

**Prior task experience increases five-year-old children's use of
proactive control: Behavioral and pupillometric evidence**

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Research Highlights

- We examined whether learning task knowledge from prior task experience can help 5-year-olds to use proactive control in different task-contexts.
- Prior task experience prompted 5-year-olds to respond more quickly and accurately and to show greater cue-related pupil dilation in a similarly-structured task with different stimuli.
- Directly encouraging the use of proactive control was not critical for promoting the subsequent use of proactive control.
- Prior task experience leads 5-year-olds to increase the use of proactive control endogenously in different task-contexts.

Abstract

Children engage cognitive control reactively when they encounter conflicts; however, they can also resolve conflicts proactively. Recent studies have begun to clarify the mechanisms that support the use of proactive control in children; nonetheless, sufficient knowledge has not been accumulated regarding these mechanisms. Using behavioral and pupillometric measures, we tested the novel possibility that five-year-old children ($N = 58$) learn to use proactive control via the acquisition of abstract task knowledge that captures regularities of the task. Participants were assigned to either a proactive training group or a control training group. In the proactive training group, participants engaged in a training phase where using proactive control was encouraged, followed by a test phase using different stimuli where both proactive and reactive control could be used. In the control training group, participants engaged in a training phase where both cognitive control strategies could be used, followed by a similarly-structured test phase using different stimuli. We demonstrated children in the control training group responded more quickly and accurately and showed greater cue-related pupil dilation in the test phase than in the training phase. However, there were no differences in response times, accuracies, and pupil dilation between the proactive and control training groups in the training and test phases. These findings suggest that prior task

experience, that goes beyond specific knowledge about the timing of task goal activation, can lead children to engage more proactive control endogenously, even if they are not directly encouraged to do so.

Key words: children, prior task experience, task knowledge, proactive control, pupillometry, near transfer

Introduction

Executive functions are known as the ability to regulate our thoughts and behavior towards a task goal and undergo pronounced developmental improvements during childhood (e.g., Best & Miller, 2010; Diamond, 2013; Zelazo et al., 2013). These developmental changes can be captured by qualitative changes in children's use of cognitive control strategies that vary according to the temporal dynamics of how children activate goal representations (e.g., Chatham, Frank, & Munakata, 2009; Munakata, Chatham, & Snyder, 2012). According to the Dual Mechanisms of Control theory (Braver, 2012), there are two distinct modes of engaging and operating cognitive control: i.e., proactive control and reactive control. Proactive control allows individuals to anticipate and prepare for upcoming events, thus engaging goal activation, to bias the cognitive system and prevent or minimize the effects of interference before it occurs; reactive control is mobilized later in response to unforeseen events to resolve interference after it occurs. Although children younger than five- and six-year-old mainly rely on reactive control, recent developmental studies have revealed that they are capable of engaging proactive control when encouraged to do so (e.g., Chevalier, Martis, Curran, & Munakata, 2015; Freier, Gupta, Badre, & Amso, 2021; Hadley, Acluche, & Chevalier, 2020; Jin, Auyeung, & Chevalier, 2020). The current study aimed to provide further evidence concerning the mechanisms underlying the increase in the use of proactive control in young children. Specifically, we tested whether five-year-old children learn to

use proactive control based on abstract task knowledge acquired from prior task experience.

Children's approach to cognitive control has been assessed through a variety of cognitive tasks such as the AX-CPT task (Chatham et al., 2009), the cued task-switching paradigm (Chevalier et al., 2015), and working memory tasks (Chevalier, Jame, Wiebe, Nelson, & Espy, 2014). In the cued task-switching paradigm, children are required to sort bivalent target stimuli (e.g., blue bear, blue car, red bear, and red car) according to a task cue that indicates either a color or shape matching rule. Children who engage proactive control are able to use the cue to prepare for the upcoming task, maintain the cue information, and process the target; in contrast, children who engage reactive control process the target first and then process the cue after the appearance of the target (Chevalier, Dauvier, & Blaye, 2018). Thus, engaging proactive control has been evidenced by faster response times to the target as compared to engaging reactive control (e.g., Chevalier et al., 2015). The evidence that proactive control leads to faster response times has been confirmed in adults using the AX-CPT task (Gonthier, Macnamara, Chow, Conway, & Braver, 2016). In addition, previous studies (e.g., Chatham et al., 2009; Chevalier et al., 2015; Chevalier, Meaney, Traut, & Munakata, 2020) used pupil dilation, a well-established index that is assumed to measure mental effort (e.g., Beatty, 1982). These studies find that proactive control engagement is shown by relatively greater cue-locked pupil dilation than engaging reactive control. After this, as in Chevalier et al. (2015), we treat this index for proactive control engagement. Using these measures,

previous developmental studies have demonstrated that a shift from relying only on reactive control to using either reactive or proactive control occurs around five and six years of age and that each of the two control strategies can be chosen depending on task environments (e.g., Blackwell & Munakata, 2014; Chevalier et al., 2015; Hadley et al., 2020; Lucenet & Blaye, 2014). For example, Chevalier et al. (2015) manipulated the timing of cue presentation, revealing that five-year-old children can engage proactive control when reactive control is made more difficult to access by removing the cue after target onset, although reactive control is used by default. Thus, the previous literature suggests that although five-year-old children may already have acquired, and use, proactive control as needed, they may have a higher threshold for engaging proactive control than older children.

Recent studies have begun to clarify the mechanisms supporting proactive control engagement in children. One potential driving factor is the development of working memory. Proactive control involves active maintenance of goal representations, which is also related to the development of working memory (Marcovitch, Boseovski, Knapp, & Kane, 2010; Yanaoka, Moriguchi, & Saito, 2020). Indeed, recent developmental studies have demonstrated that age-related increases in the use of proactive control are partly explained by the development of working memory performance (Gonthier, Zira, Colé, & Blaye, 2019; Kubota et al., 2020; Troller-Renfree, Buzzell, & Fox, 2020). For example, Blackwell and Munakata (2014) reported that children who engage proactive control in the task switching paradigm show faster response times in a working memory task in

which distracting activities are not required during a delay period. However, other potential factors remain under-specified. We propose and test the novel possibility that children learn to use proactive control via the acquisition of abstract task knowledge.

It has already been demonstrated that individuals acquire abstract task knowledge that captures the regularities of the task environment via instruction or through task experience (e.g., Bhandari & Badre, 2018; Botvinick, Niv, & Barto, 2009; Cole, Bagic, Kass, & Schneider, 2010; Collins & Frank, 2013; Gershman, Blei, & Niv, 2010). The current study focused on two types of task knowledge that are needed for solving a cognitive control task: knowledge of task representations and knowledge of task management. A large number of studies of cognitive control in adults and children have focused on knowledge of task representations, which includes a task goal and its associated stimulus–response mappings in a given context (e.g., Collins & Frank, 2013; Monsell, 2003; Munakata et al., 2012; Zelazo, 2015). For example, in the task-switching paradigm, activating a color (or shape) task goal biases processing toward that goal of sorting bivalent stimuli according to a color (or shape) dimension and allows the selection of appropriate stimulus-response mappings. Thus, the active maintenance of task representations can lead children to flexibly adjust to task switching and to generalize flexible behavior to novel stimuli (Kharitonova, Chien, Colunga, & Munakata, 2009; Kharitonova & Munakata, 2011; van Bers, Visser, & Raijmakers, 2014).

