# Early development of self-guided strategy improvements in children

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## Abstract

The development of cognitive control functions in children is known to be protracted. Children have particular difficulties to execute instructed tasks in a fast and error-free manner, and these problems have been linked to the slow development of attention, inhibitory control and working memory functions that rely on prefrontal brain regions. In the present study, we investigated children's ability to discover and implement improvements of their task strategy without instruction. In contrast to the widely-described problems with efficient task execution, we find children to be as likely as adults to spontaneously discover and implement a task strategy improvement that was neither mentioned by instructions nor encouraged by explicit error feedback. Across two experiments involving 40 children of 8 – 10 years and 39 adults aged between 20 and 35, we found that statistically indistinguishable proportions of 35% of children and 28% of adults discovered and used an alternative strategy that made task execution easier. This lack of detectable age differences in flexible strategy updating stood in stark contrast to substantial differences in task-execution, working memory, and inhibitory control found in the same sample. Our results suggest a previously unappreciated early development of a higher cognitive ability that presumably depends on the competitive interaction of several slowly developing cognitive control functions.

# Highlights

- Children show adult-level abilities to discover and employ alternative strategies without instructions
- Instructed task performance, working memory, and response inhibition are less functional compared to adults
- Results are replicated across two experiments

# Introduction

Over the first two decades of their lives, humans develop into remarkably adaptive and efficient decision makers. Research aiming to understand this development has often focused on children's improvements in keeping information about the ongoing task in their working memory and shield it from interference by irrelevant distractions (e.g. Baum et al., 2017; Bunge & Zelazo, 2006; Bunge & Wright, 2007; Feo, Panzeri, & Dehaene, 2018; Gur et al., 2012). These processes, commonly summarized under the term cognitive control, are regarded as a hallmark of intelligent behavior and have received extensive scientific attention, also outside the field of development (Corbetta & Shulman, 2002; Sakai, 2008). Yet, truly *flexible* goal-directed behavior also requires that already established decision making strategies can be updated based on newly or even accidentally learned information. Similar to how discovering unknown connections can allow shortcuts in navigation, learning about contingencies that are not part of the current strategy can lead to behavioral or cognitive changes that achieve the same goal in a more efficient manner. This, however, involves processes that are antithetical to the cognitive control resources employed for efficient task execution: alternative strategies can sometimes only be discovered by processing information that is irrelevant for the current strategy, akin to how exploration of unknown routes is contrary to following a known path to a goal. While useful, adaptive strategy updating is therefore regarded as a computationally complex problem (Marewski & Link, 2014) that involves so called "metareasoning" (Lieder & Griffiths, 2017). At the same time, a relative weakness of cognitive control that protects ongoing task processing might have beneficial effects for one's ability to discover alternative strategies. In this article we ask how the above described aspects of goal-directed behavior, task-set maintenance on the one hand, and flexible updating of one's decision making strategy on the other hand, shape decision making in children compared to adults.

A large developmental literature has shown that cognitive control functions involved in task maintenance are comparatively slow to mature fully (Diamond, 2013; Gur et al., 2012). The ability to focus attention on task-relevant aspects and to suppress distracting information has been found to be less effective in children in a variety of tasks, such as the anti-saccade (Fischer, Biscaldi, & Gezeck, 1997; Fukushima, Hatta, & Fukushima, 2000), Flanker (Ridderinkhof, Van Der Molen, Band, & Bashore, 1997) or Stroop (Tipper, Bourque, Anderson, & Brehaut, 1989) tasks. Working memory capacity, in addition, does not reach adult levels until late adolescence (Demetriou, Christou, Spanoudis, & Platsidou, 2002). Moreover, compared to the development of other cognitive faculties, such as language or motor control, decision making about cues with multiple features becomes mature particularly late in development, reaching adult-levels only in late adolescence (Davidson, Amso, Anderson, & Diamond, 2006; Garon, Bryson, & Smith, 2008). Interestingly, even the ability to follow explicit rules continues to enhance as children become older in middle childhood, thereby contributing to the protracted development of children's control of behavior (Bunge & Zelazo, 2006). Over the same period of time, children become increasingly able to integrate and execute different rules according to the cues provided by task context (Bunge & Wright, 2007), particularly starting from late childhood on (Davidson et al., 2006). Finally, model-based decision making is also known to develop slowly (Decker, Otto, Daw, & Hartley, 2016). Neuroscientific research has linked this protracted cognitive development to the relatively delayed maturation of the prefrontal cortex (e.g. Hartley & Somerville, 2015; Blakemore & Choudhury, 2006). Studies focusing on structural development have for instance found links between change in cortical thickness in the anterior cingulate cortex and cognitive flexibility (Kharitonova, Martin, Gabrieli, & Sheridan, 2013), and different aspects of cognitive flexibility have been linked to different subregions of the prefrontal cortex (Bunge & Zelazo, 2006). In addition, studies of functional brain development have shown that brain activation patterns and long-range connectivity involved in cognitive control continue to change throughout childhood (Luna, Padmanabhan, & O'Hearn, 2010).

The plethora of research summarized above suggests that cognitive control skills, and their underlying neural processes, mature slowly. Considerably less is known, however, about the factors that allow flexible updating of goal-directed decision-making strategies. The main goal of the present paper is therefore to ask how good children are in updating an ongoing decision-making process with an alternative strategy that achieves the same goal. This aspect of cognitive flexibility lies not in being able to identify the relevant rule based on the context. Rather it relies on the ability to assess the potential usefulness of seemingly unimportant information in the environment that may afford the discovery of a new strategy (strategy exploration). As we noted above, the relative weakness of task 'shielding' (Dreisbach & Haider, 2008) seen in children could in principle turn out to be beneficial for their ability to discover alternative strategies. In addition, children are not as influenced by instructions as adults are (Decker, Lourenco, Doll, & Hartley, 2015), but are comparatively sensitive to statistical regularities in their environment that are important for language learning (Evans, Saffran, & Robe-Torres, 2009; Saffran, Aslin, & Newport, 1996). One might therefore expect that children, due to their lower ability to inhibit irrelevant information and to follow instructions as well as their sensitivity to statistical regularities, may have an advantage or at least an equal level of alternative strategy discovery abilities compared to young adults.

