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Nicolas Chevalier

University of Edinburgh

Agnès Blaye

Aix-Marseille Université and CNRS

Nicolas Chevalier, Department of Psychology, University of Edinburgh, UK; Agnès Blaye, Laboratoire de Psychologie Cognitive, Aix-Marseille Université and Centre National de la Recherche Scientifique (CNRS), France.

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Correspondence should be addressed to Nicolas Chevalier, Department of Psychology, 7 George Square, University of Edinburgh, Edinburgh, EH8 9JZ, UK. Email: nicolas.chevalier@ed.ac.uk.

Abstract

Emerging executive control supports greater autonomy and increasingly adaptive behavior during childhood. The present study addressed whether children's greater monitoring of how they engage control drives executive control development. Gaze position was recorded while 25 six-year-olds and 28 ten-year-olds performed a self-paced task-switching paradigm in which they could proactively prepare for the next task for as long as they wanted before completing it. Gaze trajectories and performance showed that younger children were less well prepared than older children when they triggered the target, even though they could have taken longer to fully prepare. With age, children better monitor how they engage control, highlighting the contribution of metacognitive processes to executive control development.

Keywords: executive control, metacognition, monitoring, children, cognitive development.

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As children grow older, they more effectively regulate their thoughts and actions to attain their goals. For example, they pay greater attention in the classroom, more easily resist immediate temptations, and inhibit impulses to behave in a socially inappropriate manner. Emerging executive control ensures greater autonomy and more adaptive behavior, and predicts life success (e.g., Daly, Delaney, Egan, & Baumeister, 2015; Moffitt et al., 2011). During childhood, executive control changes not only quantitatively but also, and perhaps foremost, qualitatively. In other words, children do not simply engage *more* executive control with age but also engage it *better* and *more flexibly*. The present study addressed to what extent more flexible control engagement relies on growing metacognitive monitoring of control engagement.

Evidence for increasingly flexible control engagement during childhood comes from studies on the structure of executive control as well as control strategies. Studies on structural changes have shown that the main functions of executive control (i.e., response inhibition, information maintenance and updating, and shifting between tasks) progressively differentiate with age (e.g., Lee, Bull, & Ho, 2013). This differentiation suggests that children progressively draw upon different cognitive processes to implement these functions with age. Qualitative changes are perhaps even more conspicuous when children start using new cognitive strategies (Chevalier, Huber, Wiebe, & Espy, 2013), such as verbal strategies (e.g., Fatzer & Roebers, 2012) or proactive control strategies (Munakata, Snyder, & Chatham, 2012).

In particular, executive control can be engaged either proactively, by anticipating and preparing for upcoming task demands in order to avoid interference before it arises, or reactively, in the moment, to resolve interference after it occurred

(Braver, 2012). As proactive and reactive controls present complementary advantages and disadvantages, which one is most adaptive largely depends on specific task demands. Proactive control, which relies on active maintenance of goal-related information in working memory and thus sustained activity in prefrontal cortex, generally ensures high behavioral efficiency but at the cost of greater and earlier mental effort. Further, it is effective only if upcoming task demands can be reliably predicted. Reactive control, in contrast, requires less and later effort as it relies on transient prefrontal cortex activity related to retrieval of goal-related information into working memory, but it results in generally lower behavioral efficiency when task demands could have been anticipated (e.g., Braver, Paxton, Locke, & Barch, 2009; Marklund & Persson, 2012). Despite individual preferences for reactive or proactive control, adults flexibly engage the most adaptive form of control as a function of task demands (Braver et al., 2009; Chiew & Braver, 2013; Kray, Schmitt, Heintz, & Blaye, 2015). In contrast, young children are biased to reactive control, even in situations where proactive control could be more efficient (Blackwell, Chatham, Wiseheart, & Munakata, 2014; Blackwell & Munakata, 2014; Chatham, Frank, & Munakata, 2009; Chevalier, James, Wiebe, Nelson, & Espy, 2014; Lucenet & Blaye, 2014; Voigt et al., 2014). Children seem to start engaging proactive control around 6 years of age (Chevalier et al., 2014; Lucenet & Blaye, 2014), but proactive and reactive controls are engaged with increasing flexibility through late adolescence (Andrews-Hanna et al., 2011).

Critically, young children's bias towards reactive control may not stem from an *inability* to engage proactive control (due, for instance, to limited working memory capacity), but instead from a higher threshold for engaging it or failure to determine when it is appropriate to do so (Chevalier, Martis, Curran, & Munakata, 2015).

Specifically, when required to switch between two tasks (e.g., color- and shape-matching) as a function of a task cue (e.g., a palette of colors or a palette of shapes), advance information about the next task allows adult participants to proactively prepare for the next task, which results in a performance benefice, as shown by greater performance when the task cue is presented ahead of the target (e.g., Kiesel et al., 2010; Monsell, 2003; Vandierendonck, Liefooghe, & Verbruggen, 2010). Like adults, 10-year-olds engage in proactive preparation each time it is possible (i.e., each time the cue is presented early), whereas 5-year-olds wait for target onset before reactively deciding which task is relevant. However, even 5-year-old engage proactive control when the difficulty of reactive control is increased by discontinuing cue presentation after target onset, as shown by faster response times as well as event-related potential and pupil dilation markers of proactive preparation (Chevalier et al., 2015).

In light of these findings, it may be argued that qualitative changes in executive control do not exclusively reflect a wider repertoire of control strategies, but also increasingly flexible coordination of that repertoire (Chevalier, in press). Coordination of control engagement, which has been hypothesized to rely on dorsal anterior cingulate cortex (dACC) activity (Shenhav, Botvinick, & Cohen, 2013), may reflect decisions of the cognitive system about (a) which task goal is worth pursuing, (b) how much control to engage to reach it, and (c) how to engage control, i.e., which control strategy to use. Such coordination is distinct from actual control engagement (which relies on lateral prefrontal cortex) and may critically depend on the use of prior experiences to predict which control strategy (e.g., reactive or proactive) is most appropriate (i.e., most likely to succeed) for the current task demands (Chen & Siegler, 2000; Lemaire & Brun, 2014; Shenhav et al., 2013). In turn, to accumulate information about strategy efficiency (i.e., cost and benefit), one must be able to track which strategy is being used and how well is it engaged. This is key not just to optimize current control engagement (and performance) but also to compile and later use this information to predict how to best engage control in future.