In contrast, much less work concerning cognitive control has highlighted knowledge of task management, which refers to knowledge about how we approach the process of

cognitive control. The specific aspect of knowledge of task management examined in the current study was knowledge about the timing of task goal activation, which differs between individuals engaging either proactive or reactive control. Proactive control requires activation of a task goal before the appearance of a bivalent stimulus; thus, it is critical to know when contextual cue information, which signals what a task goal needs to be activated, appears and disappears in the course of a trial. For instance, it is possible to use proactive control when cue contextual information always appears before target onset, and it is necessary to use proactive control when cue contextual information appears and then disappears before target onset (Chevalier et al., 2015). Furthermore, activating a task goal proactively is adaptive only when the task goal can be reliably predicted based on contextual cue information, thus it is also necessary to know about cue reliability in order to engaging proactive control efficiently (Chevalier et al., 2020). Therefore, as children become more knowledgeable about temporal structures of task environments and cue reliability, they can accumulate more task knowledge about the timing of task goal activation. We assume that this knowledge is essential in learning to engage proactive control. Recently, it has been established that adults learn when to activate a task goal in accordance with a task's temporal structure through the repetition of task experience (Bhandari & Badre, 2018, 2020; Bhandari, Badre, & Frank, 2017; Sabah, Meiran, & Dresbach, 2021). Bhandari and Badre (2018) highlighted two control 'policies' used in a working memory task, that is an input gating policy (first processing contextual information and then subsequently updating only items relevant to the context in working

memory) and an output gating policy (accumulating all information and then subsequently processing contextual information and selecting only items relevant to the context). The results indicated that adults positively or negatively transfer whichever working memory gating policy was required in a prior working memory task to a subsequent working memory task, independent of the stimulus-response mappings. It was also suggested that adults can learn a control ‘policy’ and reuse it in same-structured tasks that use different stimulus-response mappings, resulting in successful goal-directed behaviors in the different task environment. However, to the best of our knowledge, no developmental studies have examined the effect of learning abstract task knowledge on engaging cognitive control. Our primary purpose was to examine whether children learn to use proactive control through the acquisition of knowledge of task management (specifically, knowledge about the timing of task goal activation).

To verify this, we used the cued task-switching paradigm employed by Chevalier et al. (2015), in which participants were required to make either a color or shape judgement to a Christmas gift that appeared with task cues that specified which sorting rule to use. We used their two conditions that differ in the timing of cue disappearance to form the two participant groups (see Figure 1). Specifically, in the “Proactive Possible” condition, the cue was presented along with the gift and remained visible after the onset of the target, so that cue-based proactive preparation was possible but not necessary. In the “Proactive Encouraged” condition, early cue presentation was terminated before the onset of the target, thus making reactive control more challenging, and providing a strong

incentive to process the cue proactively. Using these two conditions, we formed the two participant groups (see Figure 1). In the proactive training group, children first experienced the “Proactive Encouraged” condition in a training phase, followed by the “Proactive Possible” condition with different stimuli in a test phase. In the control training group, children engaged the “Proactive Possible” condition in a training phase, followed by a second “Proactive Possible” condition in a test phase using different stimuli. In line with Chevalier et al. (2015), we selected five-year-old children as participants who one would expect to have started to use proactive control while relying primarily on reactive control (e.g., Gonthier et al., 2019). In addition to behavioral data, we collected pupillometry measurements to examine whether cue-related pupil dilation, a measure of proactive control engagement (Chevalier et al., 2015), would be larger when children had the opportunity to engage in proactive control.

(Insert Figure 1)

Through three planned contrasts, we tested three predictions. First, we predicted that children in the proactive training group would exhibit faster response times and larger pupil dilation in the training phase than children in the control training group, suggesting that the cognitive control mode employed during training would differ between children in the two groups; that is, proactive control would be engaged in the proactive training group and reactive control would be engaged in the control training group. Second, we expected that children in the control training group would respond more quickly and accurately in the test phase than in the training phase, i.e., positive transfer of a collective

body of task knowledge would occur. Such a result would not unequivocally indicate exactly what task knowledge was being transferred (i.e., knowledge of task representations and task management). Thus, we could not strongly predict whether positive transfer among children in the control training group would involve either a transition to engaging proactive control or a more efficient engagement of reactive control. There were therefore two conflicting predictions about pupil diameter in this group, and we examined whether pupil diameter would be larger in the test phase than in the training phase or not for children in the control training group. Finally, our last prediction was that in the test phase children in the proactive training group would exhibit faster response times and larger pupil dilation than children in the control training group. This prediction follows from the assumption that the experience of the “Proactive Encouraged” condition would help five-year-old children exert control more proactively in different task-contexts than that of the “Proactive Possible” condition, i.e., a positive transfer of knowledge of task management would occur. That is, this result would suggest knowledge of task management uniquely contribute to learn to engage proactive control.

We also expected that five-year-old children would respond more slowly and less accurately in switch trials than in no switch trials, indicating switch costs in response times and correct response rates (e.g., Cragg & Chevalier, 2012). However, previous pupillometry studies have reported inconsistent evidence for switch costs. Although studies with adults have demonstrated larger task-evoked pupillary responses for switch trials (e.g., da Silva Castanheira, LoParco, & Otto, 2020; van der Wel & Van

Steenbergen, 2018), Chevalier et al. (2015) failed to find such effects in children. Thus, it might be predicted in two conflicting ways: a) that larger pupil dilation would be seen in switch trials than non-switch trials, b) that there would be no difference in pupil dilation between switch and non-switch trials. Furthermore, it was difficult to make strong predictions regarding the relation between switch costs and the transfer of task knowledge. Thus, it might also be predicted in two conflicting ways: a) that negative/positive transfer of task knowledge would not be related to switch costs, b) that negative/positive transfer of task knowledge would reduce switch costs.

Method

Participants

Although the novelty of this study made it difficult to determine the appropriate sample size, following Chevalier et al. (2015) we decided to collect data from 40 five-year-old children per group. However, due to the COVID-19 pandemic, data collection had to be terminated before reaching the target sample size. Finally, 58 five-year-old children attending preschool in Japan, participated in this experiment and were randomly assigned to either the proactive training group ($N = 29$, $M = 66.2$ months, $SD = 3.41$ months, age range: 60–71 months) or the control training group ($N = 29$, $M = 66.8$ months, $SD = 2.98$ months, age range: 60–71 months). All the participants were native Japanese speakers, and they hailed from a predominantly middle-class socioeconomic background. This study was approved by the institutional review boards

of the University of Tokyo (19-334: The development of strategic skills in executive functions). We obtained written informed consent from the children's parents and verbal assent from the children prior to their participation.

Apparatus, design, and materials

The experiment used a laptop (Microsoft Surface Pro 4) and was programmed in PsychoPy (Peirce, 2007). All the participants were seated at a distance of 60 cm from the display, experienced eye tracking calibration, and then performed the two phases of the cued task-switching paradigm. In the proactive training group, children first experienced the “Proactive Encouraged” condition in the training phase, followed by a “Proactive Possible” condition with a different set of materials in the test phase. In the control training group, children first experienced the “Proactive Possible” condition in the training phase, followed by a second “Proactive Possible” condition with a different set of materials in the test phase. The tests were conducted individually in a quiet room at the preschool and required approximately thirty minutes to complete the two phases.

Following Chevalier et al. (2015), the cued task-switching paradigm was adapted for five-year-old children. In the “Santa Claus Game”, children were asked to help Santa Claus sort a set of gifts, either by color or shape. As shown in Figure 1, we used different sets of 8×8 cm targets using two dimensions in the training and test phases [Color: blue and pink (Set A), green and yellow (Set B); Shape: bear and car (Set A), airplane and doll (Set B)], and were presented with surrounding color circles [blue (Set A), black (Set B)], on which task cues were displayed. As for the task cues, 12 gray geometrical shapes

signaled that the sorting rule was denoted by shape, and 12 colorful patches signaled the sorting rule was denoted by color. We also prepared different sets of task cues in the training and test phases (see Figure 1). To measure pupillometry data accurately, all the cue and targets were roughly matched in complexity (similar cartoon design) and luminance (similar color brightness calculated based on the RGB model). To facilitate responding four 2×2 cm unidimensional response pictures (e.g., a bear, a red patch, a car, and a blue patch) were constantly presented in a horizontal row at the bottom of the screen. The same pictures were attached to each corresponding key on a numerical keypad, and children were asked to place four fingers (index and middle fingers of each hand) and press one of keys according to the relevant rule.

(Insert Figure 1)

Procedure

On each trial of the “Santa Claus Game”, a fixation cross within a color circle was displayed at the center of the screen for 1000 to 1200 msec, followed by a brown wrapped gift box within the same color circle on which the task cue (i.e., 12 gray geometrical shapes or 12 colorful patches) was presented for 1500 msec. After that, a gift within the same color circle replaced the gift box and remained, until children responded or for up to 10 seconds. Critically, the termination of the cue presented on the color circle was manipulated. In the “Proactive Encouraged” condition, the task cue changed to be an invalid cue (i.e., 12 brown circles) at the time of the target onset. Thus, children were encouraged to decide which rule they would follow based on the task cue in advance and

discouraged from only processing the target surrounded by the invalid cue. In contrast, in the “Proactive Possible” condition, the task cue remained on the color circle, even after the appearance of the target. Thus, though it was possible for children to decide which rule to follow based on a task cue in advance, it was not necessary because they could reactively process the task cue which surrounded the target.

