Received: 29 September 2020 | Revised: 3 November 2021 | Accepted: 17 December 2021

DOI: 10.1111/desc.13222

Developmental Science

WILEY

**PAPER**

# Understanding autonomous behaviour development: Exploring the developmental contributions of context-tracking and task selection to self-directed cognitive control

**Aurélien Frick**[1,2] | **Maria A. Brandimonte**[2] | **Nicolas Chevalier**[1]

[1] Department of Psychology, University of Edinburgh, Edinburgh, UK

[2] Laboratory of Experimental Psychology, Suor Orsola Benincasa University, Naples, Italy

**Correspondence**

Aurélien Frick, Department of Psychology, University of Edinburgh, 7 George Square Edinburgh EH8 9JZ, Edinburgh, United Kingdom.

Email: aurelien.frick@hotmail.com

**Funding information**

Suor Orsola Benincasa University and Research; the University of Edinburgh

## Abstract

Gaining autonomy is a key aspect of growing up and cognitive control development across childhood. However, little is known about how children engage cognitive control in an autonomous (or self-directed) fashion. Here, we propose that in order to successfully engage self-directed control, children identify, and achieve goals by tracking contextual information and using this information to select relevant tasks. To disentangle the respective contributions of these processes, we manipulated the difficulty of context-tracking via altering the presence or absence of contextual support (Study 1) and the difficulty of task selection by varying task difficulty (a)symmetry (Study 2) in 5–6 and 9-10-year-olds, and adults. Results suggested that, although both processes contribute to successful self-directed engagement of cognitive control, age-related progress mostly relates to context-tracking.

**KEYWORDS**

cognitive control development, context-tracking, self-directed control, task selection, voluntary task-switching

Cognitive control, the goal-directed regulation of thoughts and actions, plays a critical role in children's lives. For instance, to answer a question asked by a teacher (i.e., the goal), children must adaptively engage cognitive control to inhibit their desires to directly give the answer and instead raise their hand first. Critically, with age, they are increasingly expected to do so without being explicitly prompted by the teacher: they need to become more self-directed (as opposed to externally driven) when engaging cognitive control.

Given the goal-directed nature of cognitive control, goals—the mental representations of an intention to perform an action or reach a state (Miller & Cohen, 2001)—are critical in control engagement. The more concrete a desired goal is (e.g., behave appropriately at school), the more easily it can be translated into rules (Badre & Nee, 2018) that guide the relation between the context (e.g., when at school) and the expected actions (e.g., remain quiet). However, these goals or rules are often hierarchical, involving embedded levels of contexts as well as goals and sub-goals (Badre, 2008). For instance, the action of remaining quiet may also depend on second-order contexts (e.g., the classroom or the playground) that signal the validity of the sub-goal or first-order rule of remaining quiet when at school.

Developmental research on cognitive control has often been conducted with externally driven tasks, such as paradigms where children have to switch between different goals according to a contextual cue (for a review, see Diamond, 2013). This research has revealed that 3- to 4-year-olds have few difficulties switching between first-order goals or rules (e.g., in the colour game, the red cars go on the left and the blue cars go on the right), but performance continues to improve through late adolescence when there are two or more rules or contexts governing stimulus-action-mapping (e.g., a cue indicating which game to play between the colour and shape game, whilst the shape game conflicts with the colour game as the cars go on the left and the teddy-bear go on the right; see Doebel & Zelazo, 2015). In such situations, part of children's difficulties reside in correctly identifying the relevant goals (or rules), termed as goal identification, to successfully engage cognitive control (Chevalier, 2015; see also Broeker et al., 2018). Consistently, young children first process the stimulus before the contextual

https://doi.org/10.1111/desc.13222

cue, resulting in poor cognitive control engagement (Chevalier et al., 2018), and cognitive control performance improvement is observed when cue processing is facilitated through more transparent contextual cues (e.g., a set of shapes indicating that the shape game has to be played) and practised (Chevalier et al., 2014; Chevalier & Blaye, 2009; Kray et al., 2008, 2013).

However, goals (or rules) are particularly difficult to identify when little or no contextual cues are provided, as such situations require self-directed engagement of cognitive control. Previous research on this form of control has mainly used the Verbal Fluency task, in which children have to say aloud as many items as possible from a particular category (e.g., animals). To maximise their performance, they must self-directedly identify that a relevant strategy consists of grouping the responses into sub-categories (e.g., farm animals, zoo animals) and self-directedly switch between these sub-categories once no more items from a sub-category come to mind. Typically, children do not perform well on this task until late childhood (Barker et al., 2014; Snyder & Munakata, 2010, 2013), suggesting that the development of self-directed cognitive control lags behind the development of externally driven cognitive control (Munakata et al., 2012). However, children showed improved performance when given a contextual cue before the task (i.e., the name of three sub-categories), as it alleviates the costs of goal identification (i.e., what new sub-category to name) and strengthens abstract representations (Snyder & Munakata, 2010).

Two processes are likely to be challenging when cognitive control is engaged self-directedly. The first is the context-tracking process. Contexts may involve changes in task demands or goals and may be influenced by past actions. In particular, attainment of a specific goal (e.g., prepare breakfast) may require a series of sub-goals (e.g., make coffee, cut bread, etc.). Therefore, one needs to keep track of contextual information, including where one stands in a hierarchy of sub-goals and goals, or cues suggesting that a new goal should be pursued. The second process, task selection, consists of using this contextual information to determine when and what behaviour should be engaged in order to achieve sub-goals and goals. The relation between context-tracking and task selection may be bidirectional. Indeed, context-tracking may guide task selection by providing information about sub-goals and goals. Reciprocally, one needs to update this information through context-tracking as a function of new task selections (i.e., once a task has been selected, this selection should be considered as part of the context one is keeping track of).

Critically, the relation between context tracking and task selection may change as a function of working memory gating strategies (Chatham & Badre, 2015). The output gating strategy refers to accumulating all the contextual information and then selecting the pieces of contextual information that are relevant (context-tracking → task selection) whereas input gating corresponds to updating and selecting only relevant contextual information and ignoring irrelevant information (context-tracking ← task selection; e.g., Chatham et al., 2014; O'Reilly & Frank, 2006). In a recent study, children from 7 years of age to adolescence tended to use the output gating strategy more than the input gating strategy, although this strategy does not lead to better performance (Unger et al., 2016). However, when contextual information was presented first, children adopted an input gating strategy earlier in development, which significantly improved performance as compared to when the context was presented last, potentially because it facilitated goal identification. More recently, it has been shown that when the task required more self-directed control engagement, younger children (3- to 5-years-old) used the input gating strategy more, which improves performance (Freier et al., 2021). These studies provide important information about the relation between context-tracking and task selection, but it is unknown how these processes contribute to self-directed control development.

**Research Highlights**

- Context-tracking and task selection are key processes when individuals engage autonomous behaviours or self-directed control.
- We report that both processes contribute to self-directed control during childhood in different ways.
- Developmental progress in self-directed control is mainly due to context-tracking.

The respective contribution of context tracking and task selection to self-directed control development may be examined with the voluntary task-switching paradigm (VTS; Arrington & Logan, 2004), in which individuals self-directedly select which task to perform based on instructions to perform each task equally often and in a random manner. As such, individuals have to attain two goals that are equally important and partially dependent on each other. Indeed, despite these instructions, adults often tend to repeat the same task more often than they switch between tasks, hence showing a lower probability of switching, noted $p$(switch) than what would be expected if they repeated and switched tasks equally often (i.e., $p(\text{switch}) = 0.5$; e.g., Arrington et al., 2014; Mittelstädt et al., 2018). This $p$(switch) is considered as the hallmark of task selection in VTS and follows an inverted U-shaped pattern with adolescents and elderly people showing a lower $p$(switch) than adults (Poljac et al., 2018; Terry & Sliwinski, 2012).