So far, this idea has not been tested directly. A number of previous findings have shown that children are remarkably variable in the strategies they employ, when even performing the same task (Siegler, 1995). For instance, when adding numbers, a single child may switch between memory retrieval, finger counting or using the commutativity principle (Siegler & Robinson, 1982; Gaschler, Vaterrodt, Frensch, Eichler, & Haider, 2013). Frequent task switching, in turn, is known to weaking task maintenance or 'shielding' (Dreisbach & Wenke, 2011). The overlapping wave theory (Siegler, 1996, 1997, 2006) emphasizes that children usually use a variety of approaches to problem solve, and that they are capable of discovering new strategies that are more effective than their previous ones. Because quantitative comparisons to adults performing the same task have not been conducted, it remains unclear to what extent children's ability to discover better alternative strategies, based on seemingly unimportant or distracting information in the environment, is comparable to that of young adults.

In this study, we tested children and young adults with a task that assesses the ability to discover and implement a novel strategy (Schuck et al., 2015; Gaschler, Schuck, Reverberi, Frensch, & Wenke, 2019). Participants were instructed to perform a simple decision making task that required responding to the spatial location of a stimulus with two different buttons. Unbeknownst to participants, the stimulus color was fully correlated with the required response, such that participants in principle could use an alternative strategy based on responding to stimulus color if they discovered this correlation.

# Methods

## Participants

Fifty six children (8-10 years) and 43 young adults (20-35 years) without color blindness or learning disabilities participated in two experiments. Experiment 1 involved 28 children and 22 young adults. Experiment 2 involved 28 children and 21 young adults. Participants were excluded if their performance was statistically not different from chance (see below for details). This led to the exclusion of 16 children and 4 younger adults. The effective sample size therefore consisted of 40 children (20 female; $n_{Exp.1} = 16$, $n_{Exp.1} = 24$) with a mean age of 9.5 years and 39 young adults (12 female; $n_{Exp.1} = 21$, $n_{Exp.1} = 18$) with a mean age of 24.5 years. All participants provided informed consent and all applicable ethical regulations related to research with human participants were followed. The ethics board of the Max Planck Institute for Human Development approved all reported studies.

## Experimental Paradigms

**Main Task** Participants performed the Spontaneous Strategy Switch Task previously developed by us (Schuck et al., 2015; Gaschler et al., 2019). While our study involved two separate experiments, this main task was nearly identical across the two experiments. Specifically, the perceptual decision making task consisted of responding to a rectangular patch of colored squares (120 × 120 px) displayed within a light grey reference frame (150 × 150 px). The rectangular patch was presented centrally on the screen, but the reference frame was offset from the center by 5 px in each direction, see Fig. 1A. The patch was therefore closer to one of the four corners of the reference frame. Participants were instructed to decide which corner of the frame the patch was closer to and to choose a corresponding response key. Two response keys ([x] and [,] were used as left and right keys) were mapped onto the four corners such that for example the left key was correct for both corners along one diagonal (e.g. upper left and lower right), whereas the right key was correct for the corners of the other diagonal (lower left and upper right). The response to corner mapping was randomized across participants. The stimulus is illustrated in Figure 1A.

Importantly, the squares constituting the patch were either green or red on each trial. Although this fact was mentioned during the instructions, participants were not informed that the patch color was consistently paired with the required response after an initial training period of one block (see Fig. 1B). This meant that in trials requiring a left response (upper left or lower right), the patch was for instance always green, whereas the patch was always red in trials requiring a right response. This enabled participants who discovered this unmentioned contingency to change their decision making strategy from selecting responses based on patch location to responding based on patch color. The color to side mapping was counterbalanced across participants.

Participants were trained on this mapping before beginning the main experiment. In order to ensure that the rules were understood, the training phase lasted for at least 50 trials and was ended once the participant made less than 20% errors in 24 consecutive trials. Participants received trialwise error feedback on the monitor during this part of the experiment, informing them when the given answer was incorrect, too late, or premature.

The main task included different trial types that involved slightly different response requirements illustrated in Figure 1C. In *regular* trials, the patch and the reference frame appeared simultaneously on the screen and participants could respond as instructed immediately after stimulus onset. In *lateGo* trials, the patch appeared for 2000 ms before the reference frame appeared for 400 ms in addition to the patch. Participants were instructed to withhold responding until the frame was displayed. *NoGo* trials were identical to *lateGo* trials, except that the frame did not appear after 2000 ms and the task continued with the next trial. Participants needed to withhold responding in these trials. In *ambiguous* trials, the frame appeared simultaneously with the colored patch, but was not offset from the center. Hence the patch was not closer to any of the four corners and responding based on relative spatial position of the patch would lead to random choice behavior in ambiguous trials. During the main task, no trialwise feedback was given, but when the blockwise error rate exceeded 20%, written feedback about too many errors was given at the end of the block on the monitor.

During regular trials in Experiment 1 the frame and patch were displayed simultaneously for 400 ms. In Experiment 2 they were displayed for 800 ms simultaneously in order to make responding easier. To accommodate the longer trials, Experiment 2 was shortened by one block. The additional last block in Experiment 1 was hence excluded from analyses to ensure equivalence in power (see section below for details). Experiments 1 and 2 were identical otherwise.

**Questionnaire** Following the main experiment, participants were asked to fill out a questionnaire containing several questions about the task. These questions asked (1) whether the hidden color role was noticed [yes/no], (1b) if yes, when within the experiment it was noticed [participants indicated the proportion of elapsed time before noticing on a clockface], (2) whether the discovered color rule was used to make decisions [yes/no], (3) to report the rule by writing down which color was associated with which corner. Due to human error, questionnaire data from one participant were lost.