The “Santa Claus Game” comprised practice, training, and test phases. In the practice phase, children were first instructed to help Santa Clause sort bidimensional gifts according to either a color or shape rule. The experimenter demonstrated how to sort and respond to one of the rules with a correct key twice, followed by four practice trials completed by the children. The experimenter then demonstrated sorting by the other rule twice and children performed four practice trials. The order of rule practice was counterbalanced across participants. Following this, children were presented with 16 practice trials in a pseudorandom sequence, including 8 color trials and 8 shape trials. During the practice phase, the experimenter gave guidance and feedback in response to children’s performance.

In the training phase, children in the proactive training group experienced the “Proactive Encouraged” condition and those in the control training group experienced the “Proactive Possible” condition. The training phase comprised 2 sets of 25 trials separated by a short break; each set consisted of a start trial (not included in the analysis), 12 switch trials, and 12 no switch trials. Due to time constraints, we implemented a smaller number of trials than employed by Chevalier et al. (2015) (i.e., 50 rather than 63 trials). It is

important to note that in the test phase the set of materials (i.e., color circle, cue, and target) was different from the ones used in the training phase. Thus, after the training phase, children were introduced to novel stimuli and then presented with four practice trials for the color and shape rules, respectively. In the test phase children in both groups engaged in the “Proactive Possible” condition, in which the number of trials and the proportion of switch trials were the same as in the training phase. During the training and test phases, children were provided with no feedback.

Data recording and processing

Behavioral data. The dependent measures were response times and correct response rates in the cued task-switching paradigm. Error trials, response times more than 3SD away from the group mean, or response times less than 200 msec were excluded from the analyses of response times (1.4 % of correct responses).

Pupil dilation data. Pupil dilation was recorded at a 60-Hz sampling rate using an eye-tracking device (Tobii Pro Nano; Tobii Technology K.K.). To process gaze and pupillometric data, GazeParser (Sogo, 2013), an open-source library for video-based eye tracking, was used in conjunction with PsychoPy. Using the five points procedure, eye tracking calibration was achieved. Given that the pupil size peaks about 1000 msec after the relevant event onset in adults and children (Chevalier et al., 2015; Wierda, van Rijn, Taatgen, & Martens, 2012), data were segmented into an epoch of 1000 msec duration to measure cue-related pupil dilation, which occurs between 1000 msec and 2000 msec after the cue presentation. We also defined 200 msec immediately before the cue-presentation

as a baseline period and the dependent measure was the percentage change from this baseline so as to control for individual differences in baseline pupil diameter. Following Chevalier et al. (2015), we term the time period from 1000 msec to 1500 msec the ‘early-window’ and that from 1500 msec to 2000 msec the ‘late-window’. We assume that changes in pupil dilation during the late-window are a more sensitive measure of engaging proactive control. This is evidenced by Chevalier et al.’s (2015) finding that children who engaged proactive control exhibited greater pupil dilation than those who engaged reactive control only during the late-window and not the early-window.

Measurements for correct response trials were averaged into 16.7-msec consecutive bins. Trials that contained valid data points for less than half of the segment were discarded. Furthermore, we calculated SD based on a rolling average of samples within each trial, and pupil dilations more than 3SD away from the mean were excluded from the analyses of pupillometry data. Consistent with Chevalier et al. (2015), the pupillometry data from participants with at least 10 useable trials per condition were included in the final analyses. On average, there were 36 useable trials per condition among the five-year-old participants ($n = 46$) in the current study.

Data analysis

In the cued task-switching paradigm, we measured response times, correct response rates, and pupil dilation as dependent variables. Using the lme4 package (Bates, Maechler, Bolker, & Walker, 2015) in the R system (R Core Team, 2013), we conducted regression analyses with generalized linear mixed-models (GLMMs) for

response times and pupil dilation for each window separately. We also conducted a mixed-model logistic regression analysis for correct response rates. The model included the factors of training group (proactive training group = 1, control training group = -1), task history (test phase = 1, training phase = -1), trial type (switch trial = 1, no switch trial = -1), their two-way interactions (training group \times task history, training group \times trial type, and task history \times trial type), and their three-way interaction as fixed effects. As random factors, random intercepts for participants were included in the models for response times and correct response rates, those for participants and trials for each set were included in the model for pupil dilation. The predictors were tested by comparing the fit of the full model with the fit of the model missing each predictor; the focal comparison being the model containing the two-way interaction between training group and task history versus the model without this interaction. The significance of each predictor was represented by the coefficient, chi-square, and p-value resulting from the likelihood ratio test.

In terms of the two-way interaction between training group and task history, we were interested in three planned comparisons that mirrored our three hypotheses (see above). First, we contrasted the performance in the training phase of children in the proactive training group with those in the control training group; this tells us whether the cognitive control mode employed during training differed between the two training groups, i.e., the engagement of proactive control in the proactive training group and the engagement of reactive control in the control training group. Second, we compared the

performance of just the children in the control training group across the training and test phases, which tells us whether the collective body of task knowledge allows for positive transfer even in the absence of direct encouragement towards proactive control. Third, we contrasted the test phase performance of children in the proactive training group with that of children in the control training group, which tells us whether five-year-old children can exert control more proactively with a novel set of stimuli after the experience of the “Proactive Encouraged” condition.

Results

Behavioral analyses.

Response times. Figure 2 depicts response times for each condition and Table 1 summarizes the results of the analysis model. Our planned pairwise comparisons revealed the following three findings linked to our predictions. First, in the training phase children in the proactive training group tended to respond faster ($M = 2185$ msec) than children in the control training group ($M = 2485$ msec) ($b = -0.13$, $t = -1.78$, $p = .079$). Second, children in the control training group responded more quickly in the test phase ($M = 2240$ msec) than in the training phase ($M = 2485$ msec) ($b = -0.06$, $t = -2.89$, $p = .004$). As an additional exploratory pairwise comparison, it was revealed that children in the proactive training group tended to respond slower in the test phase ($M = 2260$ msec) than in the training phase ($M = 2185$ msec), but the difference did not reach significance ($b = 0.04$, $t = 1.66$, $p = .098$). Third, there were no significant differences between the performance in

the test phase of the control training group ($M = 2240$ msec) and proactive training group ($M = 2260$ msec) ($b = 0.02$, $t = 0.34$, $p = .739$).

Our analysis also showed a significant main effect of trial type, confirming that children experienced a switch cost in response times (switch trial: $M = 2360$ msec, non-switch trial: $M = 2230$ msec). However, there were no significant interactions involving the trial type factor (see Table 1).

In a post-hoc analysis we further examined whether the interaction between task history and training group was moderated by the number of trials that participants had experienced in either the test or training phases. Therefore, we conducted an exploratory mixed-effect regression analysis, in which the factors of training group, task history, trial type, trial number, their two-way interactions, their three-way interactions, and their four-way interaction were included as fixed effects. The factor of trial number was treated as a continuous variable. As random factors, random intercepts for participants were included in the model. The exploratory analysis showed a significant main effect of trial number ($b = -0.03$, $t = -2.34$, $\chi^2 = 5.47$, $p = .019$) and a three-way interaction with trial number, training group, and task history ($b = 0.02$, $t = 2.11$, $\chi^2 = 4.53$, $df = 1$, $p = .033$). Following our structure of principled pairwise comparisons¹, we first found that in the training phase children in the proactive training group responded faster than children in the control training group in later trials ($b = -0.05$, $t = -2.06$, $p = .043$), but not in earlier trials ($b = -0.01$, $t = -1.32$, $p = .190$). Second, children in the control training group responded more quickly in the test phase than in the training phase

in both earlier trials ($b = -0.11$, $t = -3.60$, $p < .001$) and later trials ($b = -0.12$, $t = -3.69$, $p < .001$). Third, there were no significant group differences between the proactive and control training group in either the earlier ($b = -0.01$, $t = -0.18$, $p = .854$) or the later trials ($b = 0.06$, $t = 0.82$, $p = .416$) of the test phase.