However, in the only study examining VTS performance in children, 5-years-olds showed a similar $p$(switch) to 9-year-olds and young adults (Frick et al., 2019), perhaps suggesting that children show no specific difficulty in switching between tasks in the VTS (see also Freier et al., 2017). Yet, on two novel measures in VTS, task balance (i.e., how well participants perform the two tasks equally often) and task unpredictability (i.e., how well participants perform the two tasks aleatory), 5-years-old children selected one task more often than the other (task balance) and relied on predictable strategies more than older children and adults did (task unpredictability). These results show that $p$(switch) does not capture all aspects of self-directed control in VTS, and are consistent with evidence of age-related progress during childhood in other tasks tapping self-directed control (Barker et al., 2014; Frick et al., 2021; Snyder & Munakata, 2010, 2013; White et al., 2009; for a review see Barker & Munakata, 2015). Interestingly, young children often switched between tasks on every trial (thus failing to select tasks randomly), suggesting that implementing a task switch per se is not the main difficulty at that age (see also Freier et al., 2017). Implementing a predictable pattern may be a way for these children to reduce the high costs of context-tracking and task selection, hence pointing to these two processes as the main source of children's difficulty.

The present studies extended recent research on working memory gating strategies, which have revealed the existence of two different directional relationships between context-tracking and task selection. More specifically, here, we sought to examine the contributions of context-tracking and task selection to developmental differences in self-directed control engagement. Although these two processes are linked in their functioning, they may follow different developmental trajectories in childhood. Specifically, Study 1 addressed whether decreasing the working memory demands on context-tracking by providing contextual support through working memory cues enhances VTS performance, while Study 2 varied the difficulty of task selection through task difficulty (a)symmetry, which has been shown to influence *p*(switch) in adults (Liefooghe et al., 2010; Yeung, 2010). Finally, given the limitations of *p*(switch), we considered other indices that may capture context-tracking and task selection more directly, namely task balance and task unpredictability.

# 1 | STUDY 1

## 1.1 | Introduction

Study 1 examined to what extent context-tracking contributes to age-related differences in self-directed control performance in 5–6 years-olds and 9–10 years-olds, two age groups in which there are well-established age-related differences in terms of cognitive control (e.g., better coordination between reactive and proactive control, increasing use of self-directed control over externally driven control; Chevalier, 2015; Munakata et al., 2012), as well as adults. To this aim, we used a child-friendly version of VTS (adapted from Frick et al., 2019) by providing contextual information about what has been done previously, therefore reducing the working memory demands related to this process. Specifically, in the contextual support condition, participants were shown how many times each task was played to help them keep track of which task they performed, whereas in the no contextual support condition, no such contextual information was provided, forcing participants to keep track of their performance on their own. Note that the contextual support did not directly signal which task to select, unlike task cues or alternating-runs rules as done in externally driven or less externally driven task-switching paradigms (e.g., Chevalier et al., 2018; Dauvier et al., 2012), but served as working memory cues. If the difficulties encountered by children are related to context-tracking, providing contextual support about previously performed tasks should improve their performance and reduce differences across age groups. Conversely, if the difficulty is rather related to the use of the information provided by context-tracking, the presence of contextual support should not affect performance.

## 1.2 | Methods

### 1.2.1 | Participants

Participants included 30 5- to 6-year-old children (*M* = 5.93 years, *SD* = 0.89, range: 5.00–6.85, 12 females), 30 9- to 10-year-old children (*M* = 9.64 years, *SD* = 0.95, range: 9.03–10.99, 13 females), and 29 adults (*M* = 22.55 years, *SD* = 4.56, range: 18.21–33.02, 15 females). Ten additional participants were excluded: two failed the practice blocks, four wished to withdraw or performed only with the help of the experimenter, two fell outside of the age range and two due to a crash in the program. Sample size was determined based on a prior study that used the same paradigm (e.g., Frick et al., 2019) and showed that 30 participants per age group were enough to detect effects of medium size (as we expected here). All children were recruited from the local community and adults were undergraduate students enrolled in the local university. Parental consent was obtained for all children. Parents received £10 compensation, and children received an age-appropriate prize. Adults received course credits. This study received approval from the Ethics Committee of the University of Edinburgh.

Parents filled out a demographic questionnaire to assess socio-economic status (SES) indicating that children tested in this study mostly came from a high SES background (for more details, see Supplemental Material I).

### 1.2.2 | Material and procedure

All participants were tested individually in the laboratory. They completed a child-friendly VTS similar to Frick et al. (2019) presented with E-Prime 2 (Psychology Software Tools, Pittsburgh, PA). Participants had to voluntarily switch between matching bidimensional targets (e.g., a blue teddy) according to their colour (i.e., sending it to the colour bag by pressing either the "blue" or "red" buttons) or shape (i.e., sending it to the shape bag by pressing either the "teddy" or "car" buttons; Figure 1). The Colour and Shape bags were presented on the left and right side on the monitor (order-counterbalanced across participants and conditions) and remained visible throughout the task. Each trial started with a fixation cross. After 1500 ms, the fixation cross was replaced with the onset of the target that remained on screen until participants' response was entered on the response box. After the response, the target was replaced by a present that remained for 500 ms and then appeared into the chosen bag chosen for 500 ms. In the contextual support condition, the present remained visible into the bag during the task, whereas it disappeared from the bag and was no longer visible at the onset of the next trial in the no contextual support condition. All participants were tested in the two conditions (order counterbalanced). In the first condition, the dimensions used were teddy-car-blue-red, in the second condition, the dimensions used were doll-plane-green-purple.

Participants first completed two single-blocks (one colour, one shape; order counter-balanced across participants) in which they were instructed to sort the targets either only by colour or only by shape