Little is known, however, about how children monitor control engagement. For instance, it is unknown whether children are aware of how well they are proactively preparing for an upcoming task and when this preparation process is completed. Yet, there are reasons to suspect that control engagement monitoring may improve with age, likely resulting in more optimal control engagement. Children seem to increasingly monitor their errors with age (DuPuis et al., 2014; Santesso, Segalowitz, & Schmidt, 2006) and, as previously mentioned, young children over-rely on reactive control despite being able to engage proactive control (Chevalier et al., 2015). Indeed, executive control gains and metacognitive improvement are closely related (Roderer & Roebers, 2014; Roebers, Krebs, & Roderer, 2014) and executive control development has been hypothesized to result from increasing conscious reflection on one's own cognitive functioning, which in turn yields greater ability to match available cognitive means to task demands (Zelazo, 2004).

The present study investigates whether children monitor how well they are proactively preparing for an upcoming task and strategically decide when to perform that task. Participants were 6- and 10-year-olds. At 6 years of age, children start showing evidence of spontaneous use of proactive control and may therefore not be as good at monitoring it as 10-year-olds, who are confirmed proactive control users. Children completed two conditions of a cued task-switching paradigm in which the task cue was presented ahead of the target, hence providing the opportunity to proactively prepare for the next target. Critically, proactive preparation was self-paced, that is, children decided without time pressure to trigger the target when they felt ready to respond to it, hence allowing us to examine whether or not they triggered the target *after completing* proactive preparation. Moreover, in one condition (Cue-Stays), the task cue remained visible after target onset, whereas it was removed after target onset in the other condition (Cue-Disappears). This manipulation aimed at comparing proactive preparation in contexts where such preparation was more (Cue-Disappears) or less (Cue-Stays) critical for successful performance (Chevalier et al., 2015). Finally, eye gaze trajectories were recorded to determine the quality of proactive preparation.

If children monitor effectively proactive control engagement, they should trigger the target when task preparation is complete (and they are ready for the upcoming task), as evidenced by relatively long preparation times, high accuracy and fast response times, as well as strategic eye gaze trajectories. In particular, they should first look at the task cue and then, after completion of proactive preparation, strategically move to the area where the target will appear right before triggering it in order to be ready to process it immediately on its onset, and should gaze at the target and not return to the cue afterwards. In contrast, if children inefficiently monitor proactive control engagement, they should often trigger the target before preparation is complete, resulting in faster and more variable preparation times, lower accuracy, longer response times, and less strategic eye gaze trajectories. These children should, for instance, trigger the target while still looking at the cue, and continue fixating it or return to it after target onset. If control engagement monitoring increased with age, the latter pattern would be more frequent in younger children and the former pattern more frequent in older children. Finally, as proactive preparation is even more critical when the cue disappears after target onset, the Cue-Disappears condition may provide an even stronger incentive to engage in and to monitor proactive preparation than the Cue-Stays condition, especially in younger children who are more sensitive than older children to incentive to engage control proactively.

Method

Participants

Study participants included 25 six-year-old children (mean age = 6.4 years, *SD* = 0.3 year, range = 6;0-6;11, 11 girls) and 28 ten-year-old children (mean age = 10.5 years, *SD* = 0.3 year, range = 9;11-11;0, 17 girls). Children were recruited in two elementary schools in the metropolitan area of Marseille, France. Most children were Caucasian and from middle socioeconomic status backgrounds, reflecting the demographics of the geographical area, although individual demographic information was not collected. Prior to participation, parental informed consent was obtained for all children who also gave verbal assent to participate.

Materials and Procedure

Each child was tested individually in a quiet room of their school by the same trained experimenter in a 30-min. session. Children sat 60 cm away from the monitor where the stimuli were presented and entered responses on a keyboard. After eye-tracking calibration, each child completed two conditions of a child-appropriate, cued task-switching paradigm (adapted from the advanced dimensional change card sort test; Zelazo, 2006, and similar paradigms in adults; Meiran, 1996), run with E-Prime 1.2 (Psychology Software Tools, Pittsburgh, PA). In both conditions, children had to match centrally presented, bidimensional targets (blue dog, orange dog, blue car, or orange car) with one of the response pictures (orange dog or blue car) located at the bottom right and bottom left of the monitor, by pressing the corresponding key on the keyboard (“d” or “k”) (Figure 1). Children were asked to constantly keep their left and right forefingers on the keys (as well as their thumbs on the space bar). They had to match the target with the response picture of the same shape on some trials and of the same color on others. The relevant task (color- or shape-matching) changed unpredictably and was signaled on each trial by a visual task cue (a palette of four colors or a palette of four toys) presented on the upper part of the monitor. Each target corresponded to a specific combination of a blue or orange car or dog (three different shades and exemplars of each). Response pictures, which remained constantly visible at the bottom of the screen, corresponded to a different exemplar and shade of a blue car and a different exemplar and shade of an orange dog.

Each trial started with a fixation cross in the area where the cue would subsequently be presented. After the child fixated anywhere on the screen for 500 ms, the task cue replaced the fixation cross. At that stage, the target area was still empty. Importantly, target onset was self-paced, that is, children decided when to trigger the target by pressing the space bar with their thumb. Children were told that they could take as long as they wanted before triggering the target, but once the target was on, they had to go as fast as possible, which was further stressed by the sound of a ticking clock starting on target onset. They were also explicitly told that they should trigger the target when they knew what game (color or shape) they had to play next. These instructions aimed to highlight the importance of proactive task preparation. The importance of fast and accurate responding (and thus of proactive preparation) was also highlighted through feedback, which was presented after each target response for 500 ms. Specifically, a smiley face was presented at the center of the screen if the response was accurate and fast (i.e., below 1.5 × the child's mean response time), a clock if the response was accurate but slow (i.e., above 1.5 × the child's mean response time), or a frowning face if the response was incorrect.