(Insert Table 1 and Figure 2)

Correct response rates. Figure 3 depicts correct response rates for each condition and Table 2 summarizes the results of the analysis model. Our structure of principled pairwise comparisons revealed the following three findings. First, the correct response rates in the training phase did not differ significantly between children in the control training group ($M = 71.9\%$) and the proactive training group ($M = 72.5\%$) ($b = -0.001$, $t = -0.007$, $p = .995$). Second, children in the control training group responded significantly more accurately in the test phase ($M = 80.9\%$) than in the training phase ($M = 71.9\%$) ($b = 0.33$, $z = 6.31$, $p < .001$). As an additional exploratory pairwise comparison, it was revealed that children in the proactive training group responded also more accurately in the test phase ($M = 85.1\%$) than in the training phase ($M = 72.5\%$) ($b = 0.49$, $t = 9.04$, $p < .001$). Third, there were no significant differences between the performance in the test phase of the control training group ($M = 80.9\%$) and the proactive training group ($M = 85.1\%$) ($b = 0.18$, $t = 0.89$, $p = .373$).

We also found a significant main effect of trial type, reflecting a switch cost on correct response rates (switch trial: $M = 79.3\%$, non-switch trial: $M = 82.5\%$). There were no significant interactions with the factor of trial type (see Table 2).

(Insert Table 2 and Figure 3)

Pupillometric analyses.

As noted above, late-window pupil dilation (1500-2000 msec) is a more sensitive index of proactive control than early-window pupil dilation (1000-1500 msec), thus we report results with a focus on late-window pupil dilation as follows; results for early-window pupil dilation are described in supplementary information. Figure 4 depicts percentage change in pupil dilation from baseline pupil diameter in each condition and Table 3 summarizes the results of the analysis model. In terms of the first planned pairwise comparison of the group differences in the training phase, changes in late-window pupil dilation did not differ significantly between the two groups ($b = 0.0055$, $t = 1.51$, $p = .139$) (Proactive training group: 2.57%; Control training group: 1.40%). The second planned pairwise comparison between the training and test phases in the control training group revealed important findings. During the later-window, changes in pupil dilation was significantly greater in the test phase (1.88%) than in the training phase (1.40%) ($b = 0.0023$, $t = 7.10$, $p < .001$). As an additional exploratory pairwise comparison, it was revealed that children in the proactive training group did not show changes in late-window pupil dilation across the training (2.57%) and the test phases (2.63%) ($b = -0.0003$, $t = -1.57$, $p = .158$). Finally, the third planned pairwise comparison of group differences in the test phase also demonstrated that change in late-window pupil dilation was not significantly affected by group ($b = 0.0026$, $t = 0.72$, $p = .475$) (Proactive training group: 2.63%; Control training group: 1.88%).

Our analyses revealed that the main effect of trial type was significant (see Table 3), reflecting a switch cost on late-window pupil dilation (switch trials: 2.18%; no switch trials: 2.03%). There was also a significant interaction between task history and trial type. During the late-window there was no significant effect of trial type in the training phase ($b = 0.0004$, $t = 1.27$, $p = .203$) (switch trials: 2.02%; no switch trials: 1.95%) but in the test phase, pupil dilation was significantly greater in switch trials than in no switch trials ($b = 0.0018$, $t = 5.88$, $p < .001$) (switch trials: 2.33%; no switch trials: 2.11%).

For late-window pupil dilation, we conducted two more post-hoc analyses. First, we examined whether the interaction between task history and training group differed as a function of the number of trials participants had experienced in each phase of the experiment. As in the post-hoc trial-level analysis for response times, we conducted an exploratory mixed-effect regression analysis, which included the factors of training group, task history, trial type, trial number, their two-way interactions, their three-way interactions, and their four-way interaction as fixed effects. As random factors, random intercepts for participants and trials were included in the model for pupil dilation. The exploratory analyses showed a significant three-way interaction between training group, task history, and trial number ($b = -0.0017$, $t = -10.70$, $\chi^2 = 114.33$, $p < .001$). We conducted our planned pairwise comparisons and obtained the following three findings. First, in the training phase children in the proactive training group showed larger late-window pupil dilation than children in the control training group in later trials ($b = 0.0097$, $t = 2.66$, $p = .011$), but not in earlier trials ($b = 0.0019$, $t = 0.52$, $p = .602$) (see

Figure 5a). Second, children in the control training group showed larger late-window pupil dilation in the test phase compared to the training phase in later trials ($b = 0.0046$, $t = 9.78$, $p < .001$), but not in earlier trials ($b = -0.0001$, $t = -0.20$, $p = .843$) (see Figure 5b). Third, there were no significant group differences between the proactive and control training group in either the earlier ($b = 0.0037$, $t = 1.01$, $p = .318$) or later trials ($b = 0.0021$, $t = 0.58$, $p = .564$) of the test phase (see Figure 5c).

In our second post-hoc analysis we calculated the average change in each individual's late-window pupil dilation and response times across the training and test phases and correlated these two change scores. Contrary to expectations these correlations were not significant in both the proactive training group ($r(22) = -.24$, $p = .256$) and the control training group ($r(20) = -.13$, $p = .570$).

(Insert Table 3 and Figure 4, 5)

Discussion

After the age of five or six years, children increasingly engage proactive control. However, five-year-old children mainly rely on using reactive control and have a higher threshold for engaging proactive control. Although it has been demonstrated that working memory development is closely related to increases in the use of proactive control in children, few studies have explored other potential factors supporting proactive control development. Combining behavioral and pupillometric evidence, the current study examined the novel possibility that learning task knowledge from prior experience,

especially knowledge about the timing of task goal activation, can help children to use proactive control in different task-contexts.

The use of “Proactive Encouraged’ and “Proactive Possible” conditions in a cued task-switching paradigm in the training phase of the current study allows for a direct comparison with the findings of Chevalier et al. (2015). However, somewhat in contrast to that previous work we observed relatively weak evidence that termination of early cue presentation before target onset encourages five-year-old children to engage proactive control. Descriptive statistics showed that in this training phase children in the proactive training group did respond faster and showed enlarged late-window pupil dilation than those in the control training group, but these comparisons did not reach significance. Nevertheless, the general pattern of results from the current study is in line with that of Chevalier et al. (2015). Indeed, our post hoc trial-level analysis showed that in the training phase children in the proactive training group responded significantly faster and showed significantly larger late-window pupil dilation “in later trials” than those in the control training group. Furthermore, we found clear group differences between the training and test phases of our design. Children in the control training group responded more quickly and accurately and exhibited enlarged late-window pupil dilation in the test phase than in the training phase; in contrast, children in the proactive training group did not show either faster response times or greater cue-related late-window pupil dilation in the test phase than the training phase.

These findings suggest that altering the period of cue presentation across the two different conditions of the training phase did have a meaningful effect. Though limited to later trials, the expected group differences were observed, suggesting that children in the proactive training group engaged cognitive control more proactively in later trials of the training phase than those in the control training group. The results from the control training group suggest that children did engage cognitive control more proactively in the test phase than in the training phase as evidenced by faster response times and greater cue-related pupil dilation (especially during the late-window) (e.g., Chevalier et al., 2015, 2020). In contrast, we can infer that children in the proactive training group engaged proactive control in the training phase where they were encouraged to use the cue to prepare for the target presentation, and continued to engage proactive control in the test phase where they were not encouraged to do so, resulting in no observed difference in response times and pupil dilation between the two phases. In other words, it is possible that children in the control training group had more room to engage cognitive control more proactively when it came to the test phase than children in the proactive training group. Having said this, there are two caveats to this interpretation of these findings. Given that group differences in the key dependent measures extracted from the training phase were not significant across all trials, we cannot state for certain that children in the control training group undergo a qualitative change in cognitive control mode from engaging reactive control in the training phase to engaging proactive control in the test phase. Furthermore, although it has been assumed that response times and late-window

pupil dilation are two key indices of proactive control, and although the analyses of these two dependent measures produced very similar patterns of results, they were not significantly related between participants.