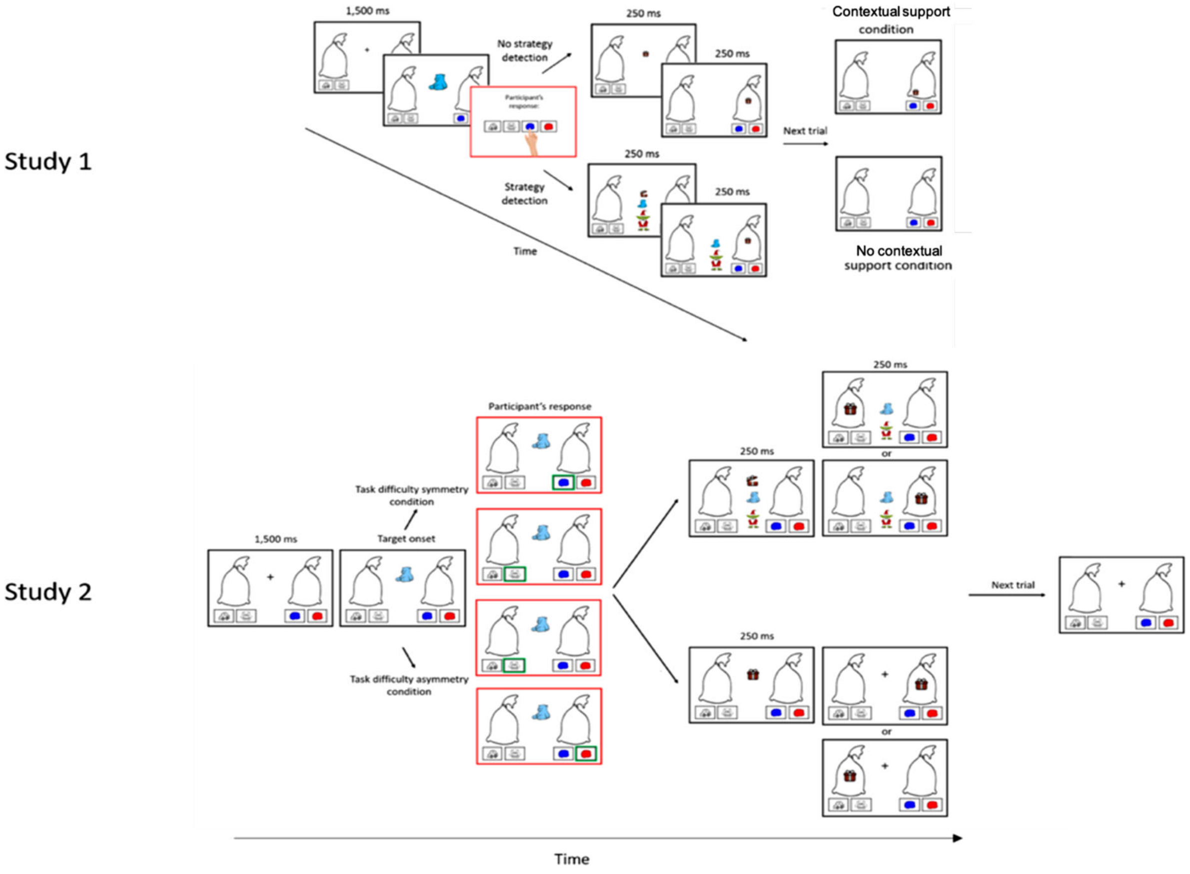

**FIGURE 1** Child-friendly voluntary task switching paradigm. Children had to voluntarily match bidimensional stimuli according to their colour or shape with the general instructions to perform the colour and shapes games equally often (i.e., place about the same number of targets in the Colour or Shape bags) and in random manner (i.e., not using a predictable strategy to avoid the theft of the target by an elf). In Study 1 (top figure), the presents remained into the bag in the next trial (environmental support condition) or disappeared from the bag in the next trial (no environmental support condition). In Study 2 (bottom figure), children had to match targets with the same dimensions in both tasks (task difficulty symmetry condition) to match targets with the same dimensions in one task whereas they had to match targets with the opposite dimensions in the other task (task difficulty asymmetry condition)

on all trials. Each block comprised four practice trials (repeated if more than two errors were made with a maximum of two times) followed by 16 test trials. Then, participants completed two mixed-blocks where they had to voluntarily switch between the two tasks, that is, fill the two bags with about the same number of toys. Importantly, they were instructed to make sure a thieving elf could not predict how they would sort the toys. The following two demonstrations were provided. First, the experimenter demonstrated a strict alternation between the two bags on seven trials (e.g., colour-shape-colour-shape-colour-shape-colour), which resulted in the elf stealing the toy. Second, the experimenter demonstrated how to successfully put about the same number of toys into each bag while not following a predictable order to prevent the elf from stealing toys (e.g., colour-colour-shape-colour-shape-shape-shape-colour-colour-shape-colour-colour). Participants then completed 16 practice trials which were repeated (maximum three times) if (a) one bag contained more than 10 toys (62.5%); (b) the elf detected one of the ten predictable patterns (see Data Processing and Analyses section); and/or (c) more than eight errors (50%) were made. No guidance was provided for the first warm-up block performed but if repetition was then needed, guidance by the experimenter was provided. Only those participants who successfully passed the practice block were included in the sample (5—6-year-olds: $M_{\text{number of practice}} = 1.67$; 9–10 year-olds: $M_{\text{number of practice}} = 1.12$; adults: $M_{\text{number of practice}} = 1.08$). Participants then completed two series of 40 test trials each (80 test trials per condition, 160 in total).

### 1.2.3 | Data processing

Trials were categorised as task switch trials if the bags selected (i.e., tasks) were different on trial *n* and *n*-1 (e.g., sorting a blue teddy-bear by shape in the Shape bag and then sorting a blue teddy-bear by colour in the Colour bag), but as task repetition trials if the bags selected were the same on trial *n* and *n*-1 (e.g., sorting a red car and then a blue car by colour in the Colour bag).

*P*(switch) was calculated by dividing the number of task switch trials by the total number of task switch and task repetition trials.

Task balance consisted in the difference between the proportion of Colour and Shape trials. A score was computed depending on how far the difference from 0 was. For instance, a difference of 0.125 was scored 1, 0.5 was scored 4 and so forth.

Task unpredictability was measured via occurrences of ten different strategies ranging from five basic to complex sequences: "Repetition Only" or "Switch Only" detected over seven trials (e.g., colour-colour-colour-colour-colour-colour-colour or colour-shape-colour-shape-colour-shape-colour, respectively), "One Repetition and Switch" detected over nine trials (e.g., colour-colour-shape-shape-colour-colour-shape-shape-colour), "Two Repetition and Switch" detected over eleven trials (e.g., colour-colour-colour-shape-shape-shape-colour-colour-colour-shape-shape) and "Three Repetition and Switch" detected over thirteen trials (e.g., colour-colour-colour-colour-shape-shape-shape-shape-colour-colour-colour-colour-shape). The frequency of these strategies was used during the game (i.e., when the elf appeared) to index task unpredictability. Moreover, our analyses also focused on the qualitative type of strategies.

### 1.2.4 | Data analyses

*P*(switch), task balance and task unpredictability were analysed using a Linear Mixed Model (LMM), and two Generalized Linear Mixed Models (GLMM 1 and GLMM 2) with a Poisson distribution for count data, respectively. These models were fit in R version 4.0.2 (Team R Core, 2020) using the *lme4* package (Bates et al., 2015). LMM and GLMM 1 contained age group (5-6 years old, 9–10 years-old and adults) and the contextual support condition (no contextual support, contextual support) as fixed effects and Participant as a random effect with all possible interactions. GLMM 2 included age group, the contextual support condition and strategy type (Repetition Only, Switch Only, One Repetition and Switch, Two Repetitions and Switch, Three Repetition and Switch) as fixed effects and Participant as a random effect with all interactions possible using the BOBYQA optimisation (Powell, 2009). On lmer/glmer output we performed mixed model ANOVA tables via Likelihood Ratio Test using the *mixed* function from the *afex* package (Singmann et al., 2021). This function fits the full model and then versions thereof in which a single effect is removed comparing the reduced model to the full model. Pairwise comparisons were used with Tukey's adjustments when there were multiplicity issues using the *emmeans* package (Lenth, 2020) and estimated marginal means (EMMs) from the models are reported. Plots of the results were obtained using the *ggplot2* package (Wickham, 2016) and error bars represent standard errors.

## 1.3 | Results

Results regarding task performance indexed by accuracy and reaction times (RTs) are available in Supplemental Material II.

### 1.3.1 | *P*(switch)

There were no effects of age group and contextual support condition and no interaction, $ps > 0.142$, indicating similar *p*(switch) rates across age groups and contextual support conditions (Figure 2).

### 1.3.2 | Task balance

There were main effects of age group, $\chi^2 = 9.44$, $df = 2$, $p = 0.009$, and contextual support condition, $\chi^2 = 58.71$, $df = 1$, $p < 0.001$, on whether participants performed the two tasks equally often. 5–6 year olds and 9–10 year olds performed the two task less equally often than adults ($M_{\text{5-6 year-olds}} = 1.56$ vs. $M_{\text{9-10 year-olds}} = 1.52$ vs. $M_{\text{adults}} = 0.83$; $ps < 0.021$), but they did not differ from each other, $p = 0.988$. Participants performed the two tasks more equally often with ($M = 0.77$) than without ($M = 2.06$) contextual support. Importantly, age group and contextual support condition interacted, $\chi^2 = 7.30$, $df = 2$, $p = 0.026$ (Figure 3), which revealed that in the no contextual support condition, adults performed the two tasks more equally often than younger and older children at ($M_{\text{5-6 year-olds}} = 3.26$ vs. $M_{\text{9-10 year-olds}} = 2.42$ vs. $M_{\text{adults}} = 1.10$; $ps < 0.005$) with no difference between children, $p = 0.310$. No differences across age groups were observed with contextual support, $ps > 0.382$.

### 1.3.3 | Task unpredictability

The full model comprising main effects and all possible interactions did not converge with the BOBYQA optimisation, we, therefore, reduced this model removing the highest order three-way age group × contextual support condition × strategy type interaction, and this reduced model converged, producing stable results.

