Cognition 203 (2020) 104329

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/cognit

Consistent use of proactive control and relation with academic achievement in childhood

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ARTICLE INFO

Keywords:
Proactive control
AX continuous performance task
Cued task-switching paradigm
Working memory
Verbal speed
Academic achievements

ABSTRACT

As children become older, they better maintain task-relevant information in preparation of upcoming cognitive demands. This is referred to as proactive control, which is a key component of cognitive control development. However, it is still uncertain whether children engage in proactive control consistently across different contexts and how proactive control relates to academic abilities. This study used two common tasks—the AX Continuous Performance Task (AX-CPT) and the Cued Task-Switching Paradigm (CTS)—to examine whether proactive control engagement in 102 children (age range: 6.91–10.91 years) converges between the two tasks and predicts academic abilities. Proactive control indices modestly correlated between tasks in higher but not lower working-memory children, suggesting that consistency in proactive control engagement across contexts is relatively low during childhood but increases with working memory capacity. Further, working memory (but not verbal speed) predicted proactive control engagement in both tasks. While proactive control as measured by each task predicted math and reading performance, only proactive control measured by CTS additionally predicted reasoning, suggesting that proactive control can be used as a proxy for academic achievements.

1. Introduction

Cognitive control is an important aspect of goal-directed behaviour which allows flexible adaptation to changing environments. As children grow older, they engage in cognitive control more efficiently, including inhibition of unwanted responses, flexible switching between tasks, and focusing attention on task-relevant information (Diamond, 2013; Wiebe & Karbach, 2018 for an overview). Recently, research has been focusing on how children can engage cognitive control through the recruitment of proactive and reactive control. Proactive control allows an individual to prepare for upcoming events, minimizing interference before an event occurs (e.g., Braver, 2012). For instance, children may avoid getting wet by opening an umbrella before going outside. Reactive control, on the other hand, is a late correction mechanism that involves overcoming interference after an event has occurred. In this case, children may open their umbrella only after they have noticed that they are getting wet. Around the age of five or six, children gradually transition from primarily relying on reactive control to using either form of control depending on the context (Blackwell & Munakata, 2014; Chevalier, Martis, Curran, & Munakata, 2015; Gonthier, Zira, Colé, & Blaye, 2019; Lucenet & Blaye, 2014). However, it is still unknown how consistently children engage proactive control across contexts where proactive control is beneficial, especially during the period where children begin to use the two modes of control flexibly. We examined whether age and working memory—given that proactive control engagement may critically depend on working memory since it requires continuous and active maintenance of goal-related information (Braver, 2012)—influence proactive control engagement within *each* task as well as *across* tasks. Critically, we investigated the predictive power of proactive control on academic achievements over the effects of working

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https://doi.org/10.1016/j.cognition.2020.104329
Received 15 November 2019; Received in revised form 10 May 2020; Accepted 15 May 2020

memory and other cognitive control processes.

Proactive control development has been examined in different contexts (i.e., situations with different task demands), such as the AX-Continuous Performance Task (AX-CPT) and the Cued Task-Switching Paradigm (CTS). AX-CPT involves proactive control engagement in the context of response inhibition, while CTS measures proactive control in the context of task switching. In AX-CPT, which is the most widespread measure of proactive control, participants are required to respond to a probe after being presented with a certain prime cue. An AX sequence (A cue followed by an X probe) calls for a target response, while all other prime-probe sequences (AY, BX, BY) require a non-target response. Critically, AX trials occur more frequently than the other trials, creating a bias to select the target response when either the A cue or X probe appear. Approaching the task proactively results in high accuracy and fast response times on BX trials, since the B cue allows one to rule out the possibility of a target response and simultaneously prepare for a non-target response. In contrast, it leads to difficulties on the AY trials, since proactive control results in counterproductive preparation for a target probe in the presence of an A cue. Like adults, 5 to 6 year olds already begin to show a proactive profile on this task (Chatham, Frank, & Munakata, 2009; Fischer, Camba, Ooi, & Chevalier, 2018; Lorsbach & Reimer, 2008, 2010; Lucenet & Blaye, 2014). In CTS, participants switch, for example, between shape and colour sorting rules as a function of task cues. Importantly, the cue can be displayed either *prior* to the target stimulus or simultaneously *with* the target stimulus. Proactive control engagement yields better performance when the cue is presented prior to the stimulus, as early cues enable advance preparation of how to respond to the upcoming target, whereas only reactive control is possible when the cue is presented at the same time as the target. Like in AX-CPT, proactive control engagement becomes more efficient in CTS from 5 to 10 years of age (Chevalier et al., 2015; Chevalier & Blaye, 2016; Doebel et al., 2017).

An open question is whether children engage proactive control consistently across contexts where proactive control yields a behavioural advantage over reactive control but with different cognitive demands like AX-CPT and CTS. Examining this question clarifies to what extent proactive control engagement is stable in children or dependent on cognitive demands associated with an individual task. Such information has important conceptual and methodological implications, as it speaks to the usefulness of considering proactive control and how to assess it in individual different studies. Consistency in proactive control engagement likely relies on observing that proactive control is an efficient approach (i.e., will maximize the chances of reward) in any novel context. Since upcoming task demands can be predicted reliably in both AX-CPT and CTS tasks, children who are able to evaluate task demands and understand the advantages of using proactive control may consistently do so in both tasks. However, consistency in proactive control engagement may be modulated by internal factors such as age and working memory.

As younger children (from the ages of 5 to 8) are still learning to use proactive and reactive control flexibly depending on the context, they may not be able to systematically detect the contexts in which proactive control could be efficiently recruited and thus show low consistency in its engagement. Indeed, unlike older children, younger children do not systematically engage proactive control in contexts where in fact, proactive control engagement benefits their performance (Chevalier et al., 2015; Chevalier & Blaye, 2016; Hadley, Acluche, & Chevalier, 2020). Conversely, some preschool children over-rely on proactive control engagement, even when reactive control would boost performance (Blackwell & Munakata, 2014). As experience with proactive control engagement increases, older children and adults may show greater consistency in the control mode they engage across contexts.

Further, consistency in proactive control engagement may critically depend on working memory, as proactive control requires continuous and active maintenance of goal-related information in working memory (Braver, 2012). Consistently, individual differences in working memory predict the use of proactive control in adults, as adults with greater working memory capacity engage more proactive control than adults with lower working memory capacity (Redick, 2014; Richmond, Redick, & Braver, 2015). In children, sixth-graders outperformed third-graders in proactive control engagement, but only in contexts that placed high demands on maintenance of goal-related information (Lorsbach & Reimer, 2010), and there was a relationship between age-related change in working memory performance and the efficient use of these two modes of control (Chevalier, James, Wiebe, Nelson, & Espy, 2014; Gonthier et al., 2019; Troller-Renfree, Buzzell, & Fox, 2020). Given the link between proactive control engagement and working memory, we hypothesize that working memory may also critically contribute to consistency in proactive control engagement across contexts in which proactive control is potentially beneficial. Specifically, when the working memory load in a given task is high, children with lower working memory may have to revert back to reactive control for optimal performance. In contrast, children with high working memory may have more cognitive resources to efficiently determine when proactive control should be recruited and cope better with different working memory demands associated with each task, and thus show a more consistent profile of proactive control use in contexts where proactive control is beneficial. It is important to note here that we do *not* argue that high working memory capacity individuals would engage proactive control more even in contexts where reactive control is a better approach. Instead, they may adjust control mode engagement as a function of contextual demands more flexibly than low working memory capacity individuals.

