account for general age-related speeding in the task (Faust, Balota, Spieler, & Ferraro, 1999), response times were also standardized for each participant, as in past studies interested in age differences in the AX-CPT (Braver et al., 2005; Lorschbach & Reimer, 2010; Paxton et al., 2006, 2008). More specifically, *z*-scores were computed separately for each participant and for each trial type, by subtracting the child's average response time over all trials and dividing by the corresponding standard deviation.

To summarize the use of proactive control, a proactive behavioral index was computed as $(AY - BX) / (AY + BX)$, separately for error rates and response times (Braver et al., 2009). The PBI reflects the relative balance of interference between AY and BX trials, with positive values reflecting more difficulty on AY trials, indicating proactive control, and negative values reflecting more difficulty on BX trials, indicating reactive control. A composite PBI was also computed as the average (after standardization) of the error rate PBI and the response times PBI, thus summarizing the use of proactive control with a single index (see e.g. Gonthier et al., 2016). The main advantage of the composite PBI is that it takes into account the tradeoff between speed and accuracy: positive values indicate more difficulty on AY than BX trials, as reflected in both accuracy and response times.

Of secondary interest, two other indices used in past studies and based on the signal detection theory (see Gonthier et al., 2016) were also calculated for consistency. A *d'*-context was computed as $Z(\text{Hit rate}_{AX}) - Z(\text{False alarms}_{BX})$, with *Z* representing the *z*-transform of these values; higher values of the *d'*-context reflect better use of the context provided by the cue to guide responding, indicating proactive control. An A-cue bias was computed as $1/2 * Z(\text{Hit rate}_{AX}) - Z(\text{False alarms}_{AY})$, with higher values reflecting a stronger tendency to

make a target response after an A cue, also indicating proactive control (see Richmond et al., 2015).

Working Memory Tasks.

Verbal working memory. The verbal working memory task was derived from the backward color recall task (adapted from Schmid, Zoelch, & Roebbers, 2008; see Roebbers, Schmid, & Roderer, 2010, for a presentation of the task). The task was explained to the children using a drawing of a stick figure walking on a path, with the figure progressively losing colored coins from a bag with a hole in it. In the actual task, the experimenter verbally enunciated a series of colors (without a visual support), as if they were a series of coins lost by the stick figure; children were asked to recall the series of coins in the same order. The experimenter first ensured that the child knew all the color names. In a first phase, children performed the task in forward order to familiarize themselves with the material. In a second phase, they were requested to perform the task in backward order, as if the stick figure turned back on the path and picked up the lost coins in reverse order.

Visual working memory. Participants performed a child-adapted version of the Corsi (1972) block-tapping task. Wooden blocks were arranged in their standardized configuration (Kessels, van Zandvoort, Postma, Kappelle, & de Haan, 2000) on a board. Blocks were painted and described as trees in a forest; children were requested to tap the blocks in the correct order for a little monkey toy to reproduce the path followed by its father, as demonstrated by the experimenter. In a first phase, children performed the task in forward order to familiarize themselves with the material. In a second phase, they were requested to perform the task in backward order, with the little disobedient monkey following their father's path in reverse.

Procedure and scoring. For both the forward and the backward order in each task, participants first performed three practice trials of set size 2, which were repeated if they

failed to recall at least two sequences. They then completed trials of set sizes 2 to 7, with six trials per set size. Children who correctly recalled three sequences within a set size were credited for the rest of the sequences and progressed to the next set size. The task was discontinued when a child failed all trials within a set size.

Only the data from the backward order were analyzed for both tasks. Children were given 2 points for recalling the correct stimuli in the correct order, 1 point for recalling the correct stimuli in the wrong order, and 0 points otherwise, for a maximum WMC score of 72 in both tasks. To obtain a domain-general estimate of WMC (Kane et al., 2004), a composite working memory score was also computed by standardizing the total scores on each task and then averaging the two.

Procedure

Children were tested individually in a quiet room at their school. They performed the AX-CPT in a first testing session, and the verbal and visuo-spatial working memory tasks in a second session taking place within one week.

Results

Data files can be accessed via the Open Science Framework platform at osf.io/udscf/. The data were screened for outliers using Cook's distance prior to each analysis. One child in pre-kindergarten with error rates above 50% on both AY and BX trials was excluded, yielding a final sample size of $N = 68$. All statistical analyses were performed based on the general linear model, with age treated as a continuous variable; however, descriptive statistics and figures were generated by discretizing age as a function of school grade to facilitate

interpretation of the results and comparison with prior studies³. Descriptive statistics for all measures are displayed in Table 1.

Developmental Shift of Cognitive Control Mechanisms in the AX-CPT

The first series of analyses investigated the relationship between age and performance on the AX-CPT, so as to find evidence for an actual shift from reactive to proactive control with age. The same analyses were performed for error rates and response times. There was no main effect of age on error rates, $F(1, 66) = 0.30$, $p = .584$, $\eta^2_p = .00$, suggesting that older children were not more accurate on average, but the two-way interaction between age and trial type was significant, $F(3, 198) = 3.26$, $p = .023$, $\eta^2_p = .05$, indicating that the balance of performance across trial types changed significantly with age. This two-way interaction is displayed in Figure 1, with age discretized as a function of school grade to ease visualization.

³ An alternative representation of the effect of age on performance in the AX-CPT, with age depicted as a continuous variable, is available in Appendix A.