On strategy occurrences, there were effects of age group, $\chi^2 = 21.19$, $df = 2$, $p < 0.001$, and strategy type, $\chi^2 = 75.20$, $df = 4$, $p < 0.001$, but not of contextual support condition, $p = 0.436$. Overall, 5–6 year-olds used more predictable strategies than 9–10 year-olds who used more strategies than adults ($M_{\text{5-6 year-olds}} = 0.32$ vs. $M_{\text{9-10 year-olds}} = 0.19$ vs. $M_{\text{adults}} = 0.10$; $ps < 0.048$). Participants used significantly more the "One Repetition and Switch" strategy than other strategies ($M_{\text{Repetition Only}} = 0.20$ vs. $M_{\text{Switch Only}} = 0.36$ vs. $M_{\text{One Repetition and Switch}} = 0.42$ vs. $M_{\text{Two Repetitions and Switch}} = 0.17$ vs. $M_{\text{Three Repetitions and Switch}} = 04$, $ps < 0.015$), but this strategy did not differ from the use of the "Switch Only" strategy, $p = 0.930$. Age group interacted with strategy type, $\chi^2 = 40.73$, $df = 8$, $p < 0.001$ (Figure 4). 5–6 year-olds used more the "Switch Only" strategy than other strategies ($M_{\text{Repetition Only}} = 0.59$ vs. $M_{\text{Switch Only}} = 1.22$ vs. $M_{\text{One Repetition and Switch}} = 0.62$ vs. $M_{\text{Two Repetitions and Switch}} = 0.11$ vs. $M_{\text{Three Repetitions and Switch}} = 0.06$; $ps < 0.001$). 9–10 year-olds used more the "Switch Only" and "One Repetition and Switch" strategies than the "Three Repetitions and Switch" strategy ($M_{\text{Switch Only}} = 0.33$ vs. $M_{\text{One Repetition and Switch}} = 0.35$ vs. $M_{\text{Three Repetitions and Switch}} = 0.05$;

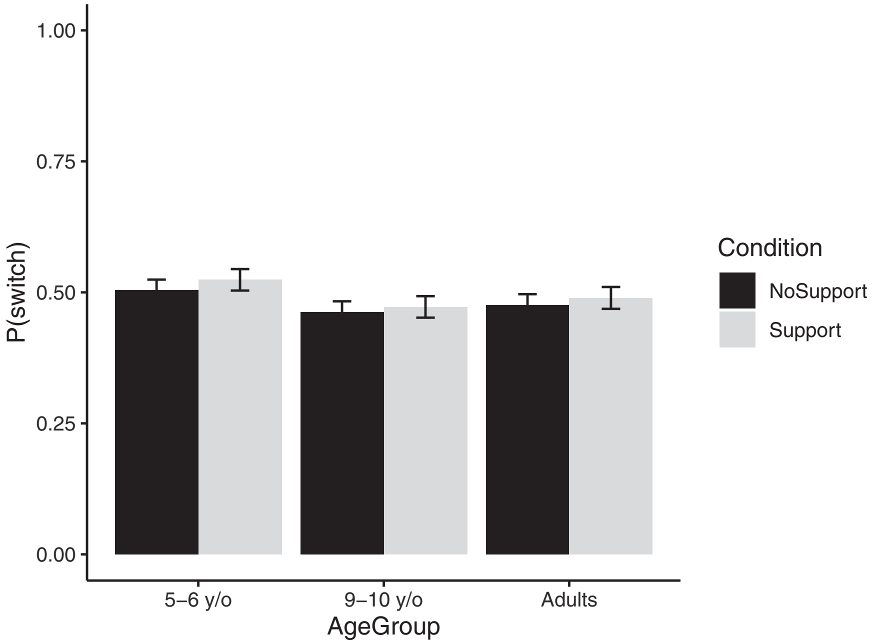

**FIGURE 2** *P*(switch) as a function of age group (5–6 year-olds, 9–10 year-olds, adults) and environmental support condition (environmental support, no environmental support). All age groups showed similar *p*(switch) which did not differ across environmental support conditions

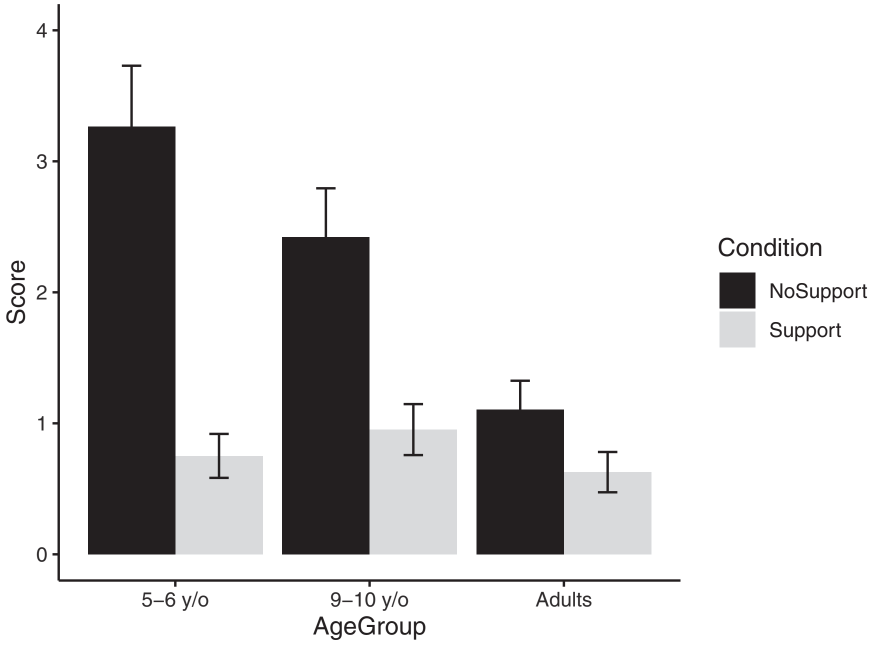

**FIGURE 3** Score of difference as a function of age group (5–6 year-olds, 9–10 year-olds, adults) and environmental support condition (environmental support, no environmental support). Error bars represent standard errors. Children showed greater asymmetry between the two tasks in the no environmental condition than in the environmental condition than adults. No differences were observed between age groups in the environmental support condition

$ps < 0.018$). No other differences were observed, $ps > 0.079$. Adults used more the “One Repetition and Switch” strategy than the “Repetition Only” and “Three Repetitions and Switch” strategies ($M_{\text{Repetition Only}} = 0.07$ vs. $M_{\text{One Repetition and Switch}} = 0.34$ vs. $M_{\text{Three Repetitions and Switch}} = 0.02$; $ps < 0.029$). Finally, 5–6 year-olds used more the “Repetition Only” and “Switch Only” strategies than 9–10 year-olds and adults (9-10 year-olds: $M_{\text{Repetition Only}} = 0.20$; adults: $M_{\text{Switch Only}} = 0.12$; $ps < 0.004$) with no differences between these latter two age groups, $ps > 0.055$. Other comparisons were not significant, $ps > 0.075$, and no other interactions were significant, $ps > 0.065$[1].