A related question is whether proactive control measured in different contexts predicts other cognitive abilities. Of particular interest are academic abilities such as math, reading, vocabulary, and reasoning, which are closely related to cognitive control (Becker, Miao, Duncan, & McClelland, 2014; Best, Miller, & Naglieri, 2011; Blair & Razza, 2007; Brock, Rimm-Kaufman, Nathanson, & Grimm, 2009; Bull, Espy, & Wiebe, 2008; Bull & Lee, 2014; Lan, Legare, Ponitz, Li, & Morrison, 2011; Latzman, Elkovitch, Young, & Clark, 2010; Nesbitt, Baker-Ward, & Willoughby, 2013; Titz & Karbach, 2014; many of these studies examined multiple academic achievements). To date, no study has specifically focused on the relationship between proactive control and academic achievements in childhood, focusing instead on effects of inhibition, shifting, and updating on academic achievements (e.g., Johann, Könen, & Karbach, 2019). Although increasing use of proactive control is a key factor in children's cognitive development, how this may contribute to academic performance is not well documented. The ability to recruit proactive control is a skill that is most likely transferrable to academic contexts—children may benefit from using proactive control in specific skill sets (i.e., solving a math problem by planning the order of operations) or in general school activities (i.e., working on homework and planning to finish it by the deadline).

Moreover, the construct of proactive control is different from (albeit closely linked to) other components of cognitive control such as inhibition or shifting, in a sense that it refers to the way in which children implement or combine executive processes. Age-related gains in different components of cognitive control do not simply reflect growing efficiency of the same process (e.g., inhibitory control increases with age), but also more flexible engagement of executive processes as a function of task demands. Such increasing flexibly includes, but is not limited to, better coordination of reactive and proactive ways to engage executive processes related to shifting or inhibition. Depending on the context and its task demands, it may be more beneficial and less effortful to use reactive control to resolve interference (e.g., Blackwell & Munakata, 2014). Therefore, efficient coordination of control modes as a function of the cognitive demands of each context is likely to contribute to academic achievements in childhood over the effects of different dimensions of cognitive processes and working memory.

The present study investigated how consistently children engage in proactive control across contexts (AX-CPT and CTS) using a three-prong

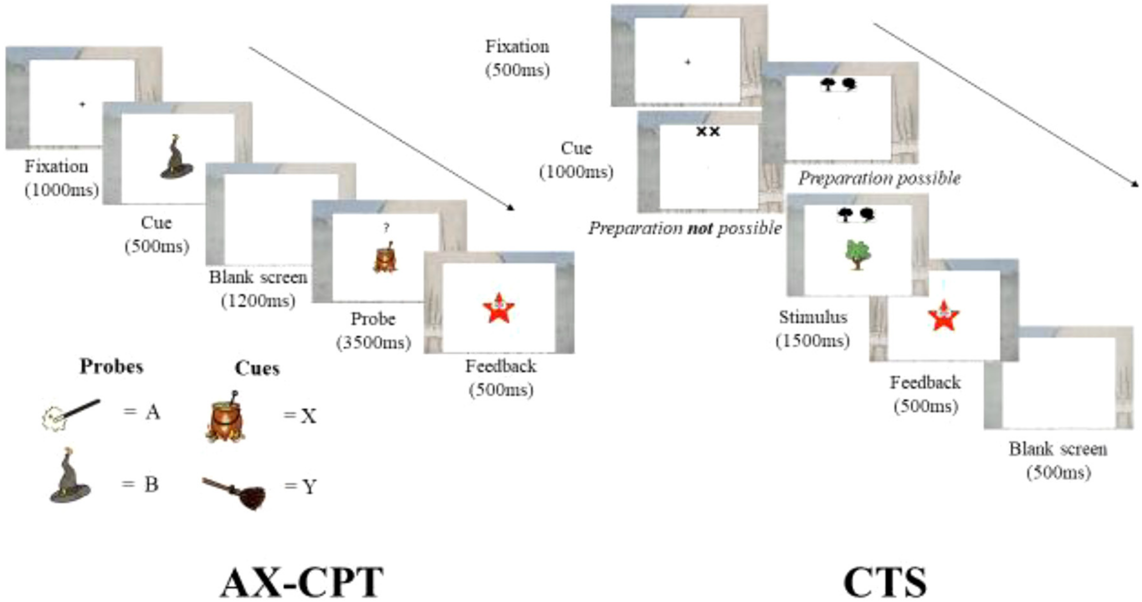

Fig. 1. Illustration of AX-CPT (left) and CTS (right). In the AX-CPT, the children are instructed to press a green button when presented first with a wand (cue) and then a cauldron (probe) (i.e., AX trial). Otherwise, they must press the yellow button (BX, AY, BY trials). In the CTS, proactive engagement is only possible when the children are presented with a cue (e.g., assessing whether the stimulus is a tree of a flower) before the presentation of the stimulus. In the trial in which preparation is not possible, "XX" is presented instead of a cue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

approach. First, we examined whether measures of proactive control correlate across tasks and whether this relation, if any, increases with age and working memory. Second, we examined to what extent proactive control engagement in each task is predicted by age, working memory, and verbal speed. Both working memory and proactive control tasks employed in this study may require children to internally verbalize their strategies as well as use their motor skills to press the button as fast as possible (AX-CPT and CTS) or point to a specific grid on the screen (Corsi-block). Therefore, we included verbal speed to test whether the relation of proactive control engagement to working memory is specific and does not merely reflect a relation with other verbal and/or motor skills. In other words, verbal speed was included as a variable as a means to control for individual variance. Third, we examined to what extent proactive control indices derived from AX-CPT and CTS differed in predicting reasoning, math, reading, and vocabulary abilities, and whether its effect contributes to academic performance over the effects of working memory and processes of cognitive control (i.e., inhibition and shifting).

We targeted 7- to 11-year olds in the current study, as children in this age range learn to flexibly use either reactive or proactive control depending on the demands of the task, becoming more efficient proactive control users (Munakata, Snyder & Chatham, 2012). Firstly, as both proactive control and working memory improve within this age range (Buttelmann et al., 2019; Gathercole, Pickering, Ambridge, & Wearing, 2004), we predicted that there would be greater consistency in proactive control engagement among older than younger children as well as children with higher working memory than lower working memory. Secondly, we expected age and working memory (while controlling for verbal speed) to predict proactive control engagement in both tasks, exploring whether the variance explained from these two variables would vary across tasks. Finally, we predicted that proactive control engagement would be linked to academic achievements in childhood (over the effects of working memory, inhibition, and shifting abilities), but explored to what extent indices of proactive control derived from the two tasks would differ in how much they would predict children's performance on math, reasoning, vocabulary, and reading skills. However, it is important to note here that the data in the current study were drawn from a larger project testing the effect of cognitive training in children with low socio-economic status (SES) backgrounds. Although there is no a-priori reason to expect relations of proactive control to academic abilities to differ across SES, we further discuss the findings in light of this specific population.