**Working memory test** Participants completed a number-sorting task as a measure of working memory. For each trial, a set of numbers was verbally read out by the experimenter. After the last number was presented, participants were asked to write down the numbers in the ascending order on the answer sheet. A total of 15 sets of numbers divided into five levels were used, starting from four numbers at the first level and one number was added for each consecutive level. A set of numbers was assessed as incorrect if a number was missing or if the sequence was not in the correct order. A maximum of fifteen points could be scored

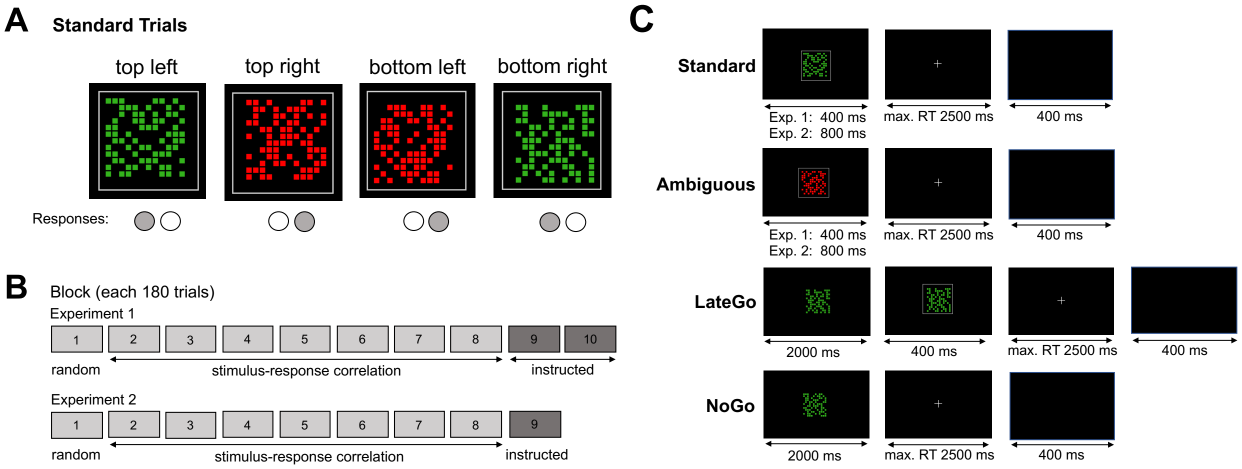

**Figure 1:** *Stimulus and Task Design.* **(A)**: Stimulus response mapping in *standard* trials. The mapping was counterbalanced across participants. Each trial involved one patch of colored squares inside a light reference frame as shown. The colored squares were shifted systematically from the center of the frame and participants had to decide which corner of the white frame the patch is closer to. **(B)**: Block order for Experiments 1 and 2. Each block started with a block in which stimulus color and corner were uncorrelated ("random blocks"). Without notifying participants, from block 2 on the required response and the stimulus color had a fixed relation in all standard trials. After block 8, participants were instructed to use the color to determine their response ("instructed blocks"). Experiments 1 and 2 differed regarding the number of instructed blocks. **(C)**: Trial structure for *Standard*, *ambiguous*, *lateGo* and *NoGo* trials. Each row shows the onset and duration of the colored squares, the white frame, the fixation cross and the response stimulus interval for one condition, see labels.

on the task. Due to human and technical errors, WM data from three participants were lost (all younger adults).

**Stroop Test** A stroop task was used as a measure of inhibition. The task consisted of 40 congruent, 40 incongruent, and 40 neutral trials. Participants were instructed to respond according to the font color of the stimulus word (e.g., for words shown in blue color, press the blue key). For congruent trials, the stimulus words ("BLUE" or "YELLOW") in their corresponding colors were presented on the screen. For incongruent trials, the stimulus words were shown with non-corresponding colors. For neutral trials, the stimulus word was "XXX" and was either shown in blue or yellow color. We computed two scores: the difference between reaction times in neutral and in congruent trials (semantic facilitation), and the difference between neutral and incongruent trials, the so called semantic interference score. Due to human and technical errors, Stroop data from seven participants was lost (six younger adults and one child, same participants for which working memory was lost plus participants for which erroneously the wrong computer program was used).

## Procedure

The experiment began with instructions about the main task that explained the above-mentioned rules to participants. While children received instructions verbally to ensure correct understanding, young adults read the same instructions themselves on the screen. Participants were asked to respond by pressing one of two response buttons on the keyboard, which were each marked with a white label. They were informed that the correct choice of button was determined by the position of the colored patches relative to the reference frame. Examples of the colored patches and white reference frame were shown during instructions. For trials where both features were available (*regular* trials), participants were asked to respond as quickly as possible. For trials where the reference frame was displayed after the colored patches (*lateGo* trials), participants were asked to wait for the frame before responding. For trials where the reference frame was not displayed (*NoGo* trials), participants were asked to not press any button. Importantly, instructions only mentioned that “each patch will be either red or green” and examples for each corner were shown in red and green. Instructions did therefore neither facilitate color use nor discourage it. A paper showing the corner-response mapping was hanging on the wall in front of the participants, which they were allowed to refer to throughout the experiment.

The main task involved 10 blocks in Experiment 1, and 9 blocks in Experiment 2 (in order to accommodate the longer regular trials) (Fig.1B). A subgroup of participants in Experiment 1 were erroneously tested with 11 blocks (8 children and 7 young adults, see below for details), but all data after block 9 was excluded from analyses to ensure equivalency between experiments. Each block contained 180 trials, including 80 *regular*, 32 *ambiguous*, 32 *NoGo*, 16 *lateGo* trials. Eight baseline trials in which only the fixation cross was shown and 12 additional trials that ensured balancing of transitions between trial types were included to accommodate potential fMRI follow up studies (as in Schuck et al. (2015)).