An important point to note is that, contrary to our prediction, there were no reliable differences in response times, correct rates, and extent of pupil dilation shown by the proactive and control training groups in the test phase. This finding suggests that children engage proactive control in the test phase, regardless of whether they are directly encouraged to engage proactive control in the training phase or not. Our prediction was that learning knowledge of task management through the prior experience of the “Proactive Encouraged” condition in the training phase would lead to children in the proactive training group engaging proactive control in the subsequent “Proactive Possible” condition with different stimuli. However, given the results from the control training group, directly learning the timing of task goal activation when encouraged to use proactive control does not seem to be critical for promoting the use of proactive control. Through the experience of the “Proactive Possible” condition in the training phase, children in the control training group would have been able to learn aspects of task knowledge such as task representations and task management. Given that this group showed positive transfer across training and test phases that employed different stimuli, such task knowledge must be independent from any specific stimulus-response mappings shaped in the training phase.

Specifically, we assume that knowledge of task management and task representations independently contribute to individuals engaging proactive control. Given that proactive control is adaptive when upcoming events or task demands can be reliably predicted (e.g., Braver, 2012), one can infer that children in the control training group would notice a fixed order between cue and target stimuli and learn the predictable structure of cue-target presentations in the training phase, which might help them to engage proactive control and to learn task knowledge about the timing of task goal activation. In addition, learning more about task goals, which is an aspect of knowledge of task representations, might also help children adapt to a same-structured task with different stimulus-response mappings swiftly, and so partly contribute to them engaging proactive control in the test phase. It can therefore be inferred that the collective body of task knowledge, and not just specific experience of using any particular cognitive control strategy, would lead five-year-old children to engage cognitive control more proactively, even when they are not being directly encouraged to do so.

It is worth considering whether the practice participants experienced during the training phase of the study may have affected the results we obtained. One may argue that the faster responses and higher accuracy in the test phase than in the training phase for children in the control training group are due to this kind of practice effect, that is, reflecting a quantitative increase in the efficiency of reactive control rather than a qualitative shift in control mode from reactive to proactive control. However, increased efficiency in reactive control should require less mental effort, and, thus, should lead to

reduced late-window pupil dilation. The fact is that the faster responses and higher accuracy were accompanied by larger late-window pupil dilation in the test phase in the control training group. It is therefore unlikely that our data can be explained by practice leading to quantitative improvements in reactive control. Nevertheless, we cannot rule out the possibility that children might have a lower threshold for engaging proactive control in the test phase based on their higher efficiency in the cued task-switching performance (in other words, proactive control could have become easier to implement due to general practice effects associated with improved performance on the task-switching paradigm). In this case, it would be the practice-driven increased efficiency of task performance rather than the transfer of knowledge of task management that promotes proactive control in the present experiment. Although the two possibilities are not mutually exclusive, future work might usefully conduct a study that can distinguish the influences of these factors.

It remains the case, however, that this study provides the first evidence – from both behavioral and pupillometric results – that prior task experience increases 5-year-old children’s use of proactive control. However, these findings are not inconsistent with previous accounts of metacognitive coordination of cognitive control (Chevalier et al., 2015). That study argued that the bias toward reactive control among five-year-old children results from either a higher threshold for engaging proactive control or a failure to determine when it is appropriate to do so. The current findings suggest that prior task experience either lowers the threshold for engaging proactive control in five-year-old

children or helps them to determine when to use such control. Taking the metacognitive coordination account (Chevalier et al., 2015) into consideration, one can assume another type of task knowledge about the result of using cognitive control strategies, which is children's evaluation about how beneficial it is to use a particular cognitive control strategy in a given context. In the current study, children would learn such meta-task knowledge about the result of using a proactive control strategy (e.g., it is advantageous to use proactive control in the "Proactive Encouraged" condition) as well as other forms of task knowledge (e.g., task representations, task management), both of which would help them engage proactive control. Although our experimental design did not allow us to map each result to different types of task knowledge, future research should address this issue.

The current study also adds to the existing literature on the effects of engaging proactive control on the switch costs observed in a cued task-switching paradigm. One might well expect that engaging proactive control would reduce switch costs, that is, being more beneficial to performance on task switch trials than repeat trials. This expectation is in line with task-switching studies showing that any advance preparation in response to an increase in cue-stimulus intervals leads to a reduction in switch costs (e.g., Meiran 2000; Monsell & Mizon, 2006; see Kiesel et al., 2010; Monsell, 2003 for reviews). However, we did not observe any significant interactions involving the factor of trial type in the analyses of either response times or correct response rates. Although unexpected at first sight, these findings with children are in fact consistent with those of

Chevalier et al. (2015). Following Chevalier et al. (2015), we interpret this as evidence that proactive control is as helpful to children in determining the relevant task on no-switch trials as it is on switch trials. Indeed, previous developmental studies have shown that the most critical challenge of the cued task-switching paradigm for young children is to identify the relevant task based on cue information under conditions of task uncertainty (Chevalier & Blaye, 2018; Chevalier, Huber, Wiebe, & Espy, 2013; Karbach & Kray, 2007). Advance preparation may therefore help young children to identify the relevant task early, thereby facilitating target processing, and doing so equally on both no-switch and switch trials.

At the same time, we also found greater cue-related pupil dilation on switch trials than on no switch trials, particularly in the test phase. Although we did not make any strong predictions about the effect of trial type on this dependent variable, this result is consistent with recent evidence from adults (da Silva Castanheira et al., 2020; Rondeel, Van Steenbergen, Holland, & van Knippenberg, 2015; van der Wel & Van Steenbergen, 2018) also demonstrating larger task-evoked pupillary responses for switch trials. Strikingly, our measure of late-window pupil dilation, which occurred between 1500 msec and 2000 msec after the cue presentation, was related to cue processing, and not response to a target. Thus, it is possible that children require more engagement of goal activation when the cue changes from the immediately preceding trial than when it repeats, leading to advanced preparation for sorting the target according to the switched rule. However, given engaging proactive control did not interact with switch costs in

response times and correct response rates, larger late-window pupil dilation in switch trials did not lead to a reduction of switch costs in the behavioral measures.

Our findings also suggest a novel perspective on previous developmental research demonstrating near transfer effects of executive function training in preschoolers (e.g., Espinet, Anderson, & Zelazo, 2013; Thorell, Lindqvist, Bergman Nutley, Bohlin, & Klinberg, 2009; van Bers, Visser, & Raijmakers, 2014; van Bers, van Schijndel, Visser, & Raijmakers, 2020). This previous work has shown that various types of training on an executive function task can help children improve their performance on a subsequent same-structured executive function task with different stimuli. These near transfer effects have been evidenced by the improvement of response times and/or accuracy rates. It is worth noting that we examined near transfer effects using measures of pupil dilation as well as such behavioral measures. Including this pupillometry measure allowed us to scrutinize near transfer effects from the viewpoint of cognitive control modes. It was shown that children in the control group showed positive near transfer effects on all of these measures. This suggests that the near transfer effects are likely to be accompanied by the increased use of proactive control.

Furthermore, our findings align with recent developmental studies concerning adaptive control (Gonthier, Ambrosi, & Blaye, 2021; Gonthier & Blaye, 2021). Gonthier et al. (2021) provided evidence for list-wide proportion congruency effects in preschoolers using the Stoop task and the Flanker task. They manipulated the proportion of congruent items in a block and demonstrated that children showed smaller interference

effects in a mostly conflicting block compared to a mostly congruent block. This pattern was not only observed for the manipulated items (i.e., 75% congruent in the mostly congruent block vs. 25% congruent in the mostly conflicting block) but also transferred to different items that were 50% congruent in the both blocks, suggesting that learning task knowledge about the regularities of conflicts in a block may encourage children to engage proactive control. It is important to note that this learning-based proactive control is likely to be implicit, given the evidence that the list-wide proportion congruency effects were not modulated by age. In contrast, Niebaum, Chevalier, Guild, and Munakata (2020) identified a subset of 5-year-olds with “explicit” knowledge about how proactive and reactive control demands varied between task components. They asked children to select either a card deck requiring proactive control or another card deck requiring reactive control in the task-switching paradigm. Their important finding was that about half of 5-year-olds who reported the differences between card decks preferentially selected the reactive option that enabled their preferred control mode and higher accuracy. To integrate these findings, further studies are needed to address whether learned task knowledge about engaging cognitive control is explicit or implicit.