2. Method

2.1. Participants

A total of 102 children (mean age = 8.68; range = 6.91–10.91; *SD* = 1.00; gender = 52 female) participated in the current study. Sixty-two of these children were tested in the UK (Scotland) and the other 40 in Germany. The children were all tested in a quiet room in their primary school. Parental consent was received for all participants. The ethics boards at the the University of Edinburgh (100-1718/1) and the University of Koblenz-Landau (116-2018) approved the study. Since the current study was part of a larger project testing cognitive control training in children with low socioeconomic status (SES), other tasks not reported here were administered on the same day. We used data that were collected prior to the cognitive training (i.e., pre-test) in this study. Children were selected from schools located in disadvantaged neighbourhoods, both in the UK (Scotland) and in Germany. In the UK, we used the Scottish index of multiple deprivation (SIMD) to identify the most deprived areas in Scotland (lowest 10%), then mapped each school's catchment area to the SIMD map to identify the schools to be recruited in this study. In Germany, most of the children (75%) were recruited in areas with a regional at-risk-of-poverty rate above the national mean (Federal Statistical Office, 2019).

2.2. Materials and procedure

2.2.1. Proactive control tasks

The proactive control tasks described below were embedded into a magic world cover story which asked children to engage in different tasks that involve magical creatures such as magicians, dragons, and trolls in order to earn magic points.

AX-Continuous Performance Task (AX-CPT). This task presented participants with sequences of pictures, including pairs of cues

(A = wand or B = hat) and probes (X = cauldron or Y = broom). At probe onset, the child was to press one of two response keys, associated to either target or non-target responses. If X occurred after A, then the green button (key "A") should be pressed, but if any other order of stimuli occurred (AY, BX, BY) the yellow button (key "L") should be pressed. AX trials made up 50% of the trials, and in the remaining 50%, AY, BX, and BY trials appeared equally often. The task consisted of a practice phase with two blocks (18 trials per block) and an experimental phase with two blocks (30 trials per block). The trials were presented randomly. Each trial began with a fixation cross in the middle of the screen (1000 ms), followed by a cue (500 ms), a blank screen (1200 ms), a probe (max 3500 ms), and a trial feedback (500 ms) (Fig. 1). We derived two indices of proactive control, both of which have been used widely in the literature: the proactive behavioural index (PBI; Braver, Paxton, Locke, & Barch, 2009) and *d'* context score (Gonthier, Macnamara, Chow, Conway, & Braver, 2016). PBI is computed as (AY − BX)/(AY + BX) for both error rates and response times. The relative balance of interference between AY and BX trials can be measured using this index, whereby a positive PBI reflects higher interference on AY trials (indicating proactive control), and a negative PBI reflects higher interference on BX trials (indicating reactive control). For instance, if the AY trials yield an average reaction time of 1000 ms and BX trials of 500 ms, then the PBI will equal to 33.33, which is a positive value reflecting proactive control. The *d'*-context score is based on the signal detection theory (Stanislaw & Todorov, 1999), which is calculated as Z(Hit RateAX) − Z(False AlarmsBX), with Z representing the z transform of these values, and thus, higher values indicate better proactive control (Barch et al., 2001). This index measures the individual sensitivity to the differences between target (AX) and non-target (BX) trials, while controlling for response biases. For example, the higher the participant has a hit rate (i.e., pressing the AX target button on AX trials) and/or lower the false alarm rate (i.e., pressing the AX target button on BX trials), the higher the *d'*-context score is, indicating greater engagement of proactive control.

Cued task switching (CTS). Participants performed two tasks (A and B) either in single-task blocks (task A or B separately) or in mixed-task blocks (switching between both tasks). One task required participants to decide whether a picture showed a tree or a flower and the other whether the picture was small or large. There were 4 blocks of practice trials (2 single blocks x 5 trials and 2 mixed blocks x 10 trials) and 4 single blocks and 6 mixed blocks of experimental trials (17 trials each). In mixed-task blocks, participants switched tasks based on a visual cue that either signalled shape- (i.e., picture of a flower alongside a tree) or size-sorting (i.e., a small circle alongside a big circle). In half of the trials (for both single and mixed blocks), the cue was presented to them 1000-ms before the stimulus appeared, making proactive preparation ahead of stimulus onset possible (i.e., cue is visible). In the other half, the cue was presented to them at the same time as the stimulus, and "XX" appeared on the screen 1000-ms before the presentation of the stimulus, rather than a cue, rendering proactive preparation impossible (i.e., cue is not visible). For convenience, we will refer to this task manipulation as "cue visibility". Half of the trials in the mixed block were switch trials (i.e., the task changed relative to the previous trial) and the other half were stay trials (i.e., the task repeated). The participant responded by pressing the same green or yellow response button on the computer keyboard as in the AX-CPT task (key "A" or "L"). Switch costs are the difference between stay trials and switch trials in the mixed-task blocks and reflect transient control processes (e.g., internal configuration, updating of goals, and linking of task to stimulus), while mixing costs are the difference between stay trials in the mixed-task blocks and trials in the single-task blocks and reflect more sustained aspects of control (e.g., maintaining activation of task sets, constantly engaging in attentional monitoring processes). Early cue presentation has been previously shown to affect both switch and no-switch trials similarly in school-age children (Chevalier et al., 2015; Doebel et al., 2017). Thus, following these prior studies measuring proactive control in CTS, indices of proactive control were calculated by subtracting the mean reaction times (RTs) and mean error rate of trials where a cue was presented before the stimulus from trials where a cue was presented at the same time as the stimulus in the mixed blocks (i.e., higher values indicate better proactive control) (Chevalier et al., 2015; Doebel et al., 2017). Moreover, switch costs in the trials where cue was presented simultaneously with the target were used for further analysis to determine the predictors of academic achievement. Since we limit the measure to trials in which the children had no opportunities to engage control in a proactive manner, we can be sure that the switch costs would not capture any recruitment of proactive control.

2.2.2. Working memory, verbal speed, and inhibition tasks

Backwards Corsi-like task. In this task, a stimulus moved in a 3 × 3 grid on the computer screen and the children were required to recall the sequence of moves in reversed order. In each trial, a stimulus was presented successively one at a time at a random location in the 3 × 3 grid with the restriction that a location could not repeat within a sequence and the centre square could not be used. The task started with two grid locations that needed to be remembered. Six trials were presented for each sequence length, which progressively increased by one location if the participant had at least 2 trials correct within a given sequence length. The maximum sequence length was set to 8. The task consisted of one block of demo trials and one block of practice phase (10 trials each) and a maximum of 7 blocks of experimental phase (6 trials each). Each trial started with a fixation cross (2000-ms), followed by the presentation of a stimulus (1000-ms) and an interstimulus interval (500-ms). Working memory was measured with the product score, which is the product of the sequence length and the sum of correctly remembered trials. For instance, 3 points were given for every correct trial in a 3-location sequence, and 4 points for every correct trial in 4-location sequence. This composite measure takes both the number correct and the span length into account, which is a more reliable and finer-grained measure than maximum span length reached (Kessels, Van Zandvoort, Postma, Kappelle, & De Haan, 2000). In order to minimize the differences in children's native language (German vs. English), we chose a WM task that does not rely on verbal information. Moreover, recent evidence suggests that children can engage in non-verbal forms of proactive control, such as visual rehearsal of locations where items where previously presented in a visuospatial working memory task (Morey, Mareva, Lelonkiewicz, & Chevalier, 2018).