Each child completed two conditions (order counterbalanced across participants). The two conditions only differed in whether or not the task cue was still visible after target onset. In the Cue-Disappears condition, a non-informative picture (gray square with four crosses) replaced the cue after target onset. In the Cue-Stays condition, the cue remained visible after target onset but the specific arrangement of colors or shapes was rotated so that a perceptual change occurred at the level of the cue in both conditions. Each condition started with four demonstration trials of one task (e.g., shape-matching), followed by four demonstration trials of the other task (e.g., color-matching), and six demonstration trials in which the two tasks were mixed. The experimenter provided guidance on demonstration trials, which could be repeated if needed, but not on the following practice and test trials. Children then completed 10 practice trials with a 10-sec. time limit for correct feedback. These trials were used to compute the time limit subsequently used, which was tailored to each child's performance to ensure that the limit was equally challenging to all participants. Children completed five additional practice trials, this time with the same time limit as on test trials (1.5 × their mean response time for the "smiley" feedback). Finally, in each condition, they completed two blocks of 31 test trials each (i.e., 62 test trials per condition). Test trials comprised 40 no-switch trials (on which the same task repeated), 20 switch trials (on which the relevant task changed), and two start trials (i.e., the first trial of each block) in each condition. This proportion of switch trial was chosen to maximize the difficulty of task switching. The relevant task changed unpredictably. 75% of the test trials were incongruent (i.e., the target color and shape matched different response pictures) while the remaining 25% were congruent (i.e., the target color and shape matched the same response picture). Children were invited to take short breaks in between blocks.

Data Processing and Analysis

Performance was indexed through mean *accuracy* (varying from 0 to 1), *preparation times* (interval between cue onset and self-paced target onset), and *response times* (interval between target onset and the response). Preparation and response times were analyzed for correct responses only. Outliers below 200 ms or above *M* + 3*SD* were discarded (2.4% of trials). Preparation and response times were log-transformed to minimize the effects of skewness and age-related baseline differences (Meiran, 1996), but we report raw values for the sake of clarity. Eye gaze position was collected with a Tobii T120 Eye Tracker and Tobii Studio (Tobii Technology AB, Danderyd, Sweden) using a 120 Hz data-sampling rate and an automatic 5-point calibration procedure performed before administrating the tasks. Fixations were categorized as a function of where they landed on the screen. The four areas of interest (AOIs) were delineated by the square outlines around the target and the response pictures, as well as a non-visible square with borders 0.5 cm away from each side of the cue. Fixations with durations lower than 40 ms were excluded. Eye gaze trajectories were identified by collating successive fixations during the cue-target and, separately, during target-response intervals. Complete and incomplete preparation should correspond to gaze trajectories where the cue and target are fixated in different order: cue then target during the cue-target interval and only the target afterwards in the case of complete proactive preparation; and only the cue area during the cue-target interval and the cue and target areas during the target-response interval in the case of incomplete preparation. As these hypotheses focused on the cue and the target AOIs, and the response pictures were infrequently fixated (<10%), only fixations landing on the cue and target were included in gaze trajectories.

Results

Preparation Times, Response Times, and Accuracy

Descriptive statistics are provided in Figure 2. The 2 (Age: 6, 10) × 2 (Condition: Cue-Stays, Cue-Disappears) × 2 (Trial Type: No-Switch, Switch) mixed ANOVA on preparation times (i.e., time taken to trigger the target after cue onset) revealed no significant effects, all *p*s > .235. Surprisingly, younger and older age groups showed similar preparation times (M = 1,664 ms and M = 1,642 ms, respectively) that did not vary between switch and no-switch trials (M = 1,687 ms and M = 1,620 ms, respectively) or between conditions ($M_{\text{Cue-Stays}}$ = 1,620 ms and $M_{\text{Cue-Disappears}}$ = 1,687 ms).

Accuracy and response times (RTs) were analyzed with mixed models using age (6, 10), condition (Cue-Stays, Cue-Disappears) and trial type (No-Switch, Switch) as categorical predictors, and preparation times as a continuous predictor. As expected, 10-year-olds responded more accurately and faster (M = .87, M = 591 ms) than 6-year-olds (M = .77, M = 1,210 ms), $F(1, 54) = 21.49$, $p < .001$, $\eta^2 = .18$ and $F(1, 54) = 84.47$, $p < .001$, $\eta^2 = .86$, respectively. Responses were also more accurate and faster on no-switch trials (M = .85, M = 880 ms) than switch trials (M = .78, M = 921 ms), $F(1, 148) = 65.37$, $p < .001$, $\eta^2 = .56$ and $F(1, 148) = 5.57$, $p = .019$, $\eta^2 = .06$, respectively, hence showing significant switch costs. Most importantly, longer preparation times were associated with greater accuracy (estimated coefficient = .068) and faster response times (estimated coefficient = -.15), $F(1, 148) = 12.71$, $p < .001$, $\eta^2 = .11$ and $F(1, 148) = 4.87$, $p = .028$, $\eta^2 = .05$, respectively. This finding points out the benefit of longer preparation. None of the other effects reached significance, all *p*s > .087.

Because of age-related differences in motor speed, similar preparation efficiency should have yielded longer preparation times at age 6 than age 10. Yet, preparation times did not differ between age groups, which suggests, along with greater accuracy and faster response times in older than younger children, that similar preparation times reflected more efficient preparation in older than younger children. To further investigate preparation efficiency, we examined gaze trajectories.