Table 1

Descriptive statistics for all measures as a function of school grade

Task	Type of measure	Measure	Pre-kindergarten		Kindergarten		1st grade	
			<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
AX-CPT	Error rates	AX	0.10	0.07	0.06	0.05	0.05	0.04
		AY	0.09	0.13	0.17	0.20	0.16	0.17
		BX	0.15	0.13	0.14	0.14	0.10	0.16
		BY	0.07	0.09	0.05	0.09	0.04	0.07
	Response times	AX	1365	300	967	388	720	177
		AY	1582	356	1246	450	956	310
		BX	1382	407	999	450	711	222
		BY	1447	344	976	410	723	238
	Standardized response times	AX	-0.08	0.13	-0.09	0.15	-0.08	0.14
		AY	0.28	0.26	0.74	0.56	0.80	0.38
		BX	-0.04	0.39	-0.08	0.38	-0.14	0.41
		BY	0.12	0.46	-0.09	0.34	-0.13	0.35
	Summary indices	PBI errors	-0.22	0.41	0.00	0.50	0.10	0.51
		PBI RTs	0.07	0.11	0.13	0.12	0.15	0.11
		PBI composite	-0.39	0.59	0.09	0.90	0.26	0.84
		<i>d'</i> -context	2.40	0.89	2.61	0.67	2.85	0.76
A-cue bias		0.03	0.27	0.27	0.35	0.28	0.34	
Working memory	Recall scores	Verbal WM	16.46	4.19	22.81	5.18	22.28	4.65
		Visual WM	16.23	4.77	26.81	9.62	29.08	9.40
		WM composite	-0.78	0.53	0.34	0.80	0.40	0.67

Note. PBI = Proactive Behavioral Index; WM = Working memory; RTs = Correct response times.

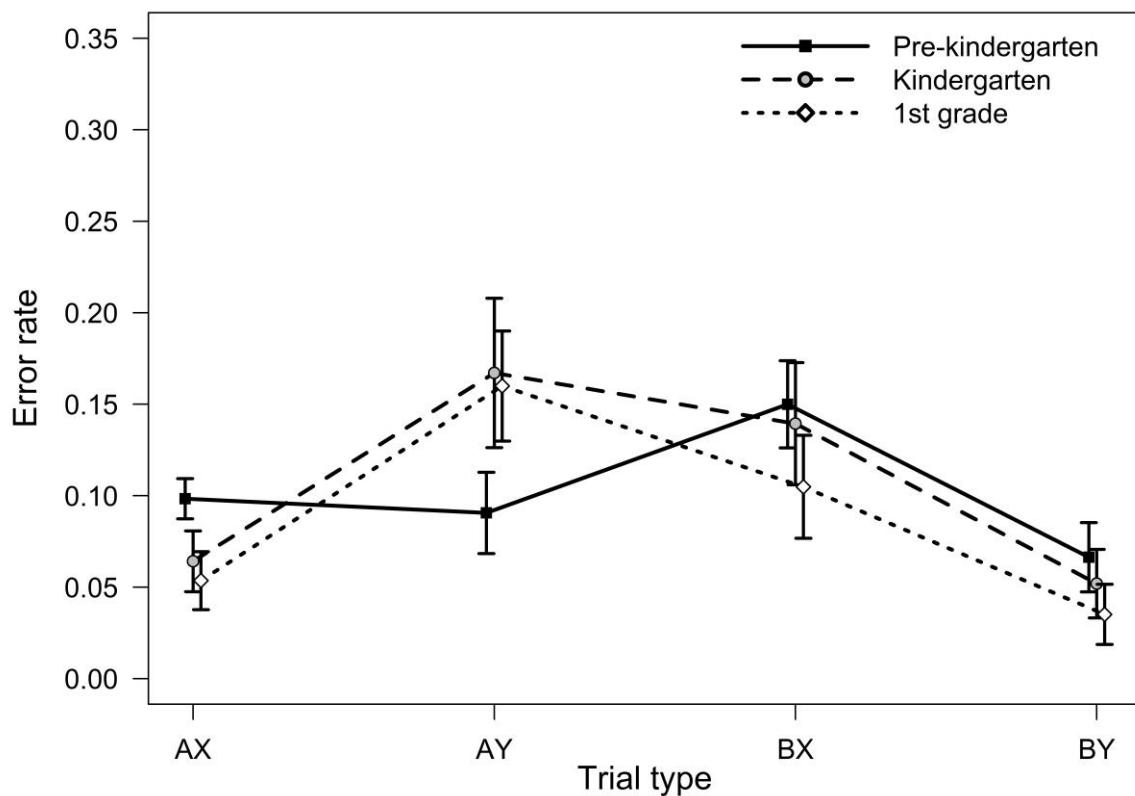


Figure 1. Error rates as a function of trial type and age. Error bars represent within-subjects standard errors of the mean (Morey, 2008). The statistical analysis corresponding to this figure was performed with age treated as a continuous variable.

Overall, Figure 1 showed that children in pre-kindergarten demonstrated a predominantly reactive pattern of performance, with higher error rates for BX trials than for AY trials (see Table 1). This pattern completely changed for kindergarten and 1st grade children, who demonstrated more errors on AY trials than on BX trials, close to the proactive pattern typically observed in young adults. This developmental shift from reactive to proactive control on AY and BX trials was reflected in a significant linear increase with age for the PBI computed for error rates, $F(1, 66) = 5.54$, $p = .022$, $\eta^2_p = .08$, $r = .28$. The regression equation predicted a negative PBI, corresponding to predominant use of reactive

control, for children younger than 5.83 years (70 months). The effect of age was also significant for the A-cue bias, $F(1, 66) = 7.21$, $p = .009$, $\eta^2_p = .10$, $r = .31$, and marginally significant for the d' -context, $F(1, 66) = 3.52$, $p = .065$, $\eta^2_p = .05$, $r = .23$.