Colour-naming test. This paper-and-pencil task was used to measure verbal speed. It involved four different shapes, which were assigned to four specific colours, that were presented at the top of the test sheet. Below, the sheet included shapes without colour. Children were required to name the corresponding colour for each shape as quickly and accurately as possible. There were 5 practice items and 43 test items. The total of correctly named items within 45 s was used for further analyses.

Antisaccade task. The Antisaccade task requires the participants to inhibit the reflexive urge to look at a visual cue that appears suddenly on the peripheral field of the screen and instead look in the opposite direction in order to identify the target quickly displayed on that other side of the monitor. First, a fixation cross was presented in the middle of the screen for 1500 to 3250-ms until the gaze signal was detected. Then a cue (i.e., goblin) was presented on either side of the screen for 250-ms, followed by the target stimulus for 100-ms. The targets were randomly chosen from the set of target stimuli (dog, pig, donkey, goose) with the restriction that they appear equally often (i.e., twice during a practice block). After the presentation of the target stimulus, the mask (i.e., tree) appeared to cover up the target stimulus and the participants are given a maximum of 1500-ms to respond. Inter-trial interval with a blank screen appeared for 1500-ms until it proceeded to the next trial. The cue appeared on one side of the screen (50% right side) and the target and the mask on the other side. The task began with an instruction, followed by 2 blocks of practice trials (8 trials for each block) then 3 blocks of experimental trials (24 trials for each block). The practice block was repeated if the accuracy rate was < 60% but it was not repeated more than twice. The child was seated exactly 60 cm away from the monitor, as sitting further away from the monitor will make it easier to identify the animal even after fixating to the goblin. The accuracy in the experimental trials was used for further analysis to determine the predictors of academic achievement.

2.2.3. Matrix reasoning, vocabulary, reading, and math tasks

Matrix Reasoning task. We used a subtest of the Wechsler Intelligence Scale for Children (WISC-IV; Wechsler, 2004). This task assessed children's abstract reasoning and general intelligence. This was a nonverbal task in which geometrical figures are completed by choosing the correct missing piece among five alternatives. The task was aborted after three consecutive errors were made. Scores corresponded to the sum of correct responses (1 point for each trial) with a maximum score of 32. Children all started from item 1 regardless of age, rather than adjusting the start point depending on their age.

Peabody Picture Vocabulary Test (PPVT-4, Dunn & Dunn, 2007). We used a standardized test of receptive vocabulary. Participants were shown 4 pictures and were instructed to indicate the picture named by the experimenter. Scores corresponded to sum of correct responses (1 point for each trial) with a maximum score of 32. The test was conducted in German in Germany and English in the UK.

Reading comprehension task. We used a subset of the Wechsler Individual Achievement Test Third Edition (WIAT-III; Wechsler, 2017). This task consisted of two short stories, and the children were asked 6–7 content-related questions for each story. Scores corresponded to sum of correct responses (13 questions in total, 1 point for partial and 2 points for full answers) with a maximum score of 26. The test was conducted in German in Germany and English in the UK.

Math problem solving task. We used a subset of the Wechsler Individual Achievement Test Third Edition (WIAT-III; Wechsler, 2017). In this task, the children were asked to solve a maximum of 25 math questions. The task was aborted when the children made three consecutive errors. Scores corresponded to sum of correct responses (1 point for each trial) with a maximum score of 25.

3. Results

Descriptive statistics of CTS and AX-CPT are presented in Table 1. Practice trials and demo trials were excluded from the analyses, as well as first trial of each block. Incorrect trials were excluded from the dataset for RTs of both tasks, and RTs that were over or below three standard deviations from the group mean were also omitted. Only 20 data points were excluded for the AX-CPT task (3364 vs. 3384 data points) and 4 data points were excluded in the CTS task (14,223 vs. 14,227 data points). Various indices of proactive control of CTS and AX-CPT are also reported in Table 1, along with the reliability of these measures. Internal reliability consistencies were obtained via bootstrapped split half correlations with Spearman-Brown corrections. Proactive control index (PCI) of CTS based on reaction time and *d'*-context scores of AX-CPT were the only measures that yielded acceptable reliability coefficients (> 0.70) (Ponterotto & Ruckdeschel, 2007).

We ran an ANOVA for both accuracy and reaction time of CTS and AX-CPT. Fixed factors in the CTS models include Trial type and Cue onset, while the AX-CPT models include only Trial type. In regards to CTS, children responded faster when the cue was presented prior to the stimulus ($F(1,594) = 37.81$, $p < .001$) but this did not yield any difference in accuracy ($F(1,594) = 2.35$, $p = .12$). There was also a main effect of Trial type for both reaction time ($F(2,594) = 22.96$, $p < .001$) and accuracy ($F(2,594) = 48.66$, $p < .001$), in which planned contrasts revealed a significant mixing cost (i.e., difference between single and stay trials) for both reaction time ($p < .001$), and accuracy ($p < .001$), as well as a significant switch cost (i.e., difference between stay and switch trials) for reaction time ($p < .001$), and accuracy ($p < .001$). A significant interaction between Trial type and Cue onset was found for reaction time ($F(2,594) = 3.53$, $p = .02$) but not for accuracy ($F(2,594) = 2.17$, $p = .11$). Planned contrasts revealed that mixing costs were smaller when the cue was presented prior to the stimulus ($p = .03$), but the magnitude of switch costs did not differ depending on cue visibility ($p = .11$). As for the AX-CPT, there was a main effect of Trial type for both reaction time, ($F(3,392) = 15.23$, $p < .001$) and accuracy ($F(3,392) = 7.03$, $p < .001$). Planned contrasts showed that children performed faster on the BX trials than AY trials ($p < .001$), but no difference was found for accuracy ($p = .08$). Moreover, the difference between AX trials and BX trials was significant for accuracy ($p < .001$) (with higher accuracy on AX trials), but not for reaction time, ($p = .16$).

Table 1
Descriptive statistics of Cued Task Switching Paradigm (CTS) and AX Continuous Performance Task (AX-CPT).