## 1.4 | Discussion

Providing contextual support about previously performed tasks enhanced performance, more specifically task balance in children, but not in adults. This suggests that part of children’s difficulty in engaging cognitive control self-directedly stems from sub-optimal context-tracking. Note that both younger and older children showed poorer task balance performance than adults, indicating that difficulties in self-directed situations remain until at least late childhood. As the use of strategies did not vary as a function of contextual support, children did not achieve greater task balance through more frequent use

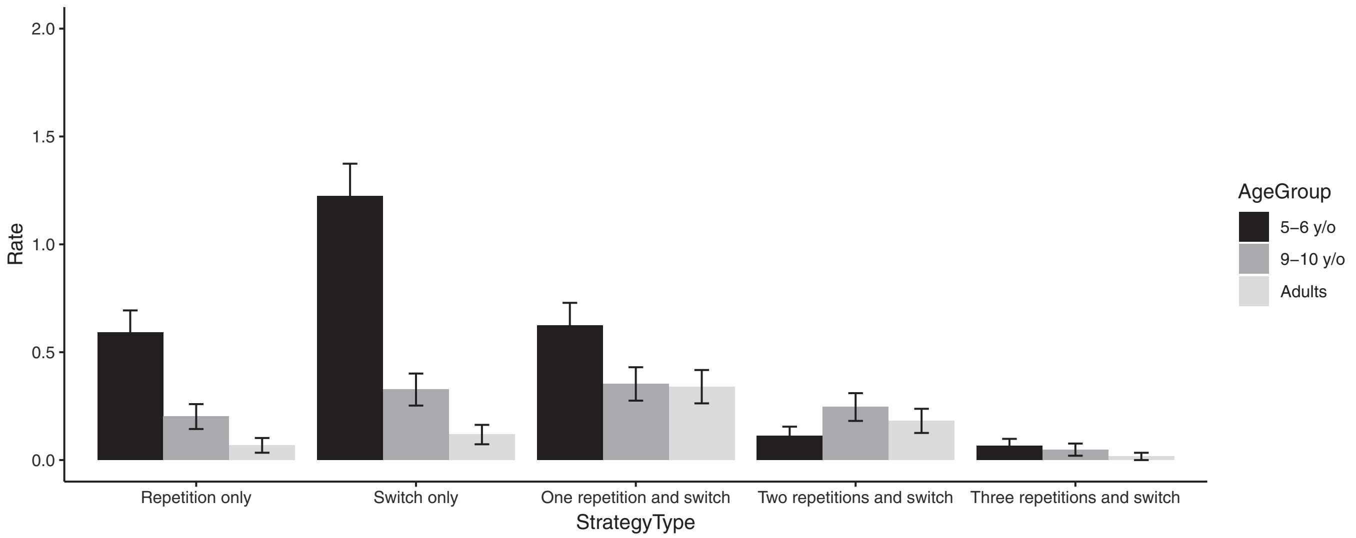

**FIGURE 4** Mean number of times each strategy was used as a function of the type of strategies (Repeat Only, Switch Only, One Repetition and Switch, Two Repetitions and Switch, Three Repetitions and Switch) and age group (5–6 year-olds, 9–10 year-olds, adults). 5–6 year-olds used significantly more strategies ("Repetition Only," "Switch Only") than other age groups and used preferentially the "Switch Only' strategy

of strategies. Instead, contextual support helped children to perform both tasks more equally often in runs of trials where they did perform them randomly; however, contextual support did not reduce the likelihood to slip into a strategy, hence not affecting task unpredictability overall. However, we provided contextual support about how often each task was performed but not about the sequence of tasks that had been performed. It is possible that the latter type of information would have resulted in more random task selection, which should be tested in future research. Further, we noted that in both conditions, younger children relied more on the "Switch Only" strategy than older children and adults, supporting previous findings reporting young children have no difficulties to generate a switch by themselves (Freier et al., 2017; Frick et al., 2019).

## 2 | STUDY 2

### 2.1 | Introduction

Study 2 addressed the role of task selection in children's VTS performance by manipulating task difficulty (a)symmetry. Indeed, task asymmetry has been shown to significantly bias participants to repeat the harder task more than the easier task, significantly affecting *p*(switch) in multiple adult studies (Liefooghe et al., 2010; Millington et al., 2013; Poljac et al., 2018; Weaver & Arrington, 2010; Yeung, 2010). This phenomenon is explained by between-task interference effects that occur when two tasks differ in their relative strength because the difficult task engages working memory to a larger extent than the easy task, making it more difficult to move away from this task, as there are fewer resources left for switching. As such, this manipulation offers an interesting way to test the contribution of task selection to self-directed control during childhood. To this end, 5–6 years-old and 9–10 years-old children, as well as, adults completed a child-adapted version of VTS, similar to Study 1. In the task difficulty symmetry condition, participants performed the same two tasks ("regular" colour and shape matching) as in Study 1. In the task difficulty asymmetry condition, participants performed the regular shape matching task (easy) and a "reversed" colour-matching task in which they had to match the target to the response option of the other colour (difficult). Critically, this particular condition also required response inhibition abilities, which are involved in the task selection process, and both are supported by the same brain areas (pre-SMA circuits; Mostofsky & Simmonds, 2008). As such, choosing a task that is demanding on inhibitory processes is likely to interfere with task selection, but not particularly with context-tracking. Overall, we expected lower accuracy and longer RTs with asymmetric than symmetric task difficulty. More critically, we expected that if task selection is an important source of difficulty and contributes to developmental differences, then task difficulty asymmetry should negatively affect performance and these effects should be more pronounced in younger than older participants. In contrast, if task selection is relatively trivial in VTS, then task difficulty asymmetry should affect response times and accuracy, but not the other indices of VTS.

### 2.2 | Methods

#### 2.2.1 | Participants

Participants were 30 5–6 year-old children ($M_{age}$ = 5.95 years, $SD_{age}$ = 0.55 years, range = 5.00–6.90 years, 17 females), 30 9–10 year-old children ($M_{age}$ = 9.98, $SD_{age}$ = 0.53, range = 6.08–10.84, 15 females) and 30 adults ($M_{age}$ = 20.68, $SD_{age}$ = 1.81, range = 18.07–26.15, 15 females)[2]. All children were recruited at the same private school and adults were students enrolled at the University of the same city. A parental consent was obtained for each child, who also gives a verbal and written assent to participate. Children received age-appropriate prices and adults received 2€ for their participation. This study received approval from the Ethics Committee of the University of Edinburgh as well as from the participating school. Participants were mostly Caucasian and as the children came from the same private school, they had the same SES background although this information was not collected.

### 2.2.2 | Material and procedure

Children were tested in a quiet room within the school and adults were tested in a quiet room at the university. They completed a child-friendly VTS paradigm, similar to Study 1, presented with E-Prime 2 (Psychology Software Tools, Pittsburgh, PA). The procedure and number of trials were the same as in Study 1 (5–6 year-olds: $M_{\text{number of practice}} = 1.50$; 9–10 year-olds: $M_{\text{number of practice}} = 1.43$; adults: $M_{\text{number of practice}} = 1.30$). The exception was that this time, participants entered their responses by pressing one of the four buttons (i.e., “q,” “w,” “o,” “p”) on a QWERTY keyboard. All participants completed two conditions (Figure 1). In the task symmetry condition, which was similar to the no contextual support condition in Study 1, participants were told to match the targets either with the button of the same Colour or with the button of the same Shape, the task symmetry condition. Conversely, in the task asymmetry condition, they had to match the target with the button of the same dimension for one game (e.g., match the targets with the button of the same shape when playing the Shape game) and to match the target with the button of the different dimension for the other game (e.g., match the targets with the button of the different colour when playing the Colour game). The order of the two working memory demands conditions was counter-balanced across participants.

### 2.2.3 | Data processing

Task performance on the easy and difficult tasks on single-task blocks within the higher working memory demands (task difficulty asymmetry condition) was examined through accuracy and RTs to ensure that these two tasks had different levels of difficulty. These analyses were performed after discarding the first trial of each block. Prior to analyses, RTs were log-transformed (to correct for skewness and minimize baseline differences between ages; Meiran, 1996). Only RTs for correct trials preceded by correct trials were kept. Finally, RTs were trimmed out if they were under 200 milliseconds (ms), to account for accidental button presses, or greater than three standard deviations above the mean of each participant (computed separately for trials from single blocks, and task repetition and task switch trials from mixed blocks) or 10,000 ms.

*P*(switch), task balance and task unpredictability were computed using the same procedure than in Study 1.