We then examined the relationship between age and response times. As expected, unstandardized response times revealed little beyond a main effect of age, $F(1, 66) = 57.01$, $p < .001$, $\eta^2_p = .46$, reflecting the fact that older children answered faster; the two-way interaction between age and trial type was not significant, $F(1, 66) = 0.60$, $p = .619$, $\eta^2_p = .01$. Critically, however, standardized response times were not affected by age, $F(1, 66) = 1.05$, $p = .309$, $\eta^2_p = .02$, and revealed a significant two-way interaction between age and trial type, $F(3, 198) = 8.28$, $p < .001$, $\eta^2_p = .11$. This two-way interaction is displayed in Figure 2. Overall, Figure 2 showed that standardized response times were relatively stable with age for AX, BX and BY trial types (with non-significant effects of age for AX and BX trials, both $ps > .30$, and slightly faster RTs for older children on BY trials, $p = .037$). The two-way interaction was mainly driven by considerable slowing of responses on AY trials for older children ($p < .001$). Pre-kindergarten children were only slightly slower on AY trials than on BX trials (see Table 1), comparable to what is observed in older adults (Braver et al., 2001, 2005; Paxton et al., 2006, 2008). On the other hand, kindergarten and 1st grade children were much slower on AY trials than BX, confirming that they heavily relied on proactive control. This developmental shift towards more proactive control was reflected in a linear increase with age for the PBI computed for response times, $F(1, 66) = 4.84$, $p = .031$, $\eta^2_p = .07$, $r = .26$.

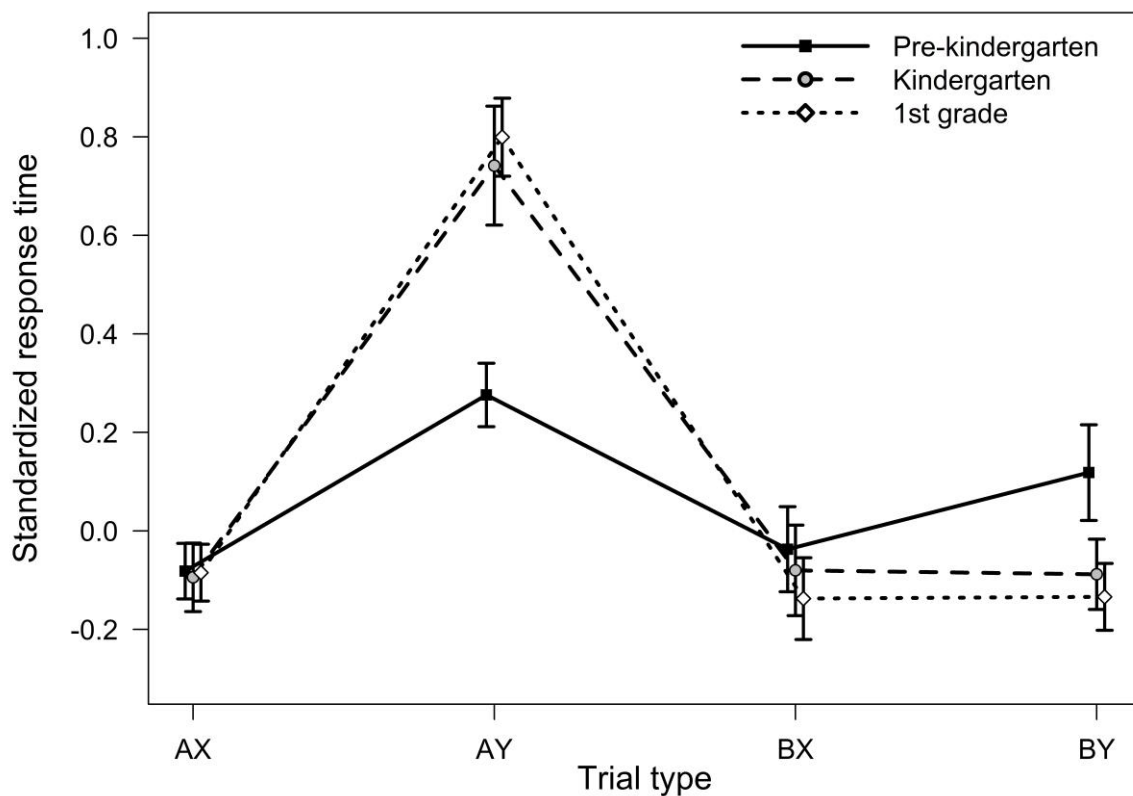


Figure 2. Standardized response times as a function of trial type and age. Error bars represent within-subjects standard errors of the mean. The statistical analysis corresponding to this figure was performed with age treated as a continuous variable.

Congruent with the reactive pattern observed in older adults, the youngest children made more errors on BX trials than AY trials, but still responded slightly more slowly to AY trials. To ensure that our results were not due to an age-related change in the speed-accuracy tradeoff, we turned to the composite PBI as a way to summarize the developmental shift in cognitive control by integrating accuracy and RT data. The composite PBI demonstrated a significant correlation with age, $F(1, 66) = 7.90$, $p = .006$, $\eta^2_p = .11$, $r = .33$, confirming a progressive linear increase in the use of proactive control as reflected by both accuracy and response times. This relationship is represented in Figure 3. As can be seen in Figure 3, the composite PBI increased from negative average values for younger children (corresponding

to dominant reactive control) to positive average values for older children (corresponding to dominant proactive control). The regression equation predicted that the turning point between reactive and proactive control – as reflected in a PBI composite equal to zero – occurred for children aged 5.62 years (or 67 months), thus confirming our estimate based on the unstandardized error rate data.