CTS Trial type	Cue onset	Mean reaction time	Mean accuracy
Single	Ahead of stimulus	910 (376) *202–3916*	0.89 (0.31)*0* *.48–1.0*
Single	Simultaneously	953 (387) *249–3821*	0.90 (0.30)0 *.54–1.0*
Stay	Ahead of stimulus	970 (394) *210–3694*	0.83 (0.37)0 *.41–1.0*
Stay	Simultaneously	1128 (415) *233–3737*	0.82 (0.39)*0* *.41–1.0*
Switch	Ahead of stimulus	1009 (422) *236–3252*	0.80 (0.40)0 *.45–1.0*
Switch	Simultaneously	1183 (436) *203–3983*	0.78 (0.42)*0* *.45–1.0*
Switch costs	Ahead of stimulus	42 (107) *−182.69–372.44*	0.02 (0.11) − *0.29–0.25*
Switch costs	Simultaneously	58 (124) *−227.46–543.57*	0.03 (0.10) − *0.33–0.20*
Mixing costs	Ahead of stimulus	56 (141) *−279.80–551.20*	0.06 (0.10) − *0.33–0.20*
Mixing costs	Simultaneously	158 (206) *−489.93–783.53*	0.10 (0.12) *−0.41–0.09*

AX-CPT Trial type	Mean reaction time	Mean accuracy
AX	673 (258) *106–1815*	0.90 (0.31)*0* *.23–1.0*
AY	795 (242) *64–1760*	0.83 (0.38)*0* *.20–1.0*
BX	632 (346) *12–1817*	0.76 (0.42)*0* *.10–1.0*
BY	641 (306) *16–1796*	0.89 (0.32)0 *.40–1.0*

Proactive control index	Mean	Reliability
CTS		
Reaction time	157 (134)	0.74
Error rate	0.03 (0.10)	0.40
AX-CPT		
Proactive Behavioural Index (PBI) Reaction time	0.13 (0.14)	0.19
Proactive Behavioural Index (PBI) Error rate	0.06 (0.02)	0.16
d'-context	2.13 (0.91)	0.81

Note. Numbers in brackets indicate standard deviation. Numbers in italics indicate range.

3.1. Was there a correlation between proactive control indices of CTS and AX-CPT?

We ran partial correlational analyses while controlling for age

Table 2
Correlations between proactive control index of Cued Task Switching Paradigm (CTS) and AX Continuous Performance Task (AX-CPT) while controlling for age.

Proactive control indices	CTS (RTs)	CTS (accuracy)	AX-CPT (PBI RTs)	AX-CPT (PBI accuracy)	AX-CPT (*d'*-context)
CTS (RTs)	–	0.23*	0.16	0.005	0.21*
CTS (accuracy)		–	−0.07	−0.19	−0.05
AX-CPT (PBI RTs)			–	0.12	0.13
AX-CPT (PBI accuracy)				–	0.44***
AX-CPT (*d'*-context)					–

Note. $^*p < .05$, $^{***}p < .001$.

(Table 2), in order to determine whether the proactive control indices of CTS and AX-CPT converge.

As illustrated in Fig. 2a, there was a significant correlation ($r(97) = 0.21, p = .03$) between the proactive control index of CTS based on reaction time (i.e., (RTs of trials where cue was presented simultaneously – RTs of trials where cue was presented before the stimulus) for stay and switch trials) and *d'*-context of AX-CPT. However, no other significant correlations of proactive control indices *across* tasks were found. Some internal consistencies were observed *within* tasks—children who engaged proactively in the CTS task did so for both reaction time and accuracy ($r(97) = 0.23, p = .02$) and unsurprisingly, *d'*-context correlated moderately with the PBI in accuracy for AX-CPT ($r(97) = 0.44, p < .001$). As the proactive control index of CTS based on reaction time and *d'*-context derived from AX-CPT showed the highest reliability and correlated with each other, we focused on these two indices of proactive control in subsequent analyses, which examined the predictive role of age and working memory on proactive control engagement, and how proactive control indices may predict academic abilities.

We then investigated whether consistent use of proactive control is more consolidated in older children than younger children and in a similar vein, whether children with high working memory are more consistent in their recruitment of proactive control than children with low working memory. To do so, we median-split the group by composite scores on working memory task as well as age, and created two groups for each comparison (a) groups with older (M = 9.63, SD = 0.60) and younger (M = 7.95, SD = 0.49) children (b) groups with high working memory (M = 56.80, SD = 11.13) and low working memory (M = 29.95, SD = 10.18). We then ran correlational analyses between the proactive control index of CTS based on reaction time and *d'*-context derived from AX-CPT for each group (as these two indices of proactive control were the only measures that correlated significantly in the previous analysis). As illustrated in Fig. 2b, the correlation between tasks was significant for older children ($r(43) = 0.30, p = .04$), but not for younger children ($r(50) = 0.16, p = .24$). Similar results were obtained for the working memory capacity (Fig. 2c); correlation between tasks were significant for children with high working memory ($r(45) = 0.38, p = .007$) but not for children with low working memory ($r(46) = 0.01, p = .91$). We compared the coefficients of these correlations using the cocor package in R (Diedenhofen & Musch, 2015) which applies Fisher r-to-z transformation to assess the significance of the difference between two correlation coefficients from independent samples. The results showed no difference in correlation coefficients between younger and older children ($p = .24$) but a significant difference between children with high and low working memory ($p = .03$).

3.2. To what extent did working memory and verbal speed predict proactive control index of CTS and AX-CPT?

Multiple linear regression analyses were conducted for the proactive control index of CTS (proactive control index based on reaction time) and AX-CPT (*d'*-context) separately. In both models, age and working memory (Backwards Corsi-like task) were entered as predictors and verbal speed (Colour-naming test) as a covariate. The predictors and covariate were standardized. The output (as illustrated in Fig. 3a) showed that working memory significantly predicted the proactive control indices of both CTS, $E = 53.22$, $SE = 13.24$, $p < .001$ (Fig. 3a), and AX-CPT, $E = 0.21$, $SE = 0.09$, $p = .03$ (Fig. 3b). In contrast, verbal speed did not have an effect on the proactive control index of either task (p's > 0.32). For CTS, the model explained 18% of variance in proactive control index, while for AX-CPT, the model only explained 5% of variance. This suggests that children with greater working memory performance were more likely to engage proactive control in both CTS and AX-CPT, and working memory predicted more variance in proactive control index in CTS than AX-CPT.

3.3. Did CTS and AX-CPT proactive control indices predict reasoning, vocabulary, reading, and math abilities?

We ran hierarchical regression analyses to determine whether the proactive control indices of CTS and AX-CPT predicted academic achievement in domains such as reasoning, vocabulary, reading, and math over the effects of working memory, inhibition, and shifting abilities. Four separate models were tested with reasoning, vocabulary, reading, and math scores as dependent variables. Each model included four steps: first, we included age and country (i.e., whether children were tested in Germany or UK) as covariates. In the second step,