During the first block (“random blocks”), the color in left and right response trials was chosen at random. From block 2 on, the color was associated with the correct response as described above. Following block 8, participants took a short break and were informed that the color and the response were paired. They were not informed about the exact nature of the pairing but rather asked to find the relation and base their responses on the color for the remainder of the experiment (“instructed blocks”; 2 blocks in Experiment 1, 1 block in Experiment 2). Before continuing with the task, they were also asked to complete a questionnaire assessing knowledge of the color strategy (see above).

After the main task and questionnaire were completed, participants performed the Stroop and working memory tasks. The overall duration of the experiment was approximately 160 minutes for children and 120 minutes for young adults.

# Results

All analyses were performed using R (R Core Team, 2018), employing the 'lme4' package for mixed effects modelling (Bates, Mächler, Bolker, & Walker, 2015). Post-hoc tests were adjusted using the Tukey method as implemented in the package 'emmeans'. T-tests were corrected for variance inhomogeneity using the Welch test implemented in R. Unless otherwise noted, mixed effects models included a random intercept and slope of the linear factor Block per subject as well as fixed effects for the factors Experiment, Block and Age-group ('Young Adults' vs. 'Children'). Thus, Experiments 1 and 2 were analyzed within the same mixed effects models. Since the factor Experiment did not reach significance in most cases, data was combined where necessary (see below). To determine whether participants understood the task, we tested individually whether the percentage of correct trials was significantly different from chance (based on binomial test against chance at $\alpha = .05$). Understanding of the instructed spatial task was based on corner-based choices in standard trials in blocks 7-8, i.e. after considerable practice. The principle ability to perform color-based decision-making was tested based on choices in ambiguous trials in block 9, i.e. after the instruction to use color was given. This resulted in cut-offs of min. 65% correct color-based responses and 56% corner based responses, respectively, and led to the exclusions reported above. Specifically, 5 children were excluded based on spatial task performance and 11 children plus 4 younger adults based on color task performance (after color instructions). This ensured that only performance of participants was analyzed who had the ability to perform the spatial as well as the color task in principle.

## Instructed task execution

Errors in blocks 1-8 during regular trials decreased with practice in both experiments and consistently differed between children and young adults, as reflected in main effects of Block $\chi^2(1) = 37.4$, $p < .001$ and Age-group, $\chi^2(1) = 35.3$, $p < .001$, respectively (see Fig. 2A). Post hoc tests confirmed that the main effect of Age-group was driven by younger adults committing less errors than children in Experiments 1 and 2 (7.6% vs. 20.5% and 6.1% vs. 17.3%, respectively, both $p$s $< .001$). This difference persisted throughout the task and remained present in the last two blocks before the color instruction (blocks 7-8),

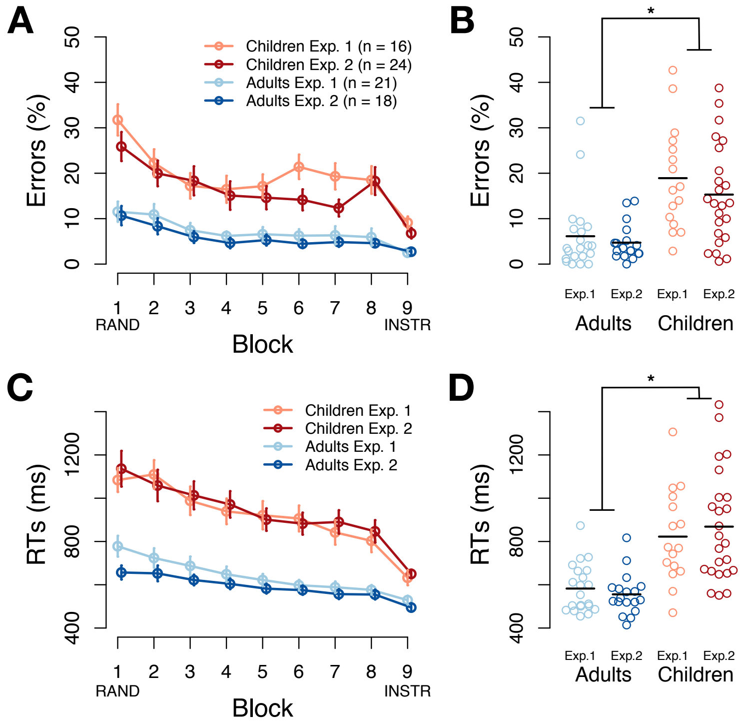

**Figure 2:** *Error rates and reaction times in regular trials.* **(A)**: Error rates as a function of block separately for children (red) and younger adults (blue) in Experiments 1 and 2, see legend. As can be seen, large age differences in error rates persisted throughout all blocks in both experiments. **(B)**: Average error rates in the last two blocks before color use was instructed (blocks 7 and 8). Each point represents one participant, the black horizontal line the mean of each group. Colors as in panel A. **(C)**: Average reaction times (RTs, in milliseconds) over blocks, also indicating sizable and persistent differences between children and young adults. Colors as in panel A. **(D)**: Mean RTs in the last two blocks before color use was instructed, format as in panel B. Bars represent standard error of the mean. *'s reflect significant main effects of Age-group.

$p < .001$, see Fig. 2B. No main effect of Experiment or any interaction between Age-group, Block or Experiment was found. Likewise, reaction times (RTs) decreased with practice and differed between age-groups, $\chi^2(1) = 87.9$ and 46.4, $ps < .001$, respectively (Fig. 2C). Group differences persisted until the last blocks, $p < .001$, Fig 2D, although the decrease in reaction times was faster in children compared to younger adults (interaction Block × Age-group: $\chi^2(1) = 7.8$, $p = .005$).