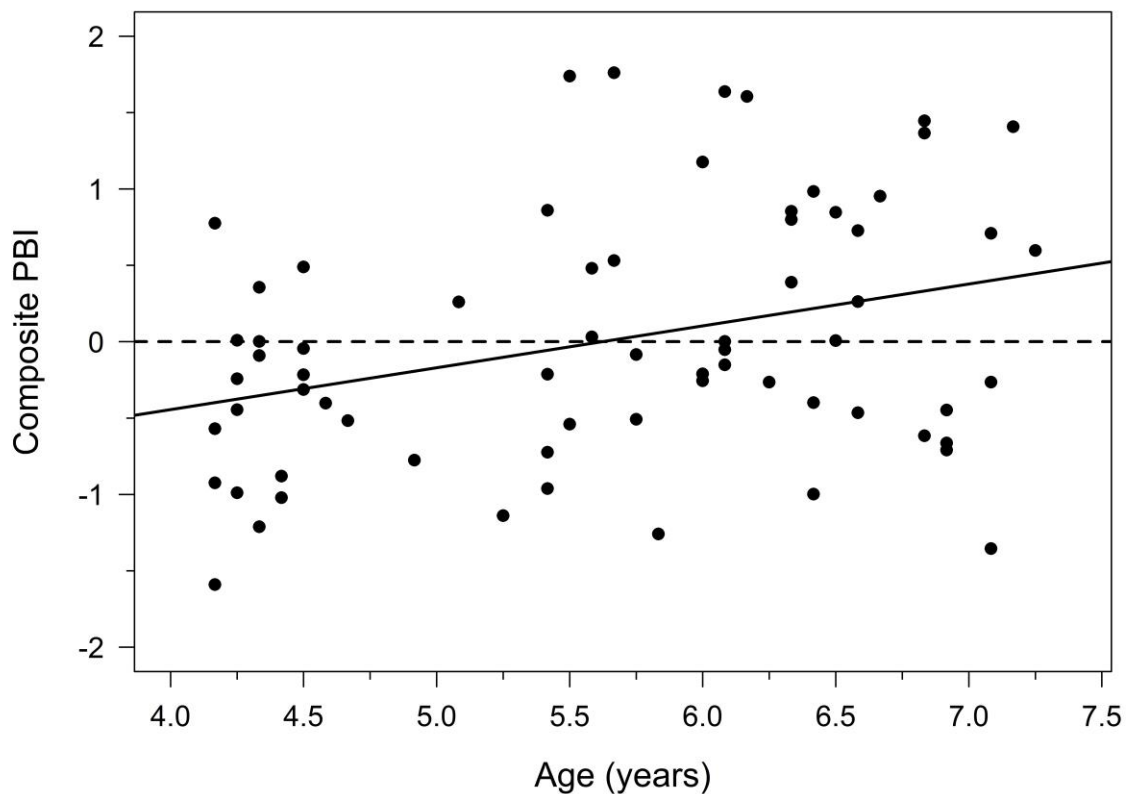


Figure 3. Relationship between age and composite PBI. The solid line represents the slope of the regression line; the dashed line is the reference of a composite PBI equal to 0, indicating perfect balance between proactive and reactive control.

Relationship of the Developmental Shift to Working Memory

The next series of analyses aimed to test the hypothesis that the developmental shift from reactive to proactive control is accompanied by age-related increases in WMC. Firstly,

the composite working memory score demonstrated a large increase with age, $F(1, 66) = 36.54$, $p < .001$, $\eta^2_p = .36$, $r = .60$, confirming developmental improvement of WMC in our sample. This relationship is represented in Figure 4a. Secondly, the composite working memory score correlated positively with the composite PBI, $F(1, 66) = 7.28$, $p = .009$, $\eta^2_p = .10$, $r = .32$, confirming that children with higher WMC tended to be more proactive. This relationship is represented in Figure 4b.