Gaze trajectories

Cue-target interval. Gaze trajectories were first probed during the cue-target interval (CTI) to examine qualitative differences in preparation. They fell into six main categories (Table 1). Trajectories where children fixated only the cue (Cue-Only) and where they started with the cue and then moved to the empty target area (Cue-then-Target) were by far the most frequent. The other trajectories consisted in fixating only the target area (Target-Only), the target area and then the cue (Target-then-Cue) or fixating both areas back and forth ending either on the cue (Back-and-Forth-Cue) or the target (Back-and-Forth-Target) and accounted for less than 12% of the trials each. Therefore, they were not further analyzed.

The proportions of Cue-Only and Cue-then-Target trajectories were analyzed with a 2 (Age: 6, 10) × 2 (Condition: Cue-Stays, Cue-Disappears) × 2 (Trial Type: No-Switch, Switch) × 2 (Trajectory: Cue-Only, Cue-then-Target) ANOVA. It revealed a significant main effect of age, $F(1, 51) = 8.25$, $p = .006$, $\eta^2_p = .14$, due to the increasing average proportion of these two strategies from 6 to 10 years of age (from 35.7% to 41.4%). This finding also shows indirectly that the other strategies decreased with age. There were also significant interactions between age and trajectory, $F(1, 51) = 11.65$, $p = .001$, $\eta^2_p = .19$, and between condition and trajectory, $F(1, 51) = 6.20$, $p = .016$, $\eta^2_p = .11$. Specifically, younger children showed more Cue-Only ($M = 45.6\%$) than Cue-then-Target trajectories ($M = 25.8\%$), $p = .031$, whereas the reverse was true of older children ($M = 31.3\%$ and $M = 51.5\%$, respectively), $p =$

.017. Cue-Only trajectories were more frequent in the Cue-Disappears condition (*M* = 41%) than the Cue-Stays condition (*M* = 36%), *p* = .026, whereas Cue-then-Target trajectories were less frequent in the Cue-Disappears (*M* = 36%) than the Cue-Stays condition (*M* = 41%), *p* = .035.

In brief, trajectories that suggest complete proactive preparation before target onset (i.e., Cue-then-Target) increased with age, whereas trajectories suggesting incomplete preparation (i.e., Cue-Only) decreased with age. Thus, older children seemed to be better at triggering the target once they were fully prepared.

Response-target interval. If, as hypothesized, the trajectories during the cue-target interval (CTI) reflect differences in proactive preparation, they should be associated with different trajectories during the target-response interval (TRI). TRI gaze trajectories were classified in six main categories: trajectories that included only the target (Target-Only), the cue followed by the target (Cue-then-Target), the target followed by the cue (Target-then-Cue), only the cue (Cue-Only), the target followed by back-and-forth fixations between the cue and target (Target-Back-and-Forth), or the cue followed by back-and-forth fixations between the two areas (Cue-Back-and-Forth). We examined to what extent Cue-Only and Cue-then-Target trajectories during the CTI were differentially associated with TRI trajectories (Figure 3) using a 2 (Age: 6, 10 years) × 2 (CTI Trajectory: Cue-Only, Cue-then-Target) × 6 (TRI Trajectory: Target-Only, Cue-then-Target, Cue-Only, Target-then-Cue, Cue-Back-and-Forth, Target-Back-and-Forth) ANOVA with proportions of trials as dependent variable.

The ANOVA yielded a significant Age × CTI Trajectory × TRI Trajectory interaction, $F(5, 255) = 5.44$, $p = .002$, $\eta^2_p = .10$. Follow-up analyses showed that the vast majority of Cue-then-Target trajectories during the CTI were followed by Target-

Only trajectories, as shown by significant pairwise differences with other TRI trajectories at both ages (all *p*s < .001). This pattern was even more pronounced for 10-year-olds (91.3%) than 6-year-olds (75.8%), $p = .001$. Target-Only TRI trajectories were less frequent after Cue-Only CTI trajectories than after Cue-then-Target CTI trajectories both in 6 year-olds (30% vs. 75.8%) and in 10-year-olds (54.2% vs. 91.3%), *p*s < .001. Conversely, Cue-then-Target TRI trajectories were more frequent after Cue-Only than after Cue-then-Target CTI trajectories in both 6-year-olds (45.8% vs. 7.7%) and 10-year-olds (23.8% vs. 0.1%), *p*s < .001. In younger children, Cue-then-Target TRI trajectories were even more frequent than Target-Only TRI trajectories when 6-year-olds gazed only at the cue during the CTI, $p < .001$.

In brief, at both ages, fixating the cue then the target area before triggering the target (Cue-then-Target CTI trajectory) was mostly associated with "direct" trajectories after target onset (i.e., Target-Only TRI trajectories). In contrast, when children only gazed at the cue during the cue-target interval, they more often needed to continue gazing at it before moving to the target after its onset.

Relations between CTI trajectories and performance. We then analyzed how the trajectories during the cue-target interval related to performance with a series of 2 (Age: 6, 10) × 2 (Trajectory: Cue-Only, Cue-then-Target) ANOVAs on accuracy, response times, and preparation times (Figure 4). As some younger children did not use both types of trajectory on both trial types of each condition, we elected not to include trial types and condition to maximize sample size (i.e., include all participants) and statistical power. (When trial type and condition were also entered in the ANOVAs, only 25 ten-year-olds and 15 six-year-olds qualified for the analyses, which showed the same effects of trajectory and no interaction of trajectory with condition or trial type.)

Trajectory significantly affected accuracy and response times, $F(1, 51) = 8.48$, $p = .005$, $\eta^2_p = .14$ and $F(1, 51) = 42.93$, $p < .001$, $\eta^2_p = .46$, respectively. Responses were both more accurate and faster for Cue-then-Target ($M = .85$ and $M = 846$ ms) than Cue-Only trajectories ($M = .81$ and $M = 997$ ms), *p*s > .006. For preparation times, the main effect of trajectory was also significant, $F(1, 51) = 15.06$, $p < .001$, $\eta^2_p = .23$, interacted with age, $F(1, 51) = 4.14$, $p = .047$, $\eta^2_p = .08$. Preparation times were longer for Cue-then-Target than Cue-Only trajectories in younger children ($M = 1{,}651$ ms and $M = 1{,}542$ ms, respectively), $p = .004$, whereas the difference fell short of significance for older children ($M = 1{,}598$ ms and $M = 1{,}575$ ms, respectively), $p = .064$.