Investigating performance during the final instructed block revealed that adults still outperformed children after instructions to use color were given: error rates of children and adults were 9.1% vs. 2.5% and 6.8% vs. 2.7% in Experiments 1 and 2, respectively, both $ps < .01$. In addition, children benefited more from the instructions than adults in terms of error rates, interaction Block (8 vs. 9) by Age-group, $\chi^2(1) = 12.8$, $p < .001$. The same pattern was found concerning RTs ($ps < .001$ for main effect of Age-group in block 9 and interaction Block and Age-group).

## Response inhibition and working memory

We next investigated age differences in markers of executive control, in particular response inhibition and working memory. Response inhibition was assessed by investigating false

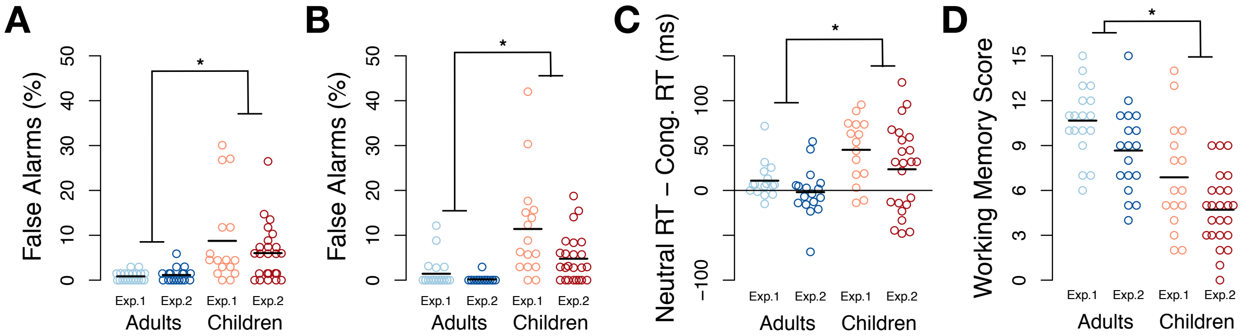

**Figure 3:** *Differences in cognitive control functions between children and young adults.* **(A)**: Percentage of false alarms in *lateGo* trials among young adults (blue) and children (red) in Experiments 1 and 2, indicating significantly less errors among young adults. **(B)**: Percentage of false alarms in *NoGo*. As in panel (A), younger adults also committed less false alarms than children. **(C)**: Average congruency effect (RT neutral - RT congruent, in ms) in the Stroop task, separately for both age-groups and experiments. Younger adults showed smaller congruency effects. **(D)**: Working memory score in a auditory working memory task, reflecting the maximum number of items that were successfully retained by each participant. Younger adult participants had on average higher working memory capacity compared to children. Each dot represents one participant, the black horizontal lines the mean of each group. *'s indicate significant age-group differences, see text.

alarm rates in *lateGo* and *NoGo* trials during the main task. This analysis showed that children and adults differed markedly in their response inhibition ability, similarly to the performance disparity seen in *regular* trials. Specifically, compared to younger adults children made significantly more premature key presses (i.e., responses before the frame was displayed, henceforth "False Alarms") in *lateGo* trials (6.0% vs.1.3%, $\chi^2(1) = 20.2$, $p < .001$, Fig 3A) as well as in *NoGo* trials (6.2% vs. 1.2%, $\chi^2(1) = 26.1$, $p < .001$, Fig 3B). To further investigate age differences in inhibitory control, we performed an additional Stroop test in which participants needed to respond to the ink color of a written color name or neutral word by pressing a button. This analysis showed that children participants had slower RTs in neutral ('XXX', colored letters) compared to congruent trials (e.g., 'YELLOW' in yellow ink) in Experiments 1 and 2, 45ms, $p < .001$, and 25ms, $p = .03$, respectively. This so called semantic facilitation effect, i.e. faster RTs in congruent versus neutral trials, was generally weak in younger adults, and only significant in Experiment 1, 10ms, $p = .04$, but not in Experiment 2, $p = .77$. Importantly, children had significantly greater semantic facilitation scores than adults in Experiment 1 as well as Experiment 2, $t(21.79) = 3.29$, $p = .004$, and $t(35.8) = 2.12$, $p = .04$, respectively, Fig 3C. Note that because participants were instructed to respond to the ink color, not respond to the written word, the semantic facilitation score reflects a failure of cognitive control. Interestingly, we did not find age-group differences in semantic interference (incongruent - neutral), which were 20ms and 46ms in