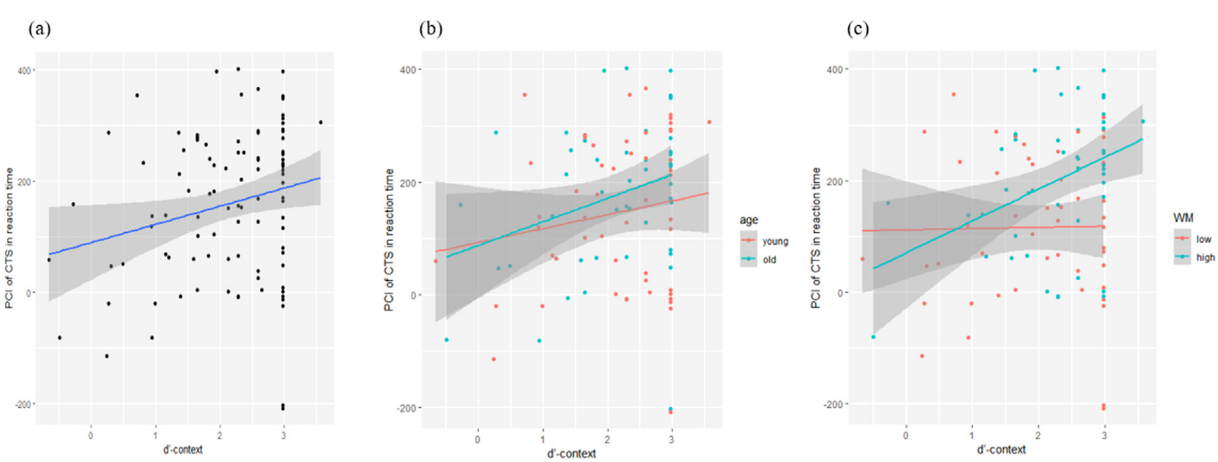

Fig. 2. Relationship between *d'*-context and proactive control index of CTS in reaction time for the entire sample (a), as a function of age (younger vs. older children) (b), and working memory (high vs. low) (c).

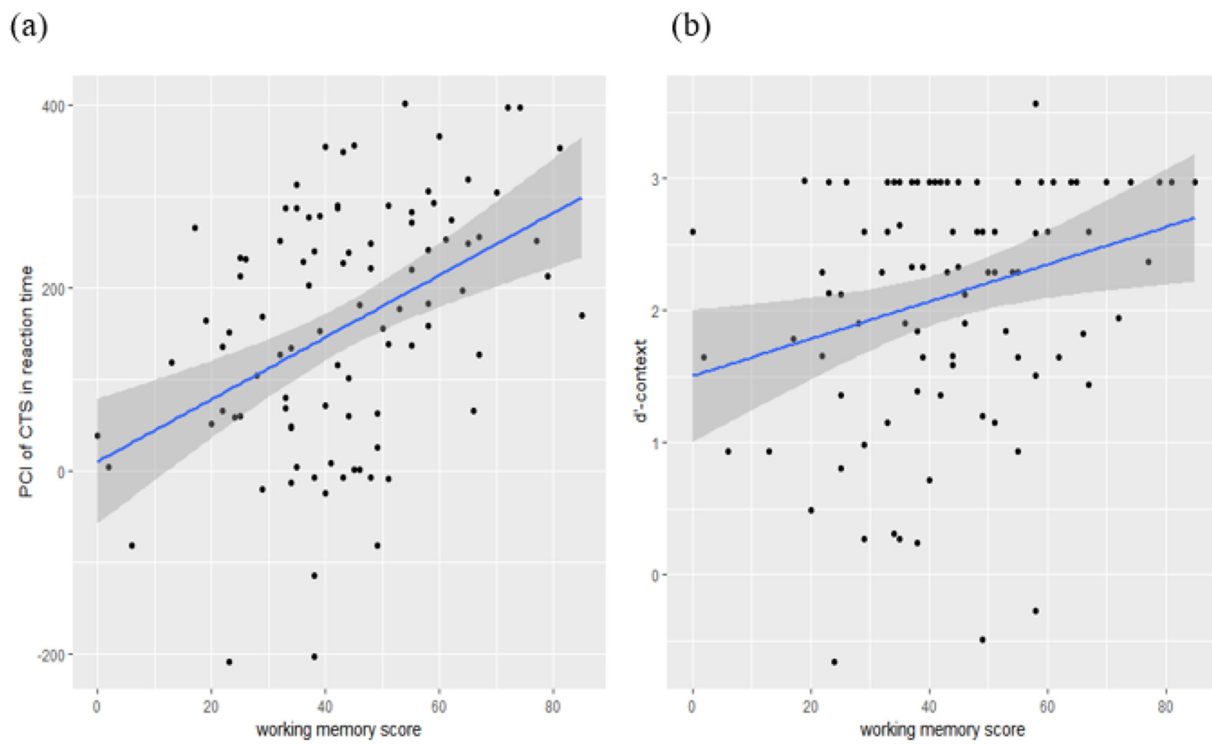

Fig. 3. Relationship between working memory score and proactive control index (PCI) of CTS in reaction time (Fig. 3a) and the relationship between working memory score and *d'*-context score (Fig. 3b).

processes of cognitive control including inhibition (i.e., accuracy on the Antisaccade task) and task-switching (i.e., switch costs in the CTS task) were included in the analysis. Working memory score (i.e., composite score on the Backwards Corsi-like task) was entered as the third step. Finally, we included proactive control indices of CTS (in reaction time) and AX-CPT (*d'*-context) as predictors. All continuous predictors were centered so that each variable had a mean of 0. A summary of these hierarchical regression models is presented in Table 3.

The results of Table 3 show that proactive control indices made a unique contribution over the effects of working memory, inhibition, and shifting for math, and reading abilities, as well as near-significant effect for vocabulary (p = .05). Furthermore, PCI of CTS was a significant predictor for math, reading, and reasoning abilities (Fig. 4), while the proactive control index of AX-CPT predicted math and reading scores, but not reasoning and vocabulary (Fig. 5). Moreover, the regression coefficients for PCI of CTS is always larger than that of *d'*-context of AX-CPT. Inhibition and shifting abilities had a significant effect on reasoning (and near-significant effects for reading), while working memory contributed to improving the model fit for reasoning and math abilities.

4. Discussion

The present study investigated three major questions concerning children's use of proactive control. First, do children engage in proactive control consistently between two different tasks that call for proactive control engagement and is the consistent use of proactive control modulated by age and working memory? Second, do working memory and age predict proactive control engagement in both contexts? Third, do the separate indices of proactive control predict the same academic abilities over the effects of working memory as well as inhibition and shifting abilities?

First, we found the expected pattern of results for CTS and AX-CPT—children showed significant switch and mixing costs on CTS and performed faster on BX trials than AY trials on AX-CPT. Importantly, our findings showed a small to moderate correlation in proactive control engagement across tasks, at least between *d'*-context scores on the AX-CPT and proactive control index of CTS in reaction time. At the conceptual level, this suggests that proactive control engagement demonstrates some consistency across tasks during childhood, which is consistent with the only other study who investigated this issue (Doebel et al., 2017). However, this association relatively low. That is, children who have begun to use proactive control as another mode of control may not yet be efficient at determining when it is adaptive to engage proactive control in a given context. However, our results may be specific to the population we examined, as the children in the current study were mostly from low socio-economic background. The ability to consistently engage in proactive control across contexts may be higher in children from high socio-economic status (SES), given that working memory capacity increases with SES (Evans & Schamberg, 2009; Hackman, Gallop, Evans, & Farah, 2015; Sarsour et al., 2011).

Our findings suggest that consistency in proactive control does not increase with age, but rather with working memory—proactive control indices significantly correlated between tasks in higher but not in lower working memory children. Thus, not only are children (and adults) with higher working memory more likely to engage proactive control (Braver, Gray, & Burgess, 2007; Gonthier et al., 2019; Redick, 2014; Richmond et al., 2015) but they are also more susceptible to do so consistently across contexts where proactive control is beneficial. Alternatively, children with greater working memory may better detect the contexts in which proactive control would be beneficial or more flexibly tailor cognitive control engagement accordingly. The link between working memory and proactive control is further highlighted by the findings that working memory, but not verbal speed, predicted the use of proactive control in each task separately, even after controlling for age-related increases. Along with recent evidence that working memory and proactive control develop in tandem (Gonthier et al., 2019), our findings suggest that working memory plays a key role in the development of proactive control during childhood.