In brief, at both ages, Cue-then-Target CTI trajectories were associated with longer preparation times, as well as better performance (i.e., greater accuracy and shorter response times) than Cue-Only trajectories, which further suggests that Cue-then-Target trajectories reflect more complete proactive preparation before target onset.

Returns to the cue. One open question is whether younger children followed the same overall cue-then-target trajectories as older children, but unstrategically triggered the target before moving to the target. If so, they should not need to fixate back at the cue any more than do older children. In contrast, if younger children do not follow that pattern, they may need to return to the cue more often. To answer this question, we analyzed the proportions of trials where children returned to the cue after fixating the target, taking into account the entire trial (without distinguishing between the cue-target and target-response intervals) (Table 1). The 2 (Age: 6, 10) × 2 (Condition: Cue-Stays, Cue-Disappears) × 2 (Trial Type: No-Switch, Switch) ANOVA showed significant effects of age, $F(1, 51) = 15.58$, $p < .001$, $\eta^2_p = .23$, condition, $F(1, 51) = 7.41$, $p = .009$, $\eta^2_p = .13$, and a significant interaction between trial type and age, $F(1, 51) = 4.88$, $p = .032$, $\eta^2_p = .09$. Younger children returned to the cue more frequently than older children (29% vs. 13%), and overall children returned to the cue slightly more frequently in the Cue-Stays than Cue-Disappears conditions (24% vs. 19%). Finally, older children surprisingly returned to the cue slightly more frequently on no-switch than switch trial (15% vs. 12%, $p = .017$), whereas there was no such difference for younger children, $p = .338$.

Therefore, younger children did not simply unstrategically kept looking at the cue despite completing preparation before target onset, but often needed to process the cue again before responding.

Discussion

To examine children's monitoring of control engagement, 6- and 10-year-olds completed two cued task-switching paradigms in which the cue was presented early, giving them the opportunity to proactively prepare for next target. Critically, target onset was self-paced so that children could trigger it when they felt ready to process it. Similar preparation times (i.e., time taken before triggering the target) across age groups resulted in faster and more accurate responding in older than younger children, suggesting that younger children did not prepare as efficiently as older children. Gaze trajectories suggest that younger children often triggered the target while they were not fully prepared, and thus continued to process the cue after target onset.

Although preparation times did not vary between age groups, they significantly predicted performance, hence confirming that children benefits from advance preparation in the task-switching paradigm (e.g., Cepeda, Kramer, & Gonzalez de Sather, 2001). Efficient preparation was associated not only with longer preparation times but also with gaze trajectories during the cue-target interval consisting in fixating the cue first, likely to determine the relevant task, and strategically moving to the target area before triggering the target so that children could immediately process it after its onset, without having to return to the cue. These trajectories yielded both faster and more accurate responses as well as short, target-only gaze trajectories during the target-response interval.

These optimal trajectories were observed on almost one third of trials in younger children and about half of the trials in older children, which is consistent with prior findings suggesting that 6-year-olds are already capable of proactive control and that this control form becomes more efficient during childhood (Chevalier et al., 2014, 2015). This development seems to result at least partially from more *systematic* and efficient engagement of proactive control engagement with age. Interestingly, gaze trajectories during the cue-target interval varied across trials within participants of each age group, which is consistent with claims that different cognitive strategies coexist at any time point in development (Chen & Siegler, 2000) and that participants may engage proactive preparation only on a subset of trials (de Jong et al., 2000).

Critically, similar preparation times were associated with much lower performance as well as with a lower frequency of mature gaze trajectories in younger than older children. These findings suggest that younger children often triggered the target *before* they were fully prepared to process it efficiently. Consequently, they needed to continue processing the cue after target onset. Similarly, in a prior study, 5- and 6-year-olds were found to gaze at the cue much longer after than before target onset, unlike adults who fixated the cue mostly during the cue-target interval and rarely returned to it afterwards (Chevalier, Blaye, Dufau, & Lucenet, 2010). Arguably the short cue-target interval in that study, which was fixed to 500 ms, may have been too short for children to complete proactive preparation before target onset. However, this argument cannot apply to the present findings since the cue-target interval was self-paced with no time pressure to rush through preparation, and yet children often decided to trigger the target before being fully prepared. Similarly, it cannot be argued that younger children were less able to proactively prepare than older children, and therefore, knowing they could not prepare any better, adaptively triggered the target early. Such an account does not hold because even younger children showed optimal preparation on a subset of trials (about 25% on average) and indeed performed better on these trials than on the others.

Instead, the findings converge to the conclusion that younger children did not monitor proactive control engagement as effectively as older children. As they grow older, children may gain better access to and increasingly reflect on their own executive functioning, allowing them to exert increasingly efficient control (Zelazo, 2004). Following this “increasing reflection” hypothesis, younger children’s representation of proactive control engagement and resulting state of task readiness (i.e., how far they were in the preparation process) may have been less accurate and thus may have provided weaker ground for target onset decisions than in older children (i.e., inefficient access and reflection on executive functioning). Another possibility is that children were aware of how well prepared they were (i.e., efficient access and reflection on their executive functioning) but failed to use this information strategically to guide target onset decisions (“increasingly strategic decision” hypothesis). Research on metacognitive development has shown that metacognitive knowledge (i.e., knowledge of cognitive functioning) can be distinguished from its use to optimize actions. For instance, 5-year-olds children can already correctly differentiate easy and difficult items in a character-learning task, yet, unlike older children, they do not strategically allocate more study time to difficult than easy items to optimize recall performance (Destan, Hembacher, Ghetti, & Roebers, 2014). In addition, children with lower metacognitive abilities tend to be overly confident in their own capacities, overestimating how well they will perform (e.g., Flavell, Speer, Green, & August, 1981). A similar phenomenon may have led younger children to overestimate how ready they were or how well they would perform with incomplete preparation. Both the "increasing reflection" and "increasingly strategic decision" hypotheses are plausible accounts for the present findings and should be tested in future studies, for instance, by asking children to rate their level of preparation on each trial.