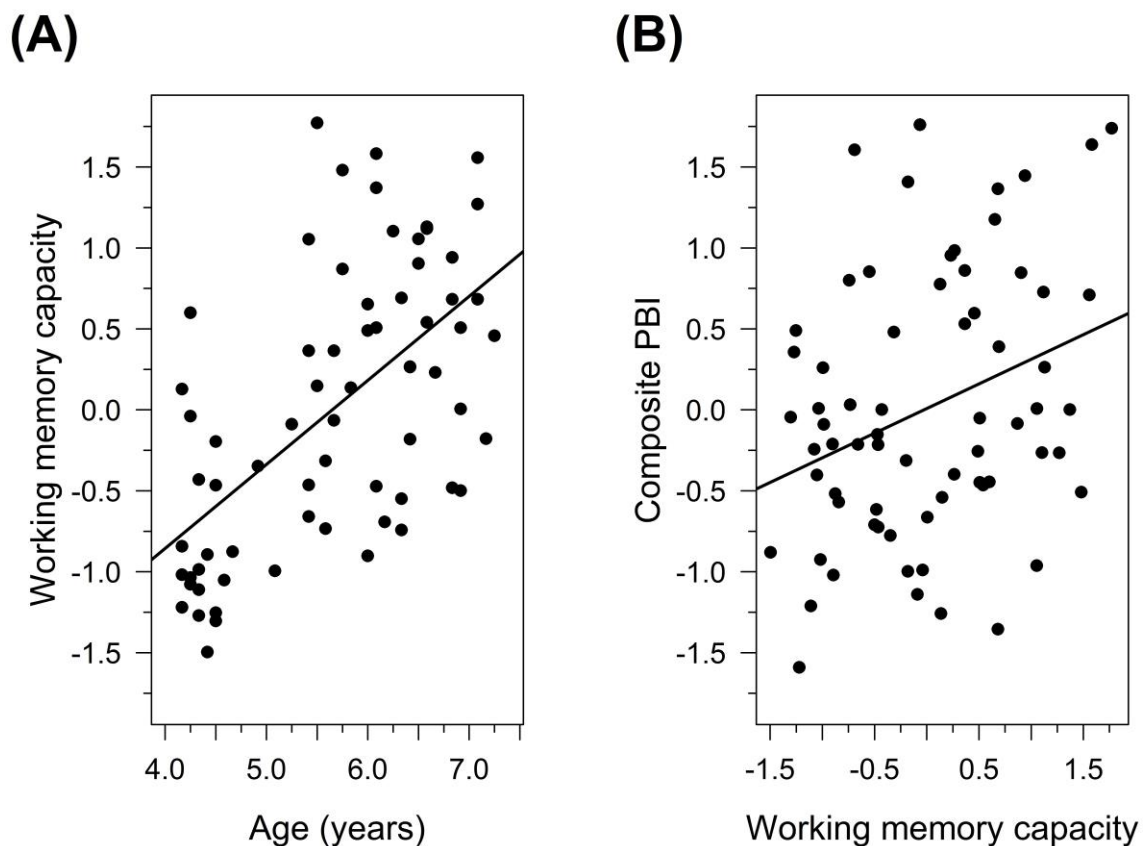


Figure 4. Relationship between age and composite working memory capacity scores (A), and between composite working memory capacity scores and composite PBI (B).

Critically, decomposing variance based on multiple regressions (i.e. a commonality analysis: Nimon & Oswald, 2013; see Chatham et al., 2009, for a similar use of this

technique) revealed that age and WMC explained largely redundant shares of variance in the use of proactive control. The results are represented in Figure 5. Whereas age and WMC alone explained respectively 10.69% and 9.93% of variance in the proactive control index, combining the two explained only 12.93% of variance, $F(2, 65) = 4.83$, $p = .011$, $R^2 = 0.13$. Shared variance between age and working memory capacity accounted for the majority of this total (59.54% of the explained variance). Neither variable retained a significant effect when partialling out the other: both the unique effect of age (3.00% explained variance, $p = .140$) and the unique effect of WMC (2.23% explained variance, $p = .201$) were non-significant. In other words, age-related increases in proactive control were accompanied by concurrent increases in WMC; there was no significant effect of age on proactive control above and beyond working memory.

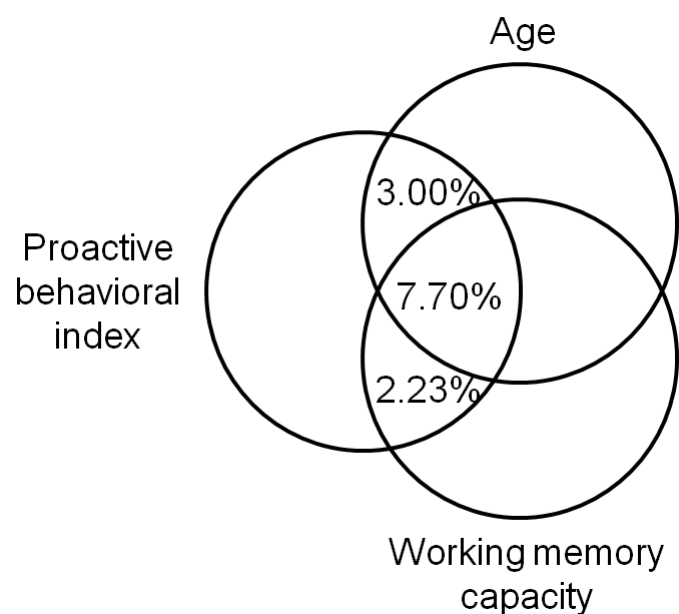


Figure 5. Percentage of variance in the proactive behavioral index explained by age and working memory capacity.

To confirm the stability of this finding, the same analyses were replicated by considering the two working memory tasks separately. The correlation between age and performance was found both for verbal WMC, $F(1, 66) = 18.20, p < .001, \eta^2_p = .22, r = .46$, and for visual WMC, $F(1, 66) = 30.17, p < .001, \eta^2_p = .31, r = .56$. The correlation with the PBI composite was also found separately for verbal WMC, $F(1, 66) = 5.76, p = .019, \eta^2_p = .08, r = .28$, and for visual WMC, $F(1, 66) = 4.70, p = .033, \eta^2_p = .07, r = .26$, confirming that the relationship between working memory and proactive control was domain-general. Lastly, shared variation between age and verbal WMC accounted for 45.20% of their total effect on the PBI composite, and shared variation between age and visual WMC accounted for 50.73% of their total effect, confirming that the age-related shift towards proactive control was accompanied by a domain-general increase in WMC encompassing both verbal and visual tasks.

Discussion

We set out to answer three major questions concerning the development of cognitive control: (1) do very young children actually rely on reactive control? (2) if so, what is the precise developmental timecourse of the shift from reactive to proactive control? (3) could this shift be driven by a concurrent increase in WMC?