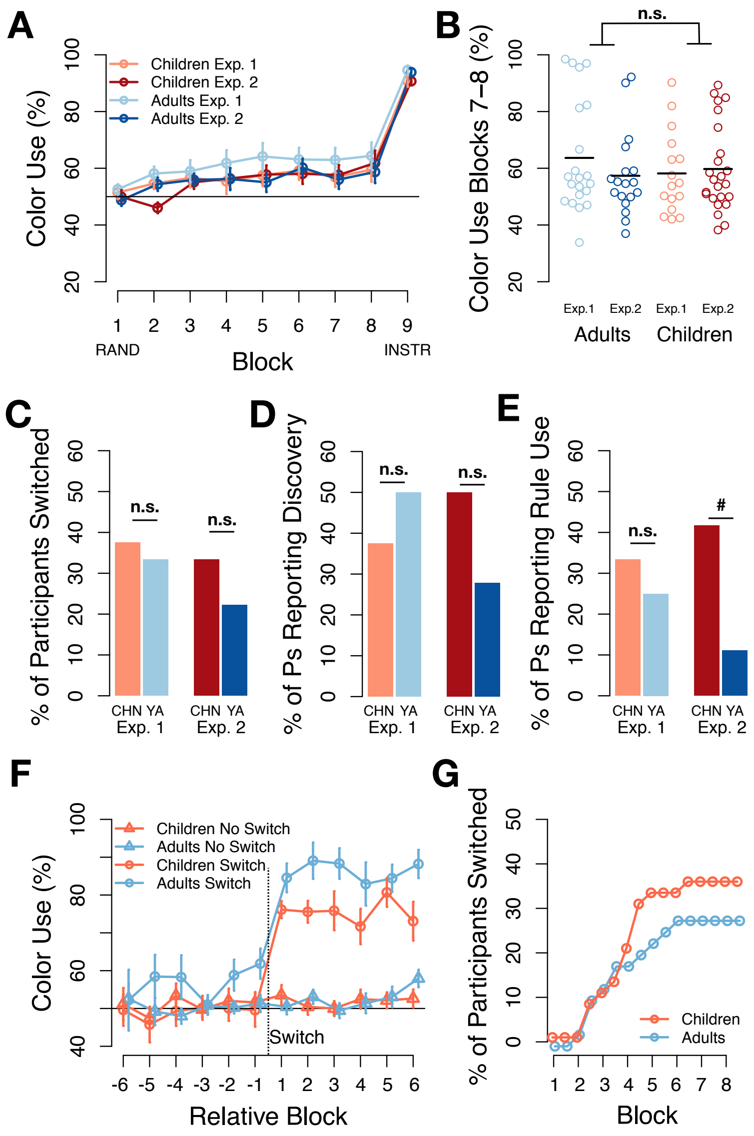

**Figure 4:** *Alternative strategy discovery and use in children and young adults.* **(A)** Percentage of color-based choices ("Color Use") in *ambiguous* trials as a function of block found in young adults (blue) and children (red) in Experiments 1 and 2. No significant differences were found. **(B)** Percentage of color use in blocks 7 and 8, before instructions were given. Each dot reflects one participant, black lines the mean. **(C)** Proportion of participants whose behavior indicated a strategy switch towards color based responding by blocks 7 and 8 ($>$ 65% color use). No difference was found between age-groups in this measure. Colors as in panel (A). 'CHN' = children, 'YA' = young adults. **(D)** Percentage of participants self-reporting discovery of the relation between colors and corners. No age-group difference. **(E)** Percentage of participants self-reporting use of a color-based strategy before instructions were given. **(F)** Percentage of color use in ambiguous trials time-locked to the mini-block in which a strategy switch was detected. Children (orange) and young adults (blue) are collapsed across Experiments 1 and 2, but shown separately for young and old participants who showed a strategy switch versus those who did not. **(G)** Time course of strategy discovery. Shown is the percentage of participants whose behavior indicated a strategy switch as a function of time, separately for each age group. Data collapsed across Experiments 1 and 2 as in panel G. The analysis illustrates that there were no group differences in when strategy changes occurred. n.s. = not significant at $\alpha = .05$. Bars represent s.e.m.

children and younger adults, respectively, $p = .15$. Finally, the verbal working memory test also indicated age differences in executive functions, with children having a lower working memory span than younger adults in Experiment 1 (7.1 vs. 10.9 correct answers, respectively, $t(23.6) = -3.4$, $p = .002$) as well as in Experiment 2 (4.7 vs. 8.7, $t(33.4) = -4.8$, $p < .001$), see Fig. 3D.

## Spontaneous strategy discovery and switch

We next investigated participants' ability to discover and use the alternative strategy. We first assessed to what extent responses in ambiguous trials were based on stimulus color.

For instance, if green was paired with left responses in standard trials, we measured the proportion of left responses in spatially ambiguous green trials and vice versa. A mixed effects model revealed an increase in color-based responding over time, i.e. a main effect of Block, $\chi^2(1) = 12.6$, $p < .001$, see Fig 4A. Importantly, main effects of Age-group, Experiment or any interactions were not significant (Age-group: $\chi^2(1) = 2.5$, $p = .11$, Experiment: $\chi^2(1) = 2.98$, $p = .08$, Interaction Age-group × Block: $\chi^2(1) = 0.7$, $p = .39$, Age-group × Block × Experiment: $\chi^2(1) = 1.6$, $p = .20$, all other interactions: $p$s $> .50$). Testing only behavior in the last 2 blocks before color instructions (7-8), we found that both groups showed significantly more color use than the expected chance level of 50%, $t(39) = 3.9$, $p < .001$ and $t(38) = 3.8$, $p < .001$, for children and young adults, respectively. This was separately true for both groups of children from Experiment 1 and Experiment 2, $t(15) = 2.2$, $p = .03$ and $t(23) = 3.1$, $p = .005$. Yet, again no age differences in color-based responding were found, 58.9% vs. 60.5%, $\chi^2(1) = 0.2$, $p = .64$, see Fig. 4B. Moreover, the proportion of participants who exhibited statistical evidence for color use in the last two correlated blocks (i.e. exhibiting a significant binomial test against 50%) was 35% among children (14/40), 28.6% among young adults (11/39) and not statistically different between age-groups, $\chi^2(1) = 0.17$, $p = .68$, see Fig 4C. This result was not affected by the choice of threshold (both $p$s $> .5$ when a higher threshold of at least 75% or a lower threshold of at least 50% color use were employed). Note that given our sample size of 40 children and 39 young adults, the above reported analysis does have power of .747 to detect a difference of only 15% between age groups (for a one sided-test $\chi^2$-test).

The lack of age differences was also evident in participants' self reports. In Experiment 1, a statistically indistinguishable proportion of 33% (5/15) of children and 43% of adults self-reported to have discovered the unmentioned task rule, $\chi^2(1) = 0.05$, $p = .82$. Likewise, no differences were found in Experiment 2 where 50% of children (12/24) and 27% (5/18) of young adults reported discovery of the alternative strategy, $\chi^2(1) = 1.29$, $p = .26$, Fig. 4D. We next asked whether the color strategy was not only discovered, but also used. 33.3% and 41.7% of children compared to 25% and 11% of young adults reported having done so in Experiments 1 and 2, respectively. Again, these proportions were statistically not different between age-groups in either Experiment, $\chi^2(1) = 0.26$, $p = .70$ and $\chi^2(1) = 3.23$, $p = .07$, Fig. 4E. Hence, no evidence was found that children had inferior abilities to discover and use the alternative decision making strategy.