The current study also has some potential limitations that can inform recommendations for other future studies. First, the expected group differences in performance in the training phase between the proactive and control training groups were not significant across all trials, but they were significant in later trials according to a post-hoc analysis. These findings are not perfectly consistent with previous work (Chevalier et

al., 2015). This may partly reflect differences in experimental design. Chevalier et al. (2015) drew their comparison between the performance of the “Proactive Encouraged” and “Proactive Possible” conditions within participants, whereas we made the comparison between participants. It is possible that manipulating the period of cue presentation is effective only within participants. This possibility is supported by some evidence in adults, suggesting that manipulating the cue-interval is effective when it occurs within participants, but not when it occurs between participants (Altmann, 2004a, 2004b). Furthermore, the number of participants and trials in the current study was smaller (29 children and 50 trials per condition) compared to that in Chevalier et al. (2015; 36 children and 63 trials per condition). This lack of power is likely to be reflected in the results of the post-hoc analysis as a function of trial number. Thus, future studies with a larger number of participants and trials may be needed to fully confirm whether the disappearance of a task cue before the target onset encourages five-year-old children to reliably engage proactive control. Any such future work using a between-participants design could incorporate a further improvement not implemented in this study. Specifically, we did not match the proactive training group and the control training group for their use of proactive or reactive control prior to the presentation of the training phase. Given that a developmental shift from relying on reactive control to proactive control occurs at around five to six years of age (e.g., Gonthier et al., 2019; Lucenet & Blaye, 2014), random variation might have caused the two training groups in the current study to have a different default profile of engaging proactive/reactive control. This concern is

substantially allayed by the fact that the post-hoc analysis of trial number effects on response times (see supplementary materials) showed that the two groups were matched in the earlier trials of the training phase with faster responses in the proactive training group emerging only in the later trials in this phase. Nevertheless, setting a common “Proactive Possible” condition as a pretest before the training phase would be a potential way of explicitly matching baseline approaches to cognitive control in the two training groups.

Another suggestion for future work follows from the fact that we did not find the expected group differences in performance in the test phase. We believe that this reflects the learning of task knowledge by children in the control training group, leading to them employing proactive control at test. However, future work is needed to determine whether more specific training of proactive control per se, of the kind experienced by our proactive training group, also leads to increased use of proactive control by children in a different task-context. Given that previous studies (e.g., Bhandari & Badre, 2018) have provided solid evidence that adults learn knowledge of task management, future studies need to address the issue of developmental changes from learning a collective body of knowledge to learning more specific knowledge.

Finally, despite the fact that working memory development is another supportive factor of proactive control engagement (e.g., Gonthier et al., 2019; Kubota et al., 2020), we did not measure its potential influence in this work. One might expect that learning task knowledge would play a compensatory role among children with low working

memory, helping them engage cognitive control more proactively. One would also need to maintain task-relevant information in working memory to learn it as long-term knowledge, thus working memory capacity might be a basis for learning task knowledge efficiently. Future studies should therefore examine the potential combined effects of working memory and learning task knowledge on the engagement of proactive control in children.

Despite these limitations, the current study provides a set of novel findings. Prior task experience helps five-year-old children to respond more accurately, quickly, and appropriately in different task-contexts. This suggests that prior task experience, leading potentially to the acquisition of a collective body of task knowledge, prompts children to engage more in proactive control endogenously, even if they are not directly encouraged to do so. We believe that our findings therefore offer important insights into the potential mechanisms behind the development of proactive control engagement in young children.

Footnote

1. Simple slopes between trial number and either training group or task history were calculated at 1 standard deviation above the mean of the trial number (earlier trials) and at 1 standard deviation below the mean of the trial number (later trials).

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Table 1. Results of Regression Analysis for Response Times

	Estimate	<i>SE</i>	<i>t</i>	χ^2	Pr ($>\chi^2$)
(Intercept)	2.30	.07	32.51		
Task history	-.04	.02	-2.60	6.75	.010
Training group	-.05	.07	-0.75	0.55	.457
Trial type	.06	.02	4.12	16.90	<.001
Task history \times Training group	.08	.02	4.92	24.15	<.001
Task history \times Trial type	.02	.02	1.00	1.00	.317
Training group \times Trial type	-.02	.02	-1.53	2.34	.126
Task history \times Training group \times Trial type	-.003	.02	-0.19	0.04	.847

Table 2. Results of Regression Analysis for Correct Response Rates

	Estimate	<i>SE</i>	<i>z</i>	χ^2	Pr ($>\chi^2$)
(Intercept)	1.78	.20	9.04		
Task history	.40	.04	10.83	120.10	<.001
Training group	.09	.20	0.45	0.20	.653
Trial type	-.13	.04	-3.53	12.35	<.001
Task history \times Training group	.09	.04	2.43	5.84	.016
Task history \times Trial type	-.04	.04	-0.98	0.95	.331
Training group \times Trial type	.003	.04	0.09	0.01	.928
Task history \times Training group \times Trial type	.05	.04	-1.26	1.58	.209

Table 3. Results of Regression Analysis for Percentage Change in Pupil Dilation

Late-window					
	Estimate	<i>SE</i>	<i>t</i>	χ^2	Pr ($>\chi^2$)
(Intercept)	1.02	.004	269.91		
Task history	.0009	.0002	4.02	16.19	<.001
Training group	.0040	.0036	1.12	1.23	.268
Trial type	.0011	.0002	4.76	22.66	<.001
Task history \times Training group	-.0014	.0002	-6.71	44.97	<.001
Task history \times Trial type	.0007	.0002	3.29	10.81	.001
Training group \times Trial type	.0001	.0002	0.33	0.11	.739
Task history \times Training group \times Trial type	.000001	.0002	0.004	0.0013	.997

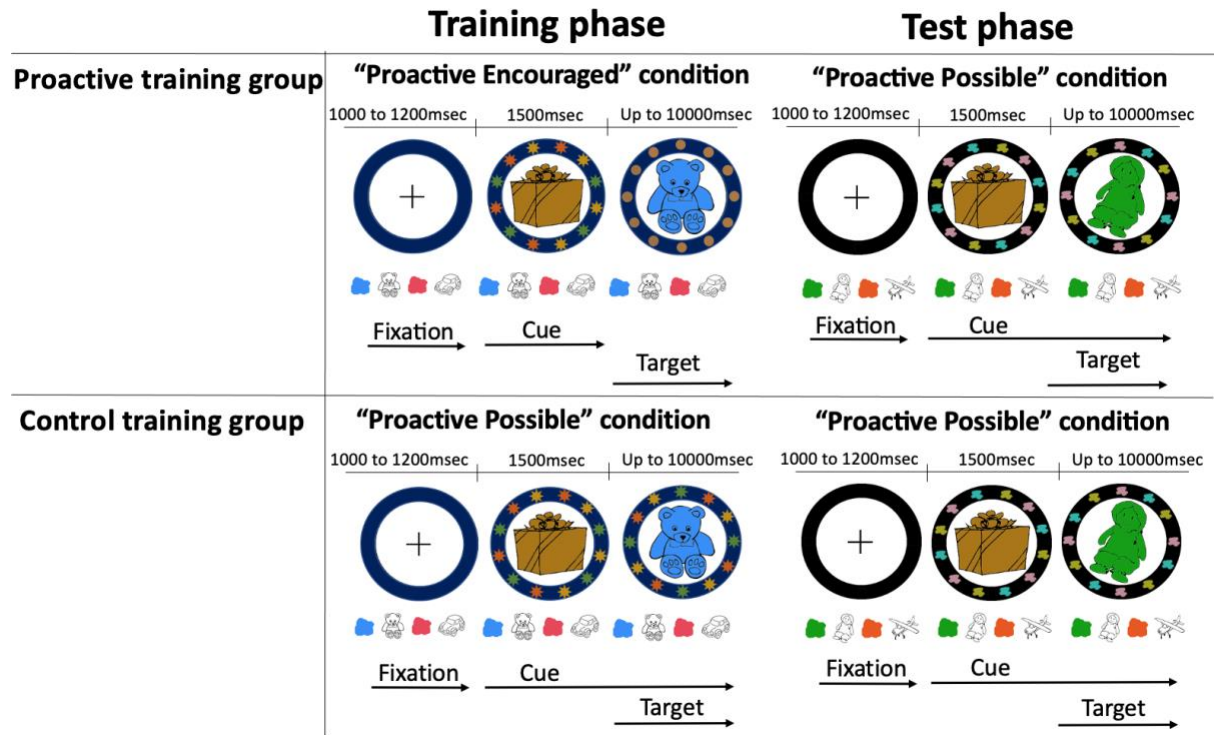


Figure 1. Illustration of the cued task-switching paradigm used in each condition.