### 2.2.4 | Data analyses

Our analyses first focused on whether the supposedly easy task was indeed less costly than the difficult task in terms of accuracy and averaged RTs within the task difficulty asymmetry condition. As such, a GLMM and LMM were performed with age group (5-6 year-olds, 9–10 year-olds and adults) and task difficulty (easy, difficult) as fixed effects and Participant as a random effect. Then, *p*(switch), task balance and task unpredictability were analysed a similar manner as in Study 1 with the difference that the task difficulty condition (symmetry, asymmetry) replaced the contextual support condition. EMMs from the models and plots with standard errors as error bars are reported.

## 2.3 | Results

Results regarding task performance indexed by accuracy and RTs are available in Supplemental Material, IV.

### 2.3.1 | Easy task versus hard task—Accuracy rates and RTs

The analysis performed on the accuracy measure showed a main effect of task difficulty, $\chi^2 = 34.72$, $df = 1$, $p < 0.001$, but not of age group, $p = 0.498$. Accuracy was lower in the harder task than in the easier task ($M_{\text{hard}} = 0.94$ vs. $M_{\text{easy}} = 0.98$; $p < 0.001$). Age group significantly interacted with task difficulty, $\chi^2 = 21.91$, $df = 2$, $p < 0.001$ (Figure 5). Five to six-years-olds and adults were significantly less accurate when the task was difficult than when the task was easy (5–6 year-olds: $M_{\text{easy}} = 0.99$ vs. $M_{\text{difficult}} = 0.91$; adults: $M_{\text{easy}} = 0.98$ vs. $M_{\text{hard}} = 0.95$; $ps < 0.002$), whereas no difference in terms of accuracy between the easy and the hard task was observed for 9–10 year-olds, $p = 0.906$. On RTs, there were main effects of age group, $\chi^2 = 97.48$, $df = 2$, $p < 0.001$, and task difficulty, $\chi^2 = 63.53$, $df = 1$, $p < 0.001$, but no interaction between these factors, $p = 0.219$. Overall, 5–6 year-olds were significantly slower than 9–10 year-olds, and 9–10 year-olds were significantly slower than adults ($M_{\text{5-6 year-olds}} = 7.28$ log-transformed ms (ln ms) vs. $M_{\text{9-10 year-olds}} = 6.74$ ln ms vs. $M_{\text{adults}} = 6.40$ ln ms; $ps < 0.001$). Moreover, participants were significantly slower on the difficult task than on the easy task ($M_{\text{easy}} = 6.64$ ln ms vs. $M_{\text{difficult}} = 6.98$ ln ms).

### 2.3.2 | *P*(switch)

On *p*(switch), there was a significant main effect of age group, $\chi^2 = 9.77$, $df = 2$, $p = 0.008$, but no effect of task difficulty (a)symmetry condition and no interaction, $ps > 0.155$ (Figure 6). Nine to ten year-olds switched significantly more than adults, but not than 5–6 year-olds ($M_{\text{5-6 year-olds}} = 0.49$ vs. $M_{\text{9-10 year-olds}} = 0.55$ vs. $M_{\text{adults}} = 0.47$; $p = 0.008$ and $p = 0.071$) and the two latter age groups did not differ, $p = 0.690$.

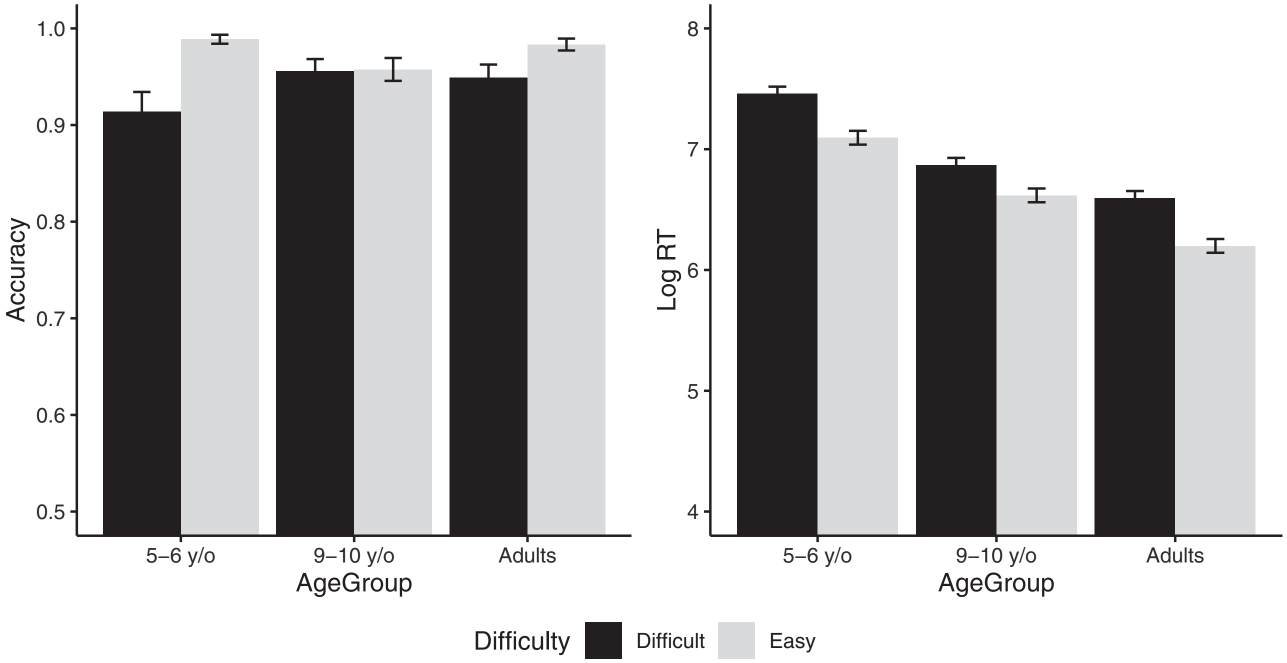

**FIGURE 5** Accuracy and log RTs as a function of age group (5–6 year-olds, 9–10 year-olds and adults) and task difficulty (easy task, hard task). Accuracy was lower and log RTs were higher in the hard task than in the easy task

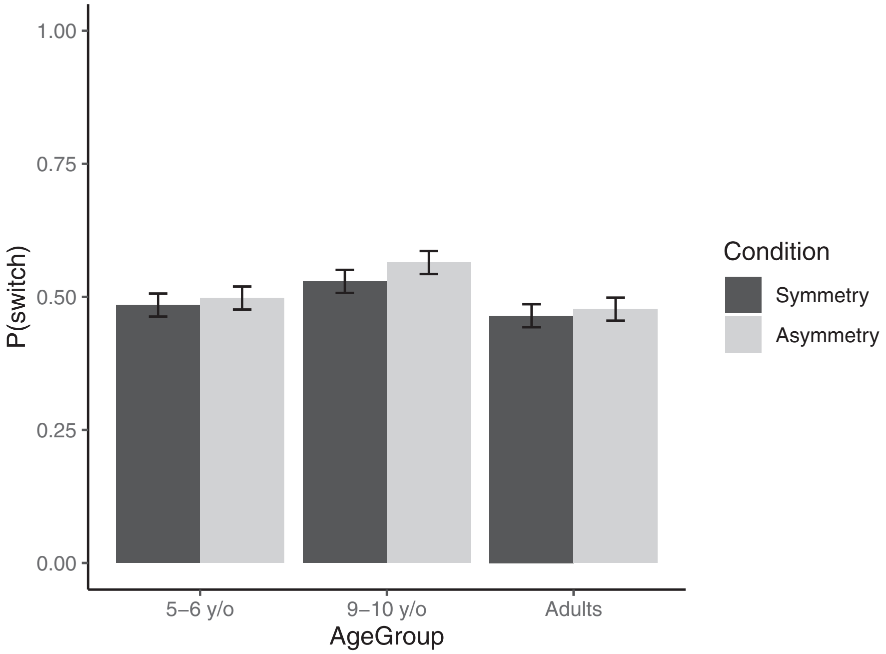

**FIGURE 6** *P*(switch) as a function of age group (5–6 year-olds, 9–10 year-olds, adults) and task difficulty (a)symmetry condition (task difficulty symmetry, task difficulty asymmetry). 5–6 year-olds and adults showed similar *p*(switch) whereas 9–10 year-olds showed higher *p*(switch) than adults. *P*(switch) did not vary as a function of task difficulty (a)symmetry conditions

### 2.3.3 | Task balance

On task balance, one subject was removed because he/she had an outlier score of 49 whereas the maximum score for other subjects was 23.