Interestingly, considering only participants who showed evidence of a strategy switch indicated that in Experiment 1 strategy-switching adults had higher levels of color use than strategy-switching children, 82% vs. 65%, post-hoc test: $p = .001$. This was not true in Experiment 2 however, 71% vs. 65%, $p = .99$ (interaction of Age group × Experiment: $p = .066$). In order to understand whether this difference was driven by younger adults showing more color-based responding only after the strategy was discovered, we identified each participants' switchpoint using the CUSUM method as in Schuck et al. (2015) and investigated color use among children and young adults time locked to each participants' own switch point. This analysis showed that in Experiment 1 among those participants who did adopt the novel strategy, young adults increased their level of color-based responding from 57% to 90% from before to after the switch, and children increased from 51% to 74%, see Fig. 4F. Although the increase was numerically bigger in young adults, there were no age differences in the increase itself, $t(9.06) = 1.6$, $p = .14$. Thus, the group difference among strategy-changing participants in Experiment 1 can best be explained as reflecting a tendency to respond based on color that was present in younger adults already before the strategy switch was fully completed. Testing *when* participants changed to the color-based strategy (again using the individual participant's switch point) showed that children and young adults did not differ in the time point of strategy switch, which occurred on average after 3.5 and 3.2 blocks for children and young adults, $t(19.2) = 0.56$, $p = .59$, Fig. 4G.

We also tested whether the lack of age differences in the proportion of color use in ambiguous trials could be explained by differences in reliability between this and other cognitive performance measures. The split half correlation between trials in the first half versus the second half of a block (average across blocks 7-8, as in Fig. 4B) was $r = .76$ for children and $r = .91$ for adults (both $p$'s $< .001$). The corresponding split half correlations for error rates (Fig. 2B) were $r = .77$ for children and $r = .70$ for adults, and $r = .55/r = .71$ for the amount of false alarms (Fig. 3A), respectively. Thus, no evidence for differences in the reliability between the measures exhibiting age differences versus those not exhibiting an age difference could be found.

## Age-differences in strategy updating versus age-differences in cognitive control and task performance

The analyses reported so far indicate the presence of substantial age-related differences in task performance and executive functions on the one hand, but no such differences in spontaneous strategy switching on the other hand. To test directly whether this pattern reflects a significant difference in the development of these different mental functions, we z-standardized all dependent variables reported above across age-groups and performed an

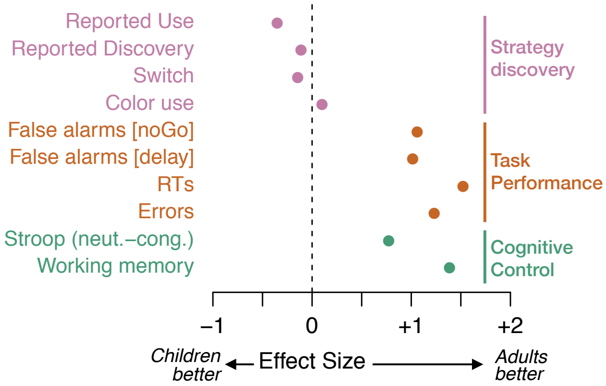

**Figure 5: Effect sizes of age-group differences across performance metrics.** A standardized effect size was individually calculated for each performance metric for purposes of comparison. Shown metrics reflect data reported in the manuscript in Figures 2–4. Data collapsed across Experiments 1 and 2. Dots on the right of the dashed line indicate that younger adults performed better than children, dots on the left side indicate that children performed better than younger adults. Colors reflect whether a metric reflects an task-independent cognitive control measure (green), task performance (orange) or strategy improvement (violet).

interaction test between Age-group and dependent variable (reflecting different cognitive abilities). This analysis included all markers of performance that were reported above, namely working memory capacity, Stroop semantic facilitation as well as RTs, error rates and false alarms in the main task, on the one hand and % color-based responding in ambiguous trials, strategy discovery and strategy use self reports on the other hand. Results revealed a main effect of Age-group ($\chi^2(1) = 29.3$, $p < .001$) that reflected the well-known overall worse performance in children compared to young adults. Importantly, the interaction between Age-group and cognitive ability was also significant $\chi^2(11) = 91.7$, $p < .001$. Fig. 5 illustrates this effect by showing standardized effect sizes for all metrics. Post hoc tests revealed significant age-group differences in favor of younger adults in RTs, Errors, False Alarms, Stroop Effects and Working Memory, all $p$s $< .001$, Tukey corrected for multiple testing. Metrics related to the discovery of the alternative strategy, in contrast, did not reveal such age-differences: Neither the percentage of color use in ambiguous trials, the proportion of participants who exhibited statistical signs of alternative strategy use nor the proportion of participants self reporting strategy change differed between age-groups, all $p$s $> .48$. The proportion of participants reporting strategy use differed in favor of children, $t = 1.99$, $p = .046$. Hence, the ability to discover and implement an alternative strategy seems to reach adult levels earlier than other markers of task execution and cognitive control.

## Discussion

The present study has investigated the ability to discover possible strategy improvements during task execution in children aged between 8 and 10 and in adults aged between 20 and 35 years. We assessed strategy discoveries that occurred even though a viable task rule was verbally instructed that allowed error-free task execution. No error feedback was given and the possibility that an alternative strategy could be found was not mentioned by instructions. Strategy improvements therefore were entirely self driven by participants and occurred spontaneously, i.e. without the presence of any discernible external events that triggered them.