Regarding the first issue, the results showed a clear age-related increase in the use of proactive control, like prior studies (e.g. Chatham et al., 2009; Lorschach & Reimer, 2008, 2010; Lucenet & Blaye, 2014). Contrary to prior studies, however, the data also revealed that the youngest children in the sample (pre-kindergartners, aged 4 to 5 years old) demonstrated a clearly reactive profile in the AX-CPT, with higher error rates on BX trials than on AY trials. In fact, this pattern of performance was very similar to the results observed in older adults (Braver et al., 2001, 2005; Paxton et al., 2006, 2008). Error rates were overall better

than chance level, confirming that children performed the task correctly. These results, based on the paradigmatic task of the dual mechanisms of control framework, are the first to empirically demonstrate the existence of the often-assumed age-related shift from reactive to proactive control. When combined with existing studies in older adults (Braver et al., 2001, 2005; Paxton et al., 2006, 2008), these data confirm that the balance between reactive and proactive control effectively shifts twice during the lifespan: very young children tend to rely on reactive control, older children and adults make progressively heavier use of the more costly proactive control, and older adults fall back to reactive control as their primary strategy.

These results raise the question of why the current pattern of reactive control in young children was never observed in prior studies, even those using the AX-CPT. The major reason is certainly age range. Our results indicated that only children younger than 5 years old demonstrated a marked preference for reactive control (see Figure 3); by contrast, almost all prior studies using the AX-CPT sampled children older than 5 years old (Lorsbach & Reimer, 2008, 2010; Lucenet & Blaye, 2014). The one exception (Chatham et al., 2009) recruited 3.5-year-old children, which may have been counter-intuitively too young, at least for the AX-CPT: these children performed close to chance level for AY and BX trials, and one third of the sample was excluded due to failure to complete the task. In other words, studies interested in the use of reactive control in children should specifically target children between the ages of 4 and 5 when using the AX-CPT.

Methodological differences may secondarily contribute to differences between studies: for example, the time allowed to respond was adjusted to the child's ability in the current study, which may have helped make the task suitable for younger children. In parallel, the modified version of the AX-CPT used by Chatham and colleagues (2009) may have encouraged children to rely on associative learning rather than cognitive control (see

Bugg, Jacoby, and Chanani, 2011, for a discussion of a similar issue): each of A, B, X and Y stimuli was represented by a single picture – cartoon characters for cues and objects for probes. While this design choice probably helped limit the complexity of the task for 3.5-year-olds, this may have led children to use neither reactive nor proactive control, instead solving the task by relying on simple associations between a character and their preferred object (see also Lucenet & Blaye, 2014). Due to the relatively low effect size of age, researchers should also be mindful of sample size: a post-hoc power analysis revealed that with the current sample size of $N = 68$, and for the observed correlation of $r = .33$ between age and the PBI, achieved power just reached the standard threshold of .80 (80% chance to detect the effect).

Our second question concerned the timecourse of the developmental shift from reactive to proactive control. Recruiting a sample of children between 4 years old and 7.5 years old allowed us to pinpoint this shift to a relatively precise time window: between 5 and 6 years old, with an average turning point around 5 and a half. This result directly confirms prior estimates for the age of the transition (e.g., Blackwell & Munakata, 2014; Chevalier, 2015; Lucenet & Blaye, 2014) – which were based on other paradigms (Chevalier, 2015), on unpublished data (Blackwell & Munakata, 2014), or on results where even the youngest children displayed a proactive profile on average (Lucenet & Blaye, 2014). With the current data coming from the main task used to assess reactive and proactive control in the literature, this time window estimate should be relatively robust. Of course, it could be the case that the shift occurs somewhat later (Chevalier et al., 2018) or even earlier (Chevalier et al., 2015) under different task conditions that encourage or discourage the use of either control mechanism.

While Figures 1 and 2 may suggest an abrupt transition in the use of proactive control between the pre-kindergarten and kindergarten, this idea does not resist a closer look at

individual differences. The impression of an abrupt shift is largely artifactual, caused by the discretization of age groups that was necessary to generate these figures: conversely, examination of Figure 3 suggests much more gradual changes, with a large proportion of children up to 7.5 years old continuing to use reactive control (as indexed by negative PBIs). In fact, this figure shows considerable variability in the use of proactive control at all ages, which was reflected in the relatively low effect size for age: at $r = .33$, the correlation between age and PBI indicates that age explained 11% of variance in cognitive control, leaving 89% of individual differences unrelated to age. Careful examination of individual data reveals a large proportion of overlap between the distributions of the PBI in the three age groups: only 14% of kindergartners and 21% of 1st grade children had PBIs strictly higher than all pre-kindergartners, and only one pre-kindergartner had a PBI strictly lower than all kindergartners and 1st grade children. On the other hand, Figure 3 also shows that children younger than 5.5 years were overwhelmingly reactive, with only four children demonstrating a PBI slightly above zero.

In sum, the picture that emerges is that of a conditional relationship: children younger than 5 and a half years tend to rely almost exclusively on reactive control, whereas older children use either reactive or proactive control. This illustration of significant inter-individual differences accompanying the developmental shift of cognitive control mechanisms is an important aspect of the current results. Such a developmental pattern can be viewed as an instantiation of Siegler's overlapping waves view of strategy development (Siegler, 1996). This conclusion also fits with the idea that older children become progressively more adept at choosing or coordinating cognitive control strategies by "tailoring control engagement to the specific demands of each task or situation" (Chevalier, 2015, p. 239).

Lastly, we found that age-related increases in proactive control occurred concurrently with age-related increases in WMC: working memory predicted the use of proactive control, most of the age-related variance in proactive control was shared with working memory, and age retained no significant effect on proactive control when partialling out WMC. These results indicate that the shift towards proactive control occurs in tandem with age-related improvements in WMC; in turn, this supports the possibility that increases in WMC are determinant for this shift, in that they make it easier for older children to perform the active maintenance of contextual information that is required to engage in proactive control. Although it does not constitute proof of a causal relationship, this conclusion is fully compatible with prior works assigning a central role to working memory in the development of cognitive control (e.g. Roberts & Pennington, 1996; see also Morra et al., 2018). Whether working memory also plays a role in the decline of proactive control in older adults remains an open question.