There was a significant main effect of age group, $\chi^2 = 7.29$, $df = 2$, $p = 0.026$, and task difficulty a(symmetry) condition, $\chi^2 = 7.48$, $df = 1$, $p = 0.006$, but no interaction between these factors, $p = 0.123$ (Figure 7). Five to six year-olds showed a significantly greater imbalance between the two tasks in comparison to adults, but did not differ from 9 to 10 year-olds ($M_{\text{5-6 year-olds}} = 3.39$ vs. $M_{\text{9-10 year-olds}} = 2.31$ vs. $M_{\text{adults}} = 2.19$; $p = 0.031$ and $p = 0.067$). Nine to ten year-olds and adults did not differ from each other, $p = 0.950$.

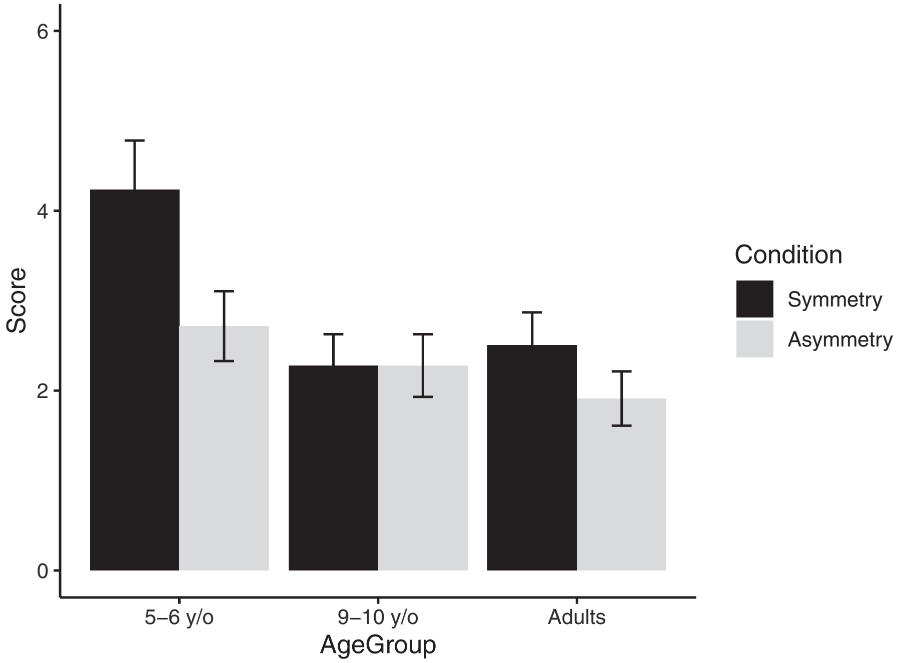

**FIGURE 7** Score of difference as a function of age group (5–6 year-olds, 9–10 year-olds, adults) and task difficulty (a)symmetry condition (task difficulty symmetry, task difficulty asymmetry). 5–6 year-olds showed greater asymmetry between the two tasks selection than 9–10 year-olds and adults. The two latter did not differ. Participants showed greater asymmetry regarding task balance in the task difficulty symmetry condition than in the task difficulty asymmetry condition

Surprisingly, participants performed significantly less equally often the two tasks in the task difficulty symmetry condition than in the task difficulty asymmetry condition ($M_{\text{task difficulty symmetry condition}} = 2.91$ vs. $M_{\text{task difficulty asymmetry condition}} = 2.29$).

### 2.3.4 | Task unpredictability

The full model comprising the main effects and all possible interactions did not converge with the BOBYQA optimisation. As in Study 1, we first removed the higher three-way interaction and ran the model again, which again did not converge. Using plots, we identified that some values of combinations of factor levels had zero variance, we, therefore, subset the data by removing those with zero variance. This reduced model finally converged but produced a warning which disappeared when removing the task difficulty (a)symmetry condition × strategy type interaction. However, keeping the age group × strategy type interaction led to inestimable estimates. We therefore removed this interaction and report the reduced converging model containing the main effects and the age group × task difficulty (a)symmetry condition interaction.

This model revealed main effects of age group, $\chi^2 = 6.83$, $df = 2$, $p = 0.009$, task difficulty (a)symmetry condition, $\chi^2 = 4.48$, $df = 1$, $p = 0.034$, and strategy type, $\chi^2 = 68.35$, $df = 4$, $p < 0.001$, on strategy occurrences (Figure 8). Five to six year-olds used significantly more strategies than 9–10 year-olds, who used significantly more strategies than adults ($M_{\text{5-6 year-olds}} = 0.41$ vs. $M_{\text{9-10 year-olds}} = 0.27$ vs. $M_{\text{adults}} = 0.14$; $ps < 0.031$). Participants used significantly more strategy in the task difficulty asymmetry condition than in the task symmetry condition ($M_{\text{task difficulty symmetry condition}} = 0.23$ vs. $M_{\text{task difficulty asymmetry condition}} = 0.30$), and used more the “Switch Only” and “One Repetition and Switch” strategies than other strategies ($M_{\text{Repetition Only}} = 0.31$ vs. $M_{\text{Switch Only}} = 0.69$ vs. $M_{\text{One Repetition and Switch}} = 0.56$ vs. $M_{\text{Two Repetitions and Switch}} = 0.17$ vs. $M_{\text{Three Repetitions and Switch}} = 0.06$; $ps < 0.001$), with no difference between these two strategies, $p = 0.438$.

The interaction between age group and task difficulty (a)symmetry condition was not significant, $p = 0.570$.

## 2.4 | Discussion

As expected, lower accuracy and higher RTs were observed in the task difficulty asymmetry condition than in the task difficulty symmetry condition, which speaks to the success of our manipulation.

Task balance and task unpredictability were differently affected by the task difficulty (a)symmetry, whereas *p*(switch) was not. Interestingly, participants were less likely to perform the two tasks equally often when the task difficulty was symmetrical than when the task difficulty was asymmetrical. Conversely, when the task difficulty was asymmetrical, participants used significantly more predictable strategies. This pattern of results suggests that only task unpredictability was negatively affected by our manipulation. More specifically regarding task unpredictability, given that the model did not allow us to test for the interactions between age group and strategy type, and task difficulty (a)symmetry condition and strategy type, we conducted