Working memory better predicted proactive control engagement in CTS than AX-CPT, explaining 18% and 5% of variance, respectively. This finding may arise from the greater working memory demands in

Table 3
Summary of the hierarchical regression analyses; The numbers indicate β value.

Independent variables	Dependent variables			
	Reasoning	Vocabulary	Math	Reading
Step 1: control variables				
Age	0.58	1.33**	1.07*	2.41**
Country	−1.25	−0.78	−0.79	−1.58
R^2	0.03	0.08	0.06	0.11
F	1.67	4.45	3.35	5.70
Step 2: inhibition and shifting				
Age	0.37	1.14*	0.96*	2.11**
Country	−1.14	−0.83	−0.76	−1.60
Inhibition	0.99*	1.00*	−0.55	1.55*
Shifting	0.35	−0.17	0.10	−0.07
R^2	0.10	0.14	0.08	0.15
ΔR^2	0.07	0.06	0.02	0.04
ΔF	4.50*	2.80 .	1.12	2.91 .
Step 3: working memory				
Age	0.22	1.12*	0.88*	2.01**
Country	−0.43	−0.74	−0.37	−1.12
Inhibition	0.58	0.94*	0.33	1.28
Shifting	0.48	−0.15	0.17	0.01
Complex Corsi Index	1.58***	0.20	0.85*	1.06
R^2	0.25	0.14	0.12	0.17
ΔR^2	0.15	0	0.04	0.02
ΔF	18.09***	0.22	4.72*	2.53
Step 4: proactive control				
Age	0.15	1.07*	0.80*	1.87**
Country	−0.51	−0.98	−0.73	−1.71
Antisaccade	0.45	0.71	−0.005	0.70
Shifting	0.56	−0.12	0.21	0.09
Complex Corsi Index	1.21**	−0.28	0.15	−0.12
AXCPT PCI (*d'*-context)	0.15	0.63	0.93*	1.57*
CTS PCI (RTs)	0.83*	0.85	1.21**	2.06**
R^2	0.29	0.19	0.25	0.30
ΔR^2	0.04	0.05	0.13	0.13
ΔF	2.40	2.88 .	7.50***	7.49***

. = p = .05, * = p < .05, ** = p < .01, *** = p < .001; N = 95 for all columns.

CTS than AX-CPT. Specifically, CTS required children not only to hold the cue information in their working memory and prepare for the upcoming target (when possible), but also to hold two separate sets of task rules in mind and switch between them. Like CTS, AX-CPT required holding the relevant cue in mind and preparing for the upcoming probe, but unlike CTS, children had to maintain a single set of task rules instead of two. Previous work has suggested that switching tasks such as CTS taps multiple cognitive processes and are more cognitively demanding than inhibition tasks like the AX-CPT (Bialystok, 2017). Thus, children's likelihood to engage proactive control may be more dependent on their working memory resources in contexts in which working memory demands are already high. In addition, variance in the data may have partially contributed to the degree of association between proactive control engagement and working memory. Proactive control index of CTS in reaction time had larger variances than *d'*-context in AX-CPT (as indicated by the distribution of data points in Fig. 3a and 3b), and therefore may have had increased probability of detecting a true correlational effect. It is however, important to note that although working memory was a significant predictor of proactive control engagement, it only predicted a modest amount of the variance, suggesting that proactive control engagement is not entirely dependent on working memory resources, but likely involves other cognitive skills such as metacognition (for consistent findings, see Chevalier, 2018; Chevalier & Blaye, 2016; Chevalier et al., 2015).

In turn, proactive control index of CTS predicted three of the four academic abilities including reasoning, math, and reading, while proactive control index of AX-CPT only predicted math and reading abilities. Sustaining prior information and using that to predict upcoming events and to prepare for an action is a control strategy that can be linked to a wide range of academic skills. For instance, using proactive control may increase verbal skills such as vocabulary and reading, since children are often required to maintain key information in their working memory while reading a passage in order to predict what may happen next in a narrative, or they may need to predict the meaning of an unknown vocabulary by inferring from context. Moreover, proactive control may be necessary when children are faced with math or reasoning problems, in which they may, for example, perform better when planning how to solve an equation beforehand (proactive control), rather than diving straight into the solving the first part of the equation that they encounter (reactive control). In addition, proactive control may be indexing a specific skill like self-regulated learning, in which learners plan their goal, set out strategies to monitor their performance, and reflect on their performance (Zimmerman, 1990). Given that self-regulated learning/strategies have been found to influence academic performance (Callan & Cleary, 2018; Cleary & Kitsantas, 2017; Daniel, Wang, & Berthelsen, 2016), it is plausible to assume that links among these three factors. Future studies should look into this relationship and examine the potentially mediating effect of proactive control on self-regulated learning and academic performance.

As working memory, which predicted proactive control engagement on each task and consistency across tasks, has been shown to be critical for the development of reading and math abilities (Bull & Lee, 2014; Gathercole, Alloway, Willis, & Adams, 2006; Nevo & Breznitz, 2011; St Clair-Thompson & Gathercole, 2006), one may wonder whether working memory accounts for the link between proactive control and academic abilities. Nevertheless, this is unlikely as the hierarchical regression model indicated that proactive control makes unique contributions to reading, math abilities (and near-significant effect for vocabulary) beyond the effects of working memory.

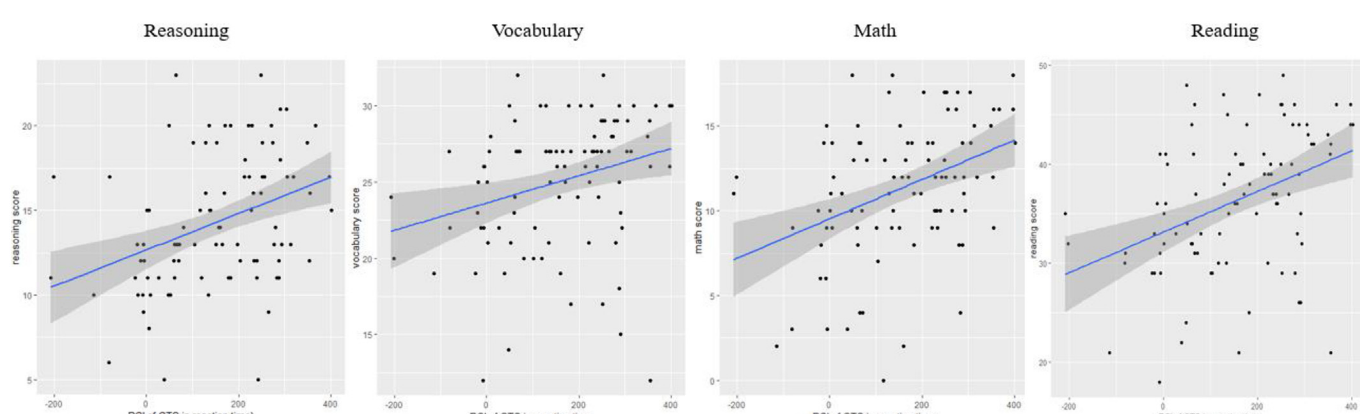

Fig. 4. Relationship between proactive control indices of CTS in reaction time and reasoning, vocabulary, math, and reading scores.