A minimal alternative interpretation of the present findings is that younger children may have triggered the target when they were indeed fully prepared, but they simply did not strategically moved their eyes to the empty target area in order to spare time after triggering it (hence the greater proportion of Cue-Only trajectories during the cue-target interval). As a consequence, they would have necessarily needed to move from the cue to the target during the target-response interval (even though they were already done with cue processing), resulting in longer response times. However, three findings speak against this interpretation. First, unlike greater response times, lower accuracy when children only gazed at the cue before target onset cannot be satisfactorily explained if children were fully prepared on these trials. Second, given increasing motor and processing speeds with age, one would expect similarly mature preparation to take longer for younger than older children, unlike the similar preparation times observed here. Third, younger children did not always merely continue gazing at the cue right after target onset before fixating on the target, they also more frequently needed to gaze back at the cue after processing the target, suggesting that they often inefficiently prepared before gazing at the target.

The distinction between suboptimal awareness of current control engagement and suboptimal use of this information to adjust control has implications for how participants assess performance success and use this information to adjust control and to later predict success for similar task demands. Suboptimal use of control information would suggest that younger children are able to successfully build a knowledge base about how to best engage control, but what develops with age—and what interventions should target—is the ability to actually adjust control based on this information. In contrast, suboptimal awareness of current control engagement may hamper children's ability to associate performance success with specifically how control was engaged. What would develop with age is the ability to build a strong "knowledge base" that can be used to adjust control and predict how to engage control most efficiently. For example, because children misrepresent how they implemented proactive control, they may wrongly believe that proactive preparation is not particularly efficient and perhaps even less efficient than reactively deciding how to process the target.

The present findings revealed that executive control development is driven partly by increasing monitoring of control engagement. Although it improves with age, monitoring of control engagement is probably not an all-or-none phenomenon. In adults, the congruency sequential effect (Gratton, Coles, & Donchin, 1992), that is, the reduction of congruency effect in conflict tasks (like the Stroop task) after an incongruent trial, is often interpreted as adjustment of control engagement (see the conflict-monitoring theory framework; Botvinick, Braver, Barch, Carter, & Cohen, 2001). Specifically, experiencing response conflict on an incongruent trial increases control engagement on the subsequent trial so that the system can better monitor conflict on that trial. Although the congruency sequential effect has rarely been examined in children, it can be observed, in certain conditions, as early as 5 years of age (Ambrosi, Lemaire & Blaye, submitted), suggesting either that metacognitive monitoring of control engagement is sufficient at that age for children to adjust control in response to conflict or control adjustment may not always be tied to metacognitive monitoring of control engagement.

Finally, contrary to our expectations, we observed whether the cue remained visible after target onset (Cue-Stays condition) or not (Cue-Disappears condition) yielded few differences, except for minimal variations in the frequencies of Cue-Only and Cue-then-Target trajectories during the cue-target interval. Whether or not the task cue remained visible after target onset had little influence on preparation. These findings contrast with prior evidence showing that removing the cue after target onset successfully encourages 5-year-olds to proactive preparation before target onset (Chevalier et al., 2015). These mixed findings may result from the difference in children's ages between that study and the present one. As previously mentioned, children start engaging proactive control spontaneously around 6 years of age (Lucenet & Blaye, 2014); thus 6-year-olds in the present study already engaged in proactive preparation even when the cue remains visible after target onset. Perhaps more surprisingly, children were found to return to the cue area after target onset even if the cue had disappeared and that area was now empty. Gazing at empty areas where relevant information used to be presented has previously been reported in adults in working memory tasks and may reflect attempts to retrieve or refresh the memory trace of this information in working memory (Mall, Morey, Wolff, & Lehnert, 2014; Morey, Cong, Zheng, Price, & Morey, 2015), which further indicates more reactive control in the younger group.

In conclusion, the present study showed that children monitor more efficiently proactive control engagement between 6 and 10 years of age, resulting in better performance in the cued task-switching paradigm. These findings highlight the previously largely understudied contribution of metacognitive monitoring of executive control engagement to executive control development during childhood. They converge with prior findings showing that this development is multi-faceted. Alongside increases in goal identification (Chevalier & Blaye, 2009), in the quantity of executive resources and control strategies that can be implemented for goal attainment (e.g., Chatham et al., 2009), growing metacognitive monitoring of control engagement is yet another critical aspect that must be considered to fully understand the developmental dynamic of executive control.

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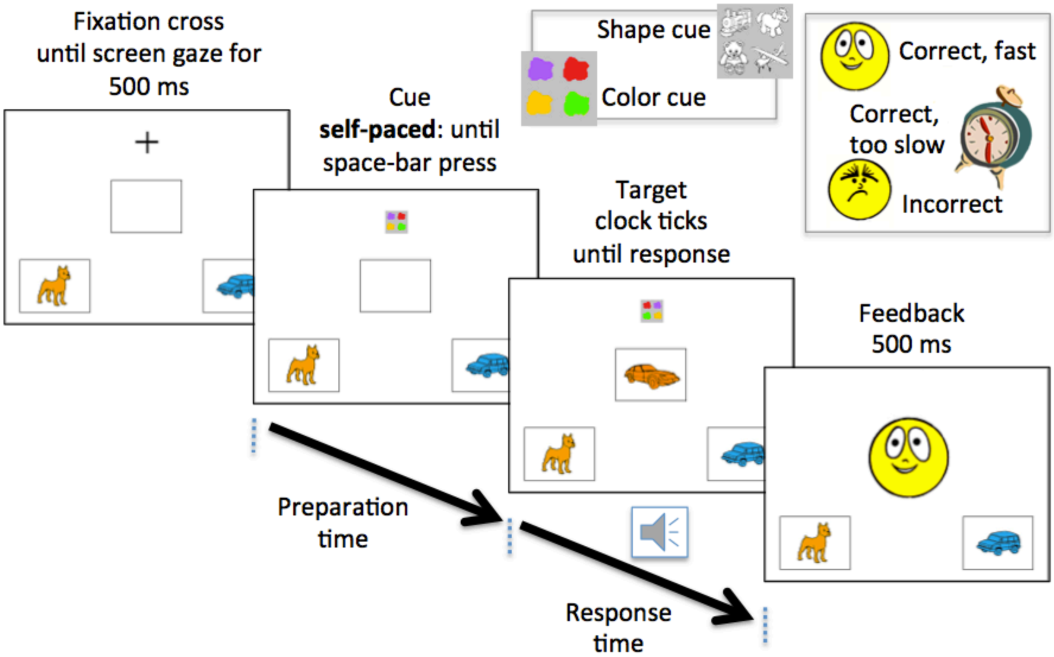