Participants sorted pictures by color and shape. In proactive-possible phases, the task cue appeared before the target, whereas it was presented on target onset in the proactive-impossible phase.

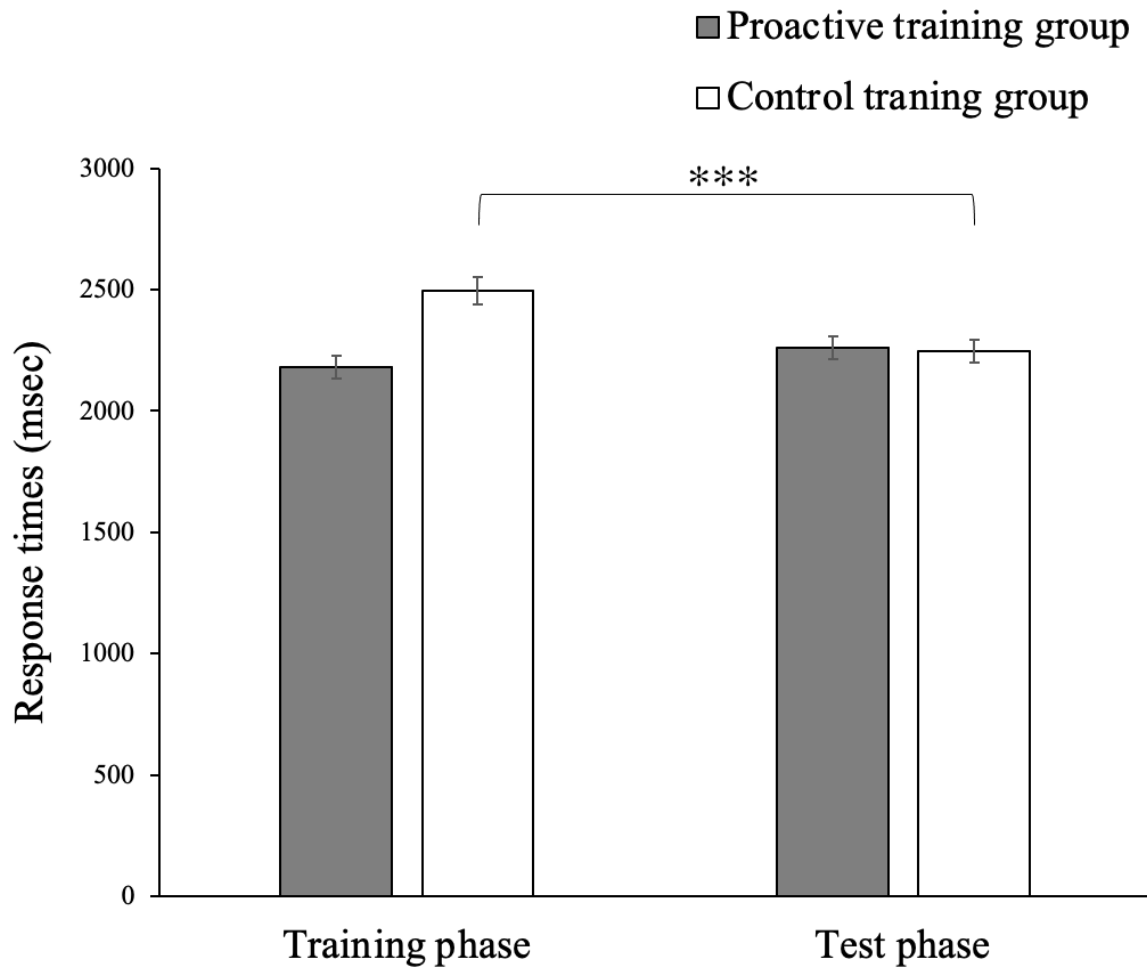


Figure 2. Mean response times in each condition. Error bars indicate standard errors.

Children in the proactive control group tended to respond faster in the training phase than those in the control training group. Children in the control training group responded faster in the test phase than in the training phase, whereas those in the proactive training group did not show such a pattern.

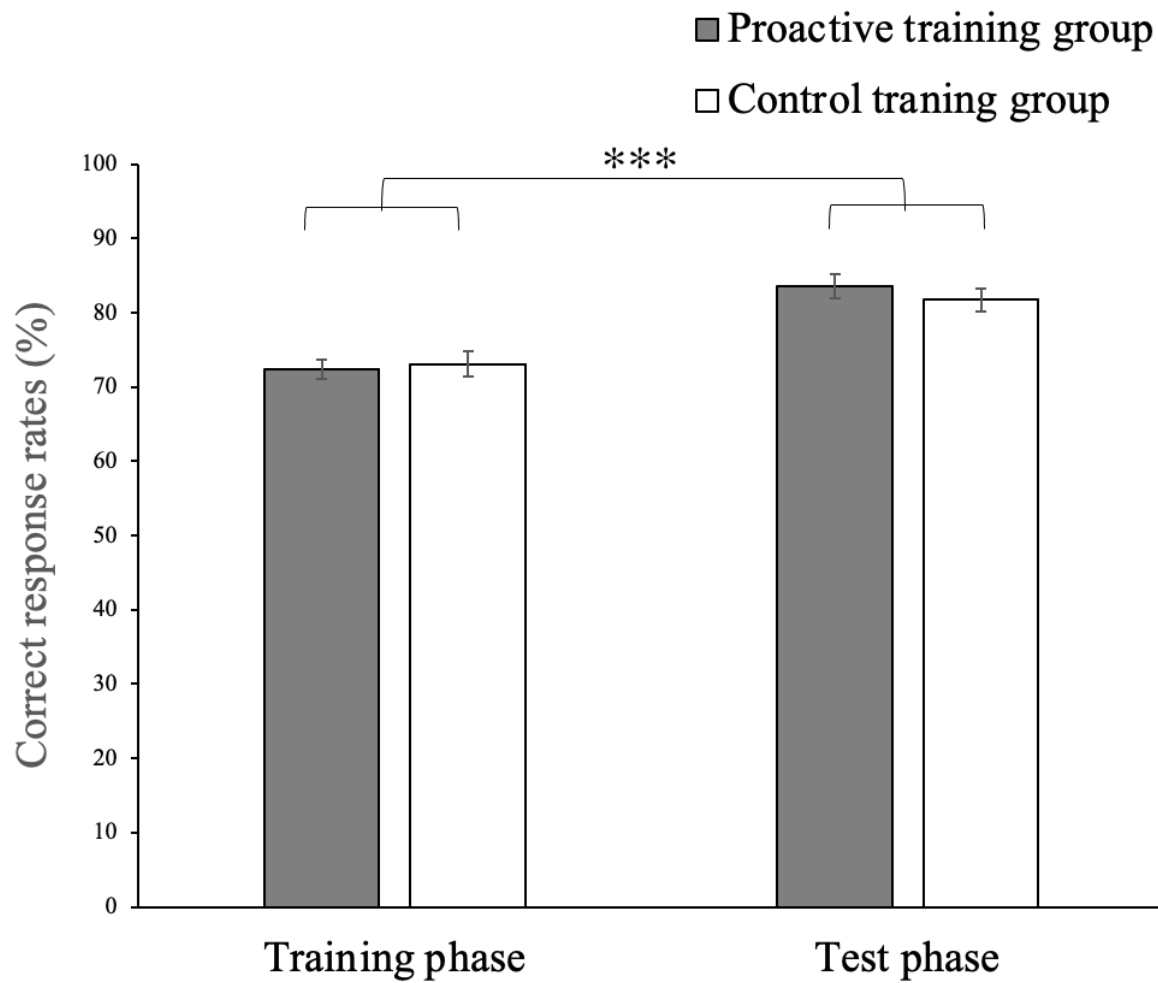


Figure 3. Mean correct response rates in each condition. Error bars indicate standard errors. Children in both training groups responded more accurately in the test phase than in the training phase.