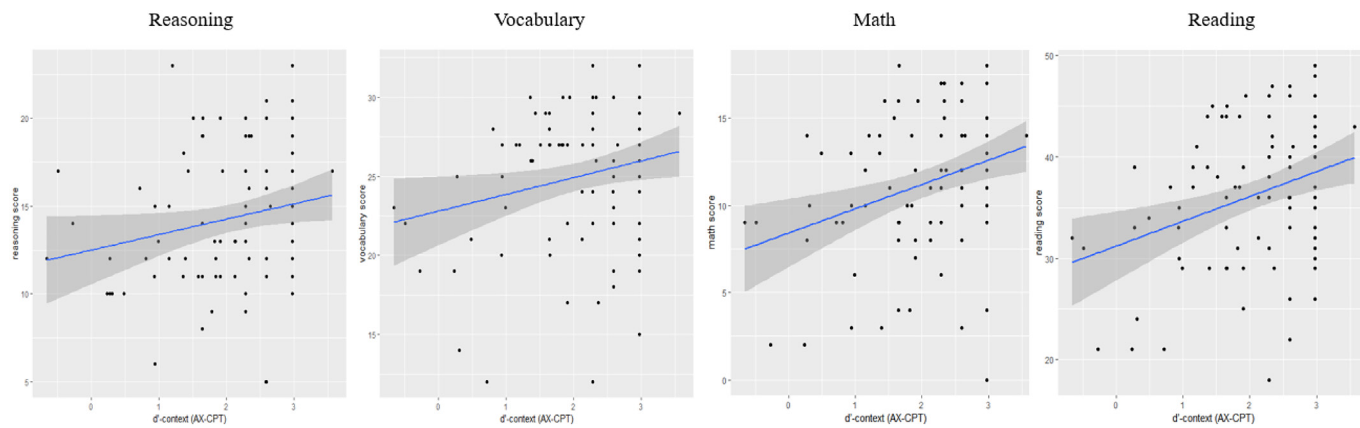

Fig. 5. Relationship between *d'*-context (AX-XPT) and reasoning, vocabulary, math, and reading scores.

Another related concern is whether proactive control is a separate construct from cognitive control processes such as inhibition and shifting. Given that the AX-CPT requires inhibiting a prepotent response, and CTS involves switching between two task sets, it is important to control for these factors when examining the unique effects of proactive control on academic achievements. Our results indicate that for reading and math abilities, proactive control indices were a significant predictor over the effects of inhibition and shifting, and there was also a near-significant effect on vocabulary scores. This adds a new perspective to the field by demonstrating that not only is growing efficiency of cognitive control important for developing one's academic performance, but also optimal adjustments of these executive resources are crucial for academic development.

At a more methodological level, our results are consistent with previous studies that found more reliable age-related differences in proactive control engagement for reaction time than accuracy in CTS (Chevalier et al., 2015; Doebel et al., 2017), as the proactive control index of CTS based on reaction time correlated better with *d'*-context on AX-CPT than proactive control index of CTS based on accuracy. In addition, since RTs typically yield more variability than accuracy and come with no ceiling effect—as shown in our data—proactive control index of CTS in reaction time showed much higher reliability than accuracy. In a similar vein, the reliability of *d'*-context was the highest among all three indices of proactive control in the AX-CPT task (*d'*-context, PBI in RTs, PBI in accuracy). Since high reliability increases the magnitude of correlations (Nunnally, 1978), it is not surprising that only proactive control indices that elicited the highest reliability and variance within each task correlated with one another. In a study which specifically tested the psychometric properties of proactive control measures in the AX-CPT task among adults, findings from multiple experiments with different participants consistently showed a high reliability of *d'*-context, when compared to PBI in reaction time and accuracy (with PBI in accuracy reflecting the lowest reliability) (Cooper, Gonthier, Barch, & Braver, 2017).

Taken together, this pattern of results highlights the importance of evaluating psychometric characteristics of a task by reporting variability and reliability of each cognitive measure, especially in studies that examine individual differences. Specifically, in the current study, only two indices of proactive control, proactive control index of CTS in reaction time (but not accuracy) and *d'*-context of AX-CPT (but not PBI in reaction time or accuracy), had acceptable reliability estimates within each task, and therefore, were evidenced to be a good measure to detect a true correlational effect. As such, future studies seeking to measure proactive control engagement with AX-CPT may consider using signal detection theory indices (e.g., *d'*-context). Moreover, proactive control index derived from CTS in reaction time, at least in the context of our study, seems to be a better and more reliable construct than accuracy, which is consistent with previous studies (Chevalier et al., 2015; Doebel et al., 2017). Finally, proactive control index of CTS seemed to be as reliable as the proactive control index of AX-CPT, as it showed stronger relationship with working memory capacity and also better predicted a wider range of academic abilities. These findings have important implications for researchers seeking to assess proactive control in children in future.

In sum, although children did use proactive control in both tasks, they showed only limited consistency in proactive control engagement across contexts. Working memory capacity seems to modulate the use of proactive control, and we found this to be true in two separate contexts. This study is in fact one of the first to show how proactive control can be used as a proxy to predict academic success in childhood. This ties into the discussion of how we can train children's cognitive control to improve their academic abilities (see Titz & Karbach, 2014; Johann & Karbach, in press). Previous work on cognitive training has mainly focused on *quantitative* increases in the children's ability to efficiently execute cognitive processes (i.e., better efficiency in task switching), however, our study highlights the importance of also promoting *qualitative* changes in the children's use of strategies in coordinating control, in order to better support children suffering from cognitive and academic deficits (Buttelmann & Karbach, 2017).

CRediT authorship contribution statement

Maki Kubota: Conceptualization, Validation, Formal analysis, Data curation, Writing - original draft, Writing - review & editing, Visualization.**Lauren V. Hadley:**Methodology, Software, Investigation, Writing - review & editing, Project administration.**Simone Schäffner:**Methodology, Software, Investigation, Writing - review & editing, Project administration.**Tanja Könen:**Conceptualization, Methodology, Writing - review & editing.**Julie-Anne Meaney:**Conceptualization, Methodology, Investigation.**Bonnie Auyeung:**Conceptualization, Methodology.**Candice C. Morey:**Conceptualization, Methodology, Writing - review & editing.**Julia Karbach:**Methodology, Writing - review & editing, Supervision, Project administration, Funding acquisition.**Nicolas Chevalier:**Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Acknowledgements

This work was supported by joint grants from the UK Economic and Social Research Council (ESRC, ES/N018877/1) and the German Research Foundation (DFG, KA 3216/2-1). We thank Priniehall Primary School, St David's R.C. Primary School, and Clovenstone Primary School for providing a test room, and the children and their parents for their participation.

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