Figure 1. Illustration of the cued task-switching paradigm. On each trial, children had to sort the target (center) with the response picture of the same color or shape (bottom) as a function of a task cue (top). Critically, early cue presentation allowed children to proactively prepare for the next target. They decided when to trigger the target by pressing the space bar. The cue remained visible after target onset in the Cue-Stays condition (illustrated here) but not in the Cue-Disappears condition.

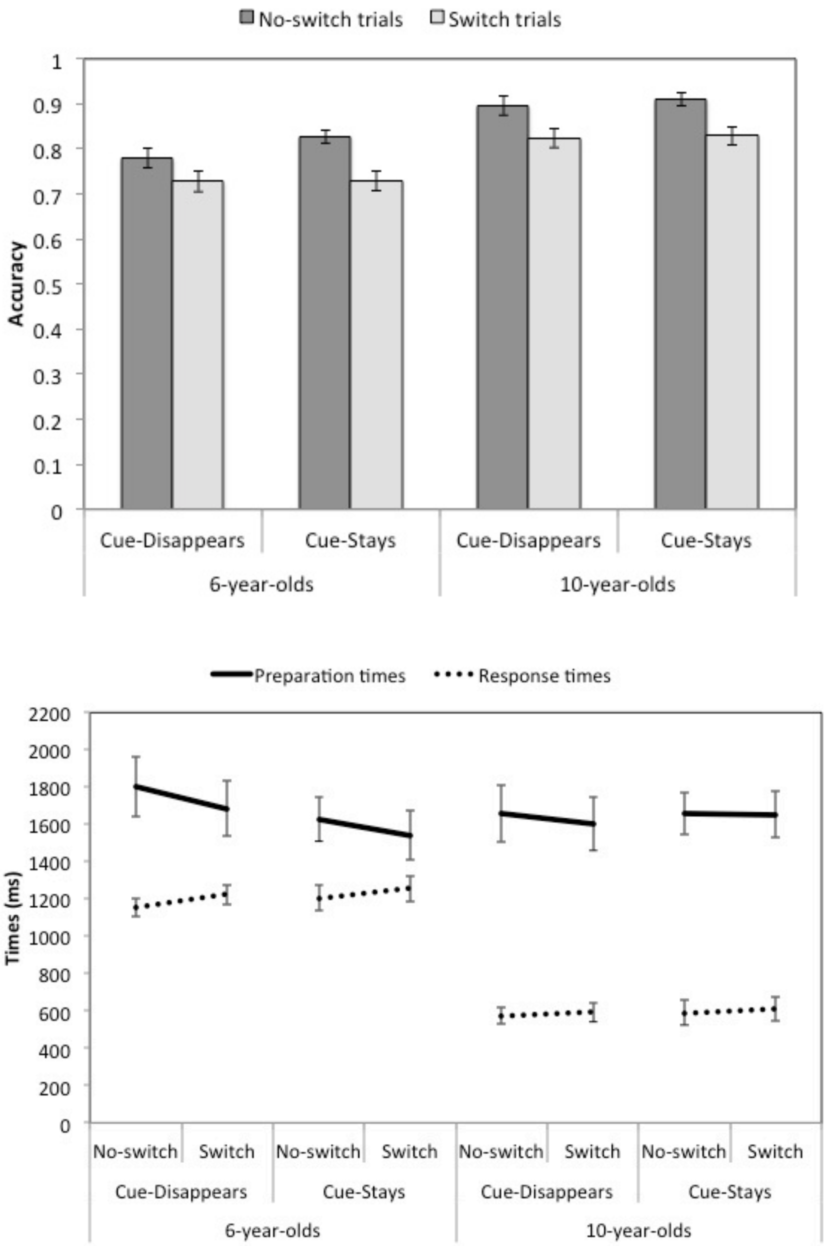

Figure 2. Accuracy (top panel), preparation times and response times (bottom panel) for each trial type, condition, and age group. Error bars show standard errors. Responses were slower and less accurate on switch than no-switch trials, showing significant switch costs. Similar response times between age groups were associated with better performance in older than younger children.