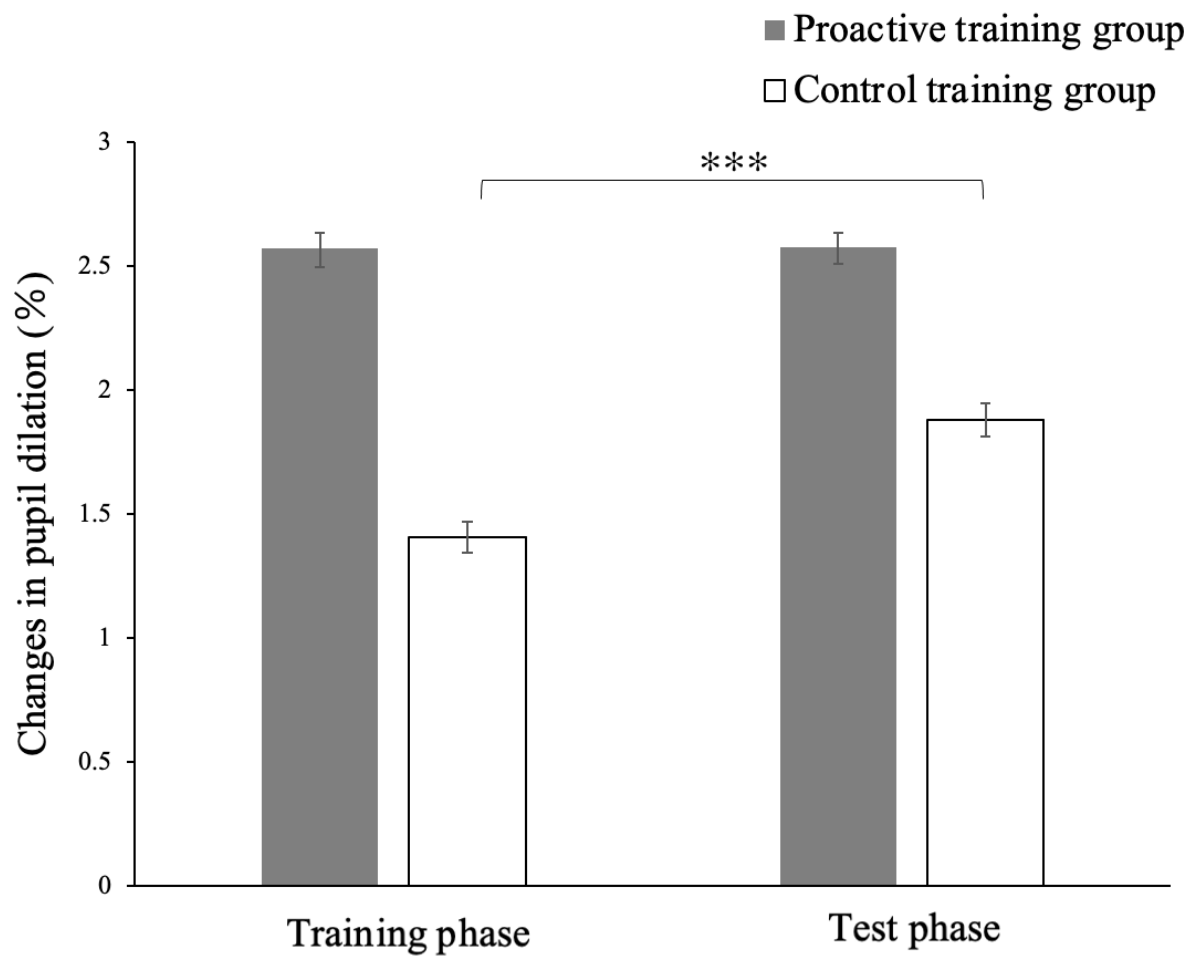


Figure 4. Change in pupil dilation in the late-window (1500msec-2000msec). Error bars indicate standard errors. During the late-window children in the control training group showed significantly greater changes in pupil dilation in the test phase than in the training phase.

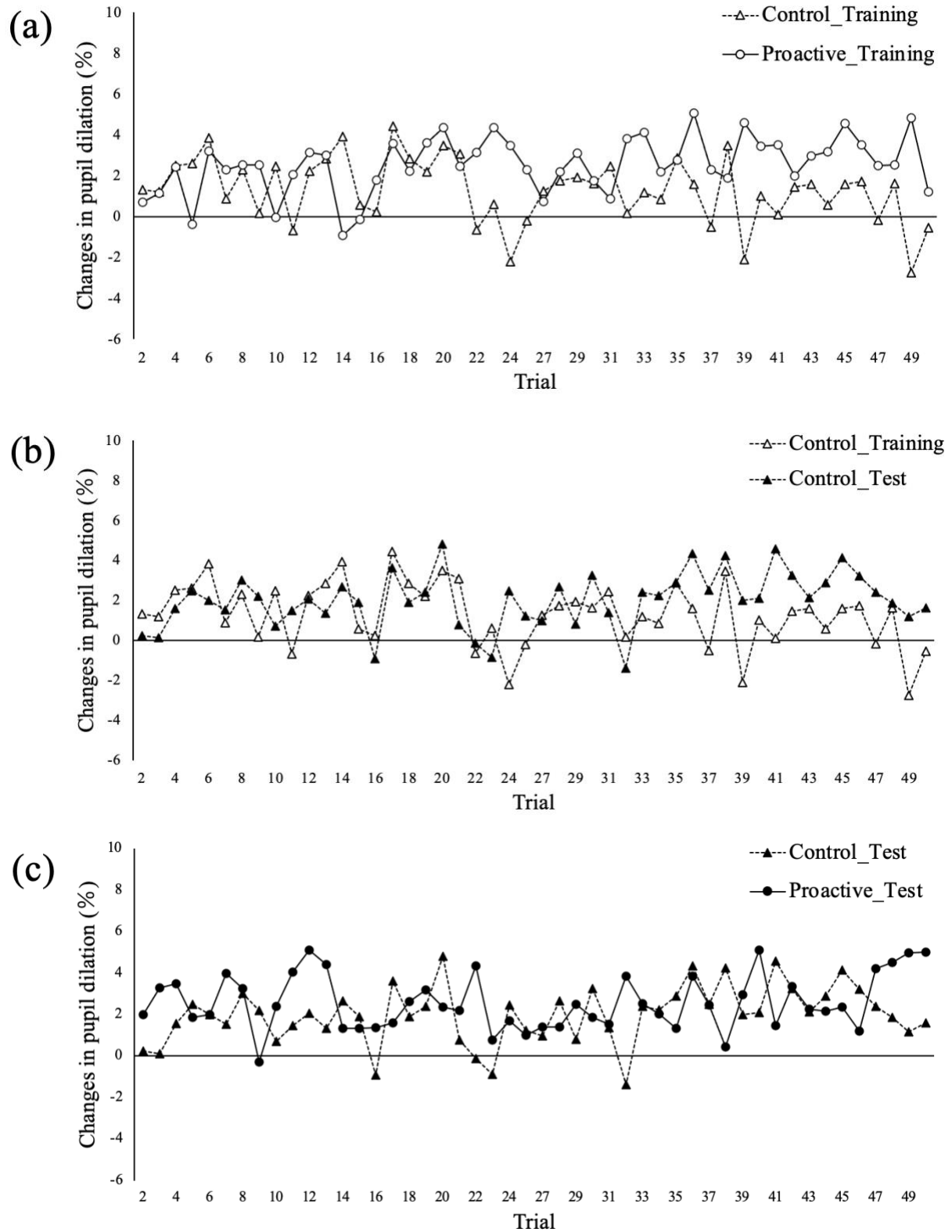


Figure 5. Change in pupil dilation in the late-window across trials: (a) In the training phase children in the proactive training group showed larger late-window pupil dilation than children in the control training group in later trials, but not in earlier trials; (b)

children in the control training group showed larger late-window pupil dilation in the test phase compared to the training phase in later trials, but not in earlier trials; (c) there were no significant group differences between the proactive and control training group in either the earlier or later trials of the test phase.