Our results showed that such spontaneous strategy improvements occurred equally often in children and adults. This finding contrasted with the superior performance found in adults relative to children in all other cognitive abilities that were measured in the same sample, in particular in task execution, working memory and cognitive control abilities. Flexible strategy updating therefore presents a remarkable exception to the well documented protracted development of decision-making relevant functions in children such as cognitive control (Diamond, 2013; Gur et al., 2012), rule following (Bunge & Zelazo, 2006), model based decision making (Decker et al., 2016) and choice exploration strategies (Somerville et al., 2017).

Our previous work has shown that strategy updating is a seemingly difficult and rare event even among adults. Specifically, we have found that although the deterministic color-location correlation could be observed in over 700 trials, only about 30% of young adult participants discovered and used the alternative strategy (Schuck et al., 2015). The present experiment involved around 600 standard trials in which the deterministic color-response relation could be observed. Only 25 out of all 79 tested participants showed behavior consistent with a strategy shift. Eleven of these cases were from the group of 39 younger adults (28%), and 14 were from the group of 40 tested children (35%). It seems conceivable that this surprisingly low number reflects the fact that those mechanisms that protect ongoing task execution are at the same time detrimental for one's ability to discover the alternative strategy, since the latter involves processing information that is considered irrelevant when following the instructed strategy (Dreisbach & Fröber, 2018; Goschke, 2000). One additionally relevant idea in this regard is the notion of developmental changes in Bayesian learning, which suggests that weaker priors in children lead to larger updates of their posterior in light of the same observation, i.e. a stronger consideration of alternative hypotheses that are consistent with new evidence (e.g. Gopnik & Wellman, 2012; Xu & Kushnir, 2013). Studies of causal reasoning indeed showed that children, preschoolers particularly, are more flexible than older children and adults in adopting unfamiliar hypotheses that are consistent with new evidence (Gopnik et al., 2017; Lucas, Bridgers, Griffiths, & Gopnik, 2014). While our data does not suggest an age-related difference favoring children, the Bayesian framework may be an useful general approach that captures the contextual factors that affect how strongly the instructed strategy is being executed as prior belief. In combination, these factors could explain why children who are almost 3-times as error prone as adults in executing the instructed strategy (18.5% vs 6.9% on average in standard trials in blocks 1-8) are equally good in discovering and implementing the alternative strategy.

Notably, however, in our own data we do not find any correlation between the amount of color use (indicating strategy discovery), and task execution (Errors: $r = -.26$, RTs: $r = -.18$), working memory ($r = -.02$) or the Stroop (semantic facilitation) effect among children ($r = -.27$; all $p$s $> .10$ uncorrected, see SI for full table of correlations). Interestingly, we found a significant *positive* relation between the Stroop effect and color use in young adults, $r = .50$, $p = .003$, indicating that young adults with worse executive functions (larger Stroop effects) were also more influenced by the color. While the present study was not designed to specifically examine the question about the factors influencing strategy discovery, the available data thus does lend only mixed empirical support for the idea that weaknesses in control functions are related to strategy discovery abilities. Further investigations are therefore needed that shed light on the factors that facilitate and impede strategy discovery, for instance testing Bayesian learning abilities more directly and utilizing update focused working memory measures such as n-back or AX-CPT tasks. In addition, given the between subject nature of the effects, larger sample sizes that yield higher power for detecting small difference between age groups will be needed.

It also remains unclear how the high levels of flexible updating could be neurally implemented in the still developing brain. Our own investigation in younger adults suggested that the spontaneous change in strategy relied on a internal simulation mechanism in medial prefrontal cortex (mPFC). In children, mPFC displays a complex structural maturation trajectory that differs between its subregions (Shaw et al., 2008), with the orbital parts following an early maturation pattern, whereas the dorsal parts follow a late maturation pattern. The cluster of mPFC found in Schuck et al. (2015) corresponds to the region that goes through structural transition between 8 and 10 years of age. In addition, it remains unclear whether children's brains exhibit similar dynamics in long range brain activity correlations that have been associated with our task (Allegra et al., 2018), given the marked changes in brain network segregation observed in children (Baum et al., 2017). This may be relevant insofar as prefrontal network dynamics have been linked to the balance between cognitive stability and flexibility (e.g., Durstewitz, Seamans, & Sejnowski, 2000; O'Reilly, 2006), suggesting that the stable states that correspond to task sets representations can be thought of as basins in a potential landscape of network state. According to this view, deeper basins are related to cognitive stability and efficient task execution, while shallower basins imply less effort to switch but higher susceptibility to distraction. In line with this idea it has been found that depth of the attractor state, as indexed by functional coupling between prefrontal areas, is related to how readily individuals switch from one task state to another in the light of ambiguous task cues (Armbruster, Ueltzhoeffer, Basten, & Fiebach, 2012). Therefore, the development of attractor stability of prefrontal networks may be a useful topic for future investigations (see also, Baum et al., 2017).

In summary, the present study has shown that children aged between 8 and 10 years are equally successful as adults in incidentally discovering strategy improvements without instructions. This equivalent effectiveness was present despite children's limitations in executing simple task rules, holding information in working memory and inhibiting prepotent responses. The comparatively well developed ability to discover novel strategies for a known task in children might offer a unique opportunity for educators in fostering learning in children. More generally, our findings highlight that the development of cognitive functions in children might result in complex dynamics of abilities that rely on the interaction of several cognitive functions and are rarely effective even in adults.

### Data Availability

The legal possibilities of making anonymized raw data openly available given the used consent forms are evaluated at the moment. Contingent on approval by the local data protection office and the ethical review board, all raw and aggregate data used to generate results in Figures 2-5 will be made publicly available upon publication.

### Code Availability

All code used to generate results in Figures 2-5 will be made publicly available upon publication.

## Author Contributions

NWS, RG, DW and YLS designed research. DSA and AL conducted research. NWS and YLS analyzed data. All authors contributed to interpreting the data and writing the manuscript.

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