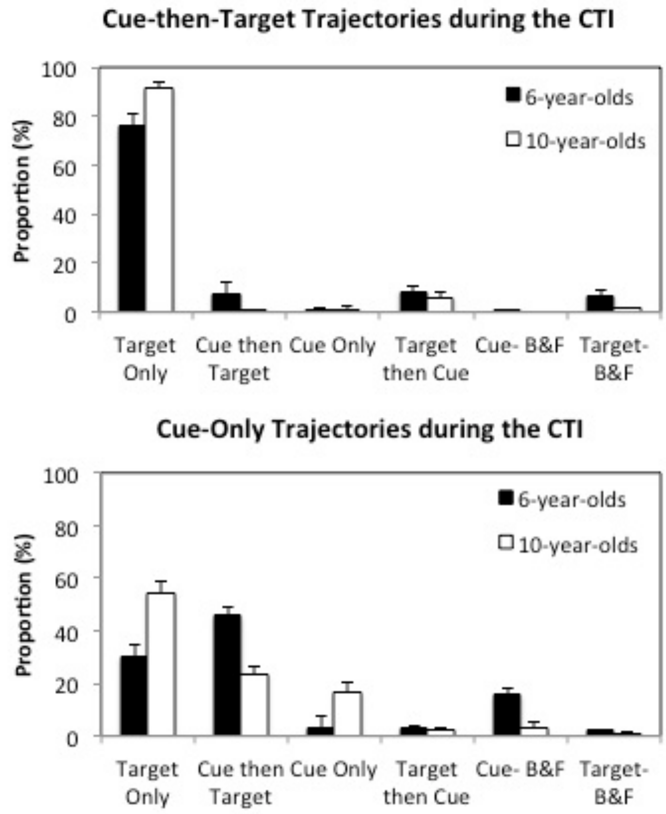

Figure 3. Proportions (%) of each type of gaze trajectory during the target-response interval (TRI) following Cue-then-Target (top panel) and Cue-Only (bottom panel) trajectories during the cue-target interval (CTI). Target-Only = gazed at the target only. Cue then Target = started with cue before moving to the target. Cue Only = gazed at the cue only. Target then Cue = started with the target before moving to the cue. Cue-B&F = started with the cue and then moved back and forth between the cue and the target. Target-B&F = started with the target and then moved back and forth between the cue and the target. Error bars show standard errors. Short Target-Only trajectories during the TRI were more frequent after Cue-then-Target than Cue-Only trajectories during the CTI.

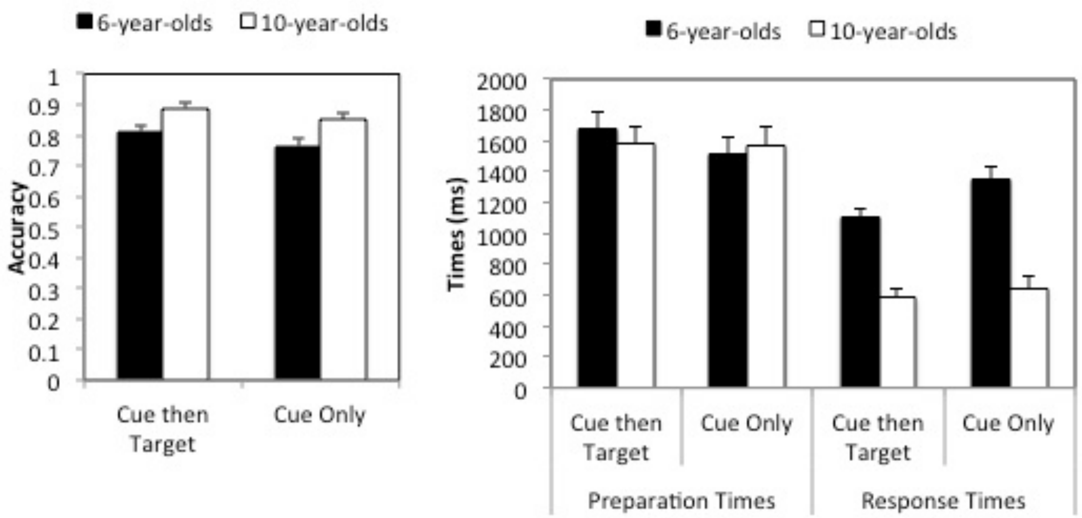

Figure 4. Accuracy (left panel), preparation times and response times (right panel) associated with Cue-then-Target and Cue-Only trajectories during the cue-target interval. Error bars show standard errors. Cue-then-Target trajectories were associated with longer preparation times, greater accuracy, and faster response times than Cue-Only trajectories in both age groups.

Table 1. *Proportions (%) of trials for each type of eye gaze trajectories during the cue-target interval and proportions (%) of trials where the participants gazed back at the cue after fixating the target (returns to the cue).*

	Cue-Disappears		Cue-Stays	
	No-Switch	Switch	No-Switch	Switch
6-year-olds				
Cue-then-Target[a]	24.6 (21.2)	19.9 (21.0)	29.1 (21.6)	29.9 (22.2)
Cue-Only[b]	47.0 (28.2)	49.5 (28.2)	43.2 (26.6)	42.8 (29.6)
Target-then-Cue[c]	7.6 (9.7)	8.4 (9.3)	7.2 (9.5)	9.3 (12.8)
Target-Only[d]	5.5 (9.2)	5.9 (8.1)	5.2 (8.9)	3.7 (7.8)
Back-and-Forth-Cue[e]	8.1 (8.3)	7.8 (9.0)	6.3 (4.9)	6.8 (8.3)
Back-and-Forth-Target[f]	7.2 (5.7)	8.5 (7.3)	7.9 (8.4)	7.5 (9.1)
Returns to the cue	24.5 (16.5)	26.7 (19.1)	32.0 (21.5)	33.0 (23.7)
10-year-olds				
Cue-then-Target[a]	48.6 (21.9)	52.8 (25.3)	54.0 (22.2)	50.9 (25.9)
Cue-Only[b]	34.1 (24.2)	33.4 (28.4)	26.7 (20.1)	30.9 (22.6)
Target-then-Cue[c]	2.9 (5.0)	2.5 (4.0)	2.3 (4.9)	2.9 (5.5)
Target-Only[d]	1.5 (3.8)	0.9 (3.3)	1.1 (2.0)	1.3 (2.9)
Back-and-Forth-Cue[e]	3.4 (3.1)	2.3 (4.0)	4.7 (5.5)	3.2 (7.5)
Back-and-Forth-Target[f]	9.5 (7.9)	8.1 (8.3)	11.1 (7.1)	10.8 (9.8)
Returns to the cue	13.1 (8.6)	10.2 (9.8)	16.0 (14.2)	13.9 (15.5)

[a] Started with cue before moving to the target; [b] gazed at the cue only; [c] started with the target before moving to the cue; [d] gazed at the target only; [e] moved back and forth between the cue and the target and ended with the cue; [f] moved back and forth between the cue and the target and ended with the target. Standard deviations are provided in parentheses.