Beyond highlighting a possible reason for the developmental shift towards proactive control, these results are also interesting in that they offer a window into the relationship between WMC and proactive control. This relationship has often been proposed in adults (e.g. Braver et al., 2007; Redick, 2014; Redick & Engle, 2015; Richmond et al., 2015), but is actually supported by little data and has not always been replicated (see Cooper et al., 2017). Part of the reason is that all healthy adults tend to be overwhelmingly proactive to begin with; this makes it difficult to investigate individual differences (see Cooper et al., 2017; Gonthier et al., 2016). Even adult participants with very low WMC typically demonstrate a proactive profile: the role of working memory has often been hypothesized based on the fact that these participants are relatively less efficient on BX trials (see e.g. Redick, 2014; Redick & Engle, 2015; Richmond et al., 2015). Comparatively, the present results showed a straightforward significant correlation between working memory and proactive control: children with below

average WMC tended to use reactive control, and the reverse was true for children with above average WMC (see Figure 4b). These results were presumably obtained because age-related differences in both WMC and proactive control are considerably larger than individual differences in healthy adults.

Limitations and Possibilities for Future Studies

The current study leaves several questions open. First, although the reactive pattern that emerged in pre-kindergarten children was quite clear (Figure 1), it would be worthwhile to confirm the present findings with psychophysiological data – such as neuroimaging or pupillometry (like Chatham et al., 2009). This would help shed more light on the precise dynamics of active maintenance of contextual information in working memory; prior studies have investigated this question in adults (e.g. Braver et al., 2009; Paxton et al., 2008), but little is known about how this process unfolds in children. Convergent evidence could also come from other paradigms designed to collect indices of reactive and proactive control, such as proportion congruency effects in the Stroop (Gonthier, Braver, & Bugg, 2016). Second, the current study does not allow for conclusions about the directionality of the correlations between working memory, proactive control and age. Current theories of cognitive control support the interpretation that a high WMC helps older children engage in proactive control, but it could also be the case, for example, that using proactive control helps older children perform better in WMC tasks (e.g. Speer, Jacoby, & Braver, 2003). Third, although the current data make an important illustration of individual differences accompanying the developmental shift in cognitive control mechanisms, they do not allow for an examination of potentially meaningful intra-individual differences. Does the same child switch between reactive and proactive control, given enough trials? Past studies in adults have investigated this question by comparing performance in successive sub-blocks of the AX-CPT: for example, older adults can start using proactive control with enough trials (Paxton et al.,

2006). Unfortunately, collecting enough trials to obtain reliable estimates of performance in each sub-block (see Cooper et al., 2017) may prove challenging in young children.

A final question is whether younger children are unable or unwilling to engage in proactive control. In the present study, the delay between the cue and the probe in the AX-CPT was 1500ms; even very young children should be able to actively maintain the identity of a single cue in memory during such a short interval (e.g. Simmering & Perone, 2013). One possibility is that the lower WMC of younger children makes it more demanding - rather than impossible - for them to engage in proactive control, which discourages them from using this mechanism. A similar point was made by Chevalier and colleagues (2015), who found that 5-year-olds who spontaneously engage reactive control can also engage proactive control when reactive control is made more difficult. An interesting way to test this possibility would be to selectively train proactive control in young children. Several studies in adults have showed that such a training can be performed (Braver et al., 2009; Gonthier et al., 2016; Paxton et al., 2006, 2008), by instructing participants on how to mentally prepare for the most likely answer during the delay between cue and probe. Extending this type of training to children could constitute a promising line of research, shedding further light on the dynamics of cognitive control development.

Conclusion

For the first time, our results provided direct empirical evidence that children younger than 5 years old preferentially use reactive control, as assessed with the AX-CPT paradigm. Children demonstrated a progressive increase in the use of proactive control between 4 years old and 7 years old, with the turning point occurring around 5.5 years old. Age-related variance in the use of proactive control was fully explained by a concurrent increase in

working memory capacity, compatible with the idea that working memory could be critical for the development of proactive control.

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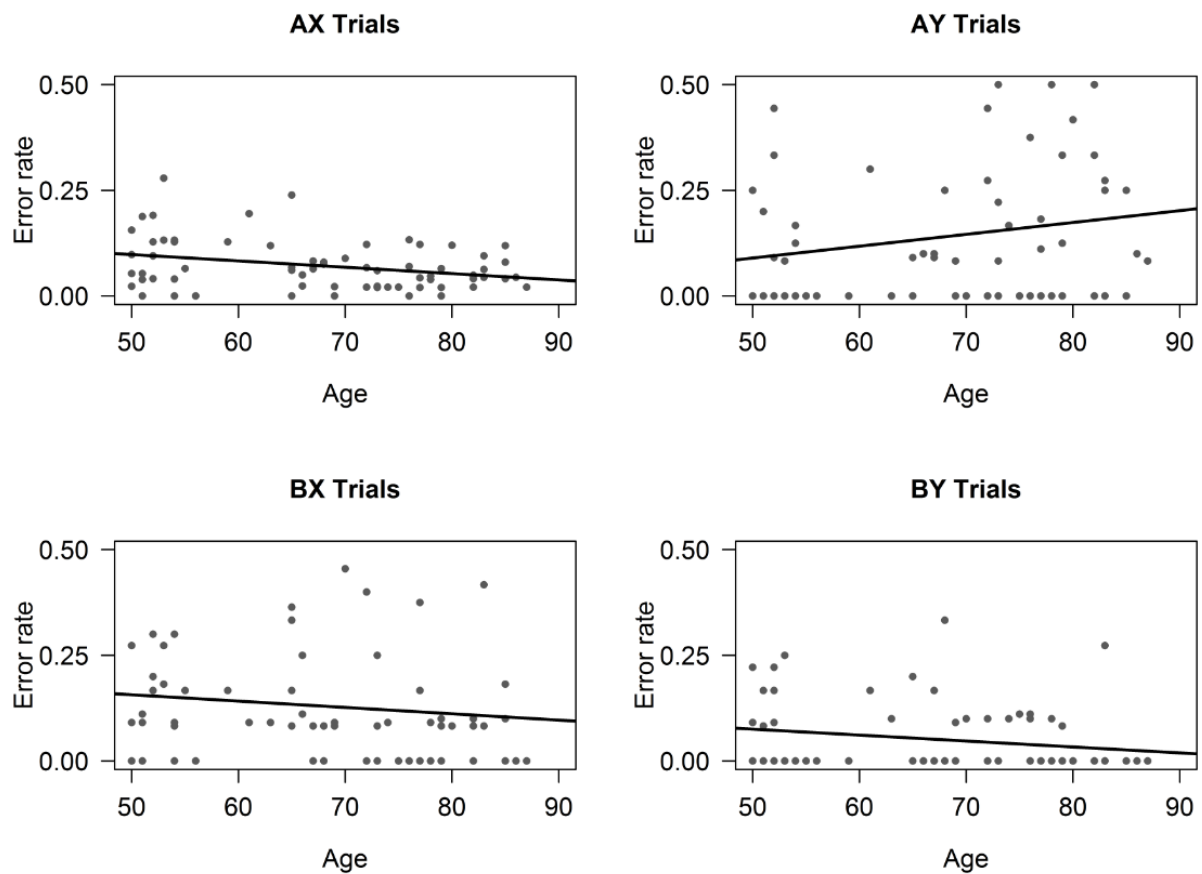
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Appendix A

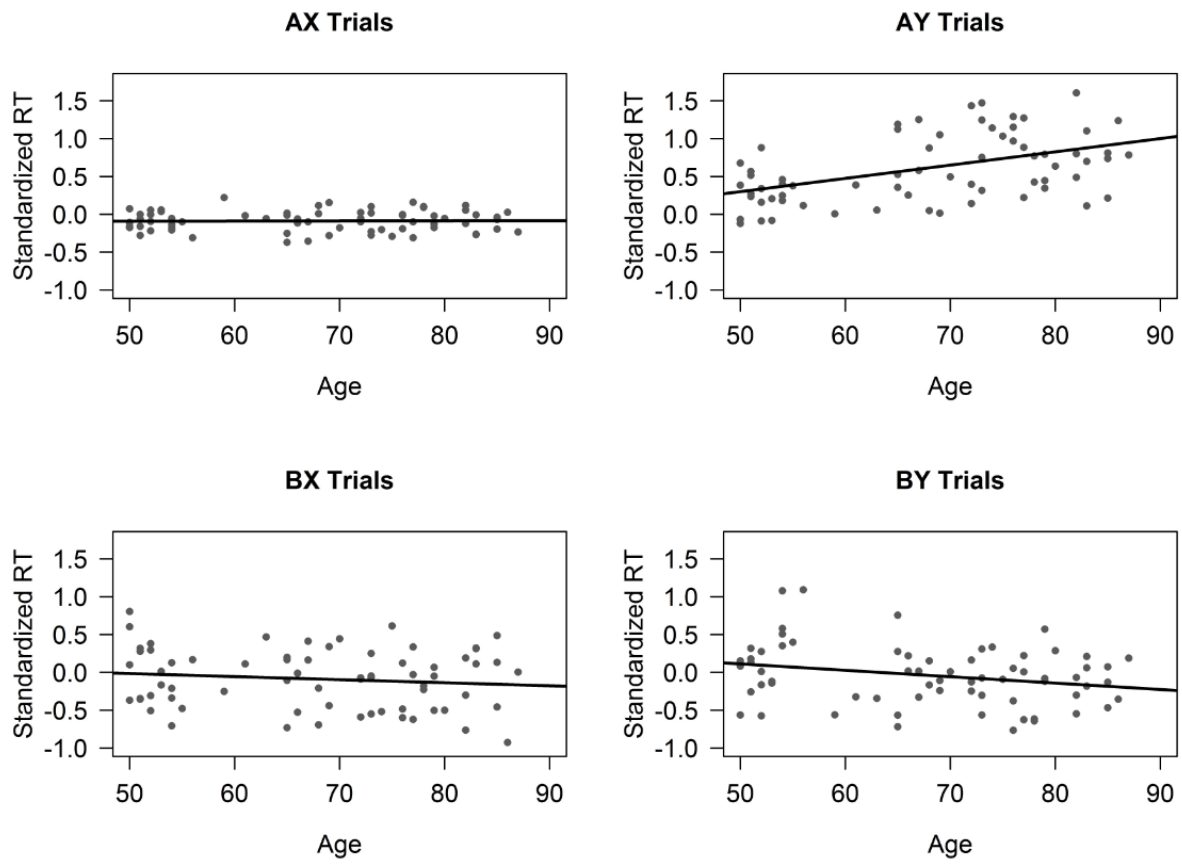
Two-way Interaction between Trial type and Age as a Continuous variable

Figure A1. Error rates as a function of age for each trial type.



Note. The black line represents the fit of a linear regression.

Figure A2. Standardized response times as a function of age for each trial type.



Note. The black line represents the fit of a linear regression.