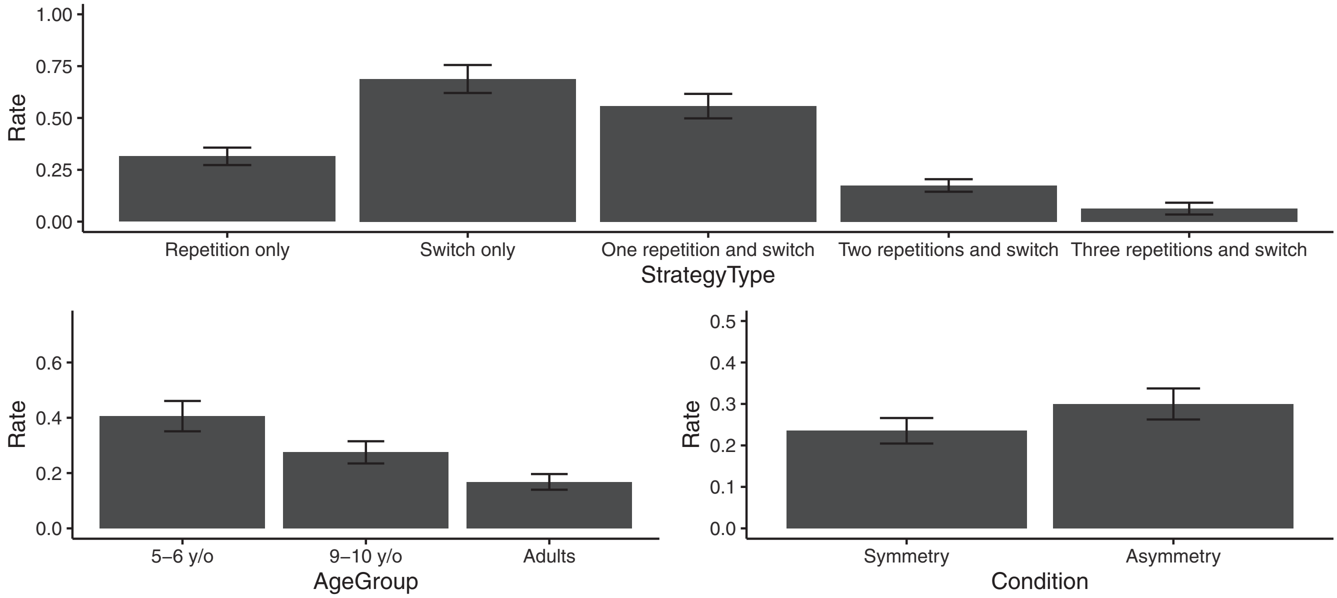

**FIGURE 8** Number of strategy used as a function of age group (5–6 year-olds, 9–10 year-olds, adults; top left figure), task difficulty (a)symmetry condition (task difficulty symmetry, task difficulty asymmetry; top right figure) and strategy type (Repeat Only, Switch Only, One Repetition and Switch, Two Repetitions and Switch, Three Repetitions and Switch; bottom figure). 5–6 year-olds used more strategies than 9–10 year-olds who used more strategies than adults. Participants used more strategies in the task difficulty asymmetry condition than in the task difficulty symmetry condition. Participants used more the "Switch Only" and "One Repetition and Switch" strategies than other strategies

a mixed ANOVA to explore these possible interactions (see Supplemental Material, V). This analysis produced similar main effects than our GLMM but more specifically revealed that participants used the "Switch Only" strategy more in the task difficulty asymmetry condition than in the task difficulty symmetry condition. This finding suggests that task selection does indeed contribute to participants' difficulty in VTS, and given the lack of interaction between age group and task difficulty (a)symmetry condition, this contribution may be similar for children and adults. To confirm this conclusion, however, it will be important in future research to examine whether alleviating the difficulty of task selection would similarly benefit children and adults (as we would expect), or differentially influence performance across age groups.

Indeed, as the "Switch Only" strategy is generally more frequent in younger children than the other age groups, increasing the difficulty of task selection may make older age groups revert to less mature engagement of cognitive control, more akin to younger children. An important question is why increasing this difficulty results in more frequent use of "Switch Only" but not the other strategies. One plausible answer is that the use of the "Switch Only" strategy reduces demands on task selection, but also context-tracking (i.e., one only needs to know what task has just been performed in order to select the new task, alleviating the working memory demands on context-tracking and task selection), whereas other strategies minimise task selection but at the cost of relatively high context-tracking demands (i.e., need to maintain information about previously performed tasks over several trials). This assumption is backed by the fact that participants performed better on task balance in the task difficulty asymmetry condition than in the task difficulty symmetry condition.

Note that participants did not perform the harder task more often than the easier task when the two tasks differed in difficulty, which is contrary to previous studies (Liefooghe et al., 2010; Millington et al., 2013; Weaver & Arrington, 2010; Yeung, 2010). One potential reason for this result is that the difference in difficulty between the two tasks in the task difficulty asymmetry condition may not have been strong enough for participants, as they were both perceptual tasks and were not strongly different in terms of working memory demands as in previous adult studies.

Finally, *p*(switch) unexpectedly varied across age groups, with older children showing a higher *p*(switch) than the other groups. This pattern may be due to the fact that older children used more the "Switch Only" strategy than other strategies and showed less variation in strategy use than younger children (see Supplemental Material, V). This suggests that *p*(switch) may be more informative about VTS performance in older children and adults than in younger children, as the two former age groups showed less variability in the strategies they used. But, the fact that *p*(switch) was not affected by the task (a)symmetry manipulation, contrary to previous studies (Liefooghe et al., 2010; Yeung, 2010), also suggests that task unpredictability might be a better index of task selection than *p*(switch).

## 3 | GENERAL DISCUSSION

The present paper tested the extent to which these context-tracking and task selection may differentially contribute to developmental progress in self-directed control. In two studies, we observed that the effect of contextual support (Study 1) was most pronounced in younger participants, whereas the effect of task difficulty (a)symmetry (Study 2) did not interact with age. Therefore, although both context-tracking and task selection may contribute to self-directed control, context-tracking seems to drive developmental progress during childhood to a much greater extent than task selection, at least in VTS. In other words, relative to adults, children disproportionately struggle to extract contextual information, however once this information has been extracted, they do not struggle more than adults to use it to identify the relevant task. Thus, our findings point out to distinct developmental trajectories, potentially reflecting more substantial age-related change in context-tracking than task selection. However, an alternative interpretation remains possible. Although context-tracking is critical for VTS performance when one attempts to perform the tasks in a pseudo-random sequence by keeping track of previous trials, one may alternatively attempt to select the task in a genuinely random fashion on a trial-by-trial basis, in which case task selection would be fully independent of context tracking. Our results may thus indicate that children are less likely than older participants to adopt a genuine random task selection approach as evidenced by the number of non-random strategies used by the latter. Future research should directly test these two possibilities and examine the developmental course of context tracking and task selection in more detail.

An important question that follows from these findings is what drives better context-tracking with age. Working memory capacity increase during childhood (e.g., Camos & Barrouillet, 2018) may play a prominent role. Working memory, which is a key component of cognitive control (Friedman & Miyake, 2017), is likely to support efficient context-tracking because this process requires maintaining contextual information without external aids and updating this information as a function of changes in the environment and/or past actions (i.e., previous task selections). Indeed, the slow development of working memory capacity during childhood and adolescence may explain why context-tracking remains challenging until late childhood. Moreover, previous behavioural research has reported that children with atypical development causing working memory impairments show poorer performance on self-directed tasks than typically developing children, whereas this difference is attenuated in externally driven tasks (Craig et al., 2016; White et al., 2009). Specifically the cingulate cortex supports successful working memory engagement (Lenartowicz & McIntosh, 2005; Rushworth et al., 2003) and the anterior cingulate cortex has been found to be involved in context-learning guiding task selection (Umemoto et al., 2017) or in voluntary choices based on the history of past actions (Kennerley et al., 2006), suggesting that context-tracking and working memory may be supported by common brain regions.

Interestingly, in Studies 1 and 2, children used systematic strategies consisting of repeating the same task or in switching tasks on every trial, which is in line with a previous study (Frick et al., 2019). The fact that even younger children had very little difficulty in switching between tasks echoes recent research using externally driven tasks showing that switch costs (i.e., the costs associated with task switching) do not vary with age whereas mixing costs (i.e., the costs associated with goal identification) decrease with age (Chevalier et al., 2018; Peng et al., 2018). Therefore, the present findings add to the growing body of evidence that goal identification may be a greater source of difficulty than switching per se in cognitive control development (Broeker et al., 2018; Chevalier, 2015). Importantly, the use of either strategy (Repetition Only and Switch Only) may be a way for children to ease context-tracking demands, as they only require keeping track of the task performed on the immediately preceding trial. These strategies also facilitate task selection, but at the cost of reduced randomness. Further, younger children showed substantial variability in the types of strategy they used, more so than older children and adults. Although we did not measure working memory capacity, the types of strategy that children used may relate to individual differences in working memory capacity, as has been previously shown in a different task-switching paradigm at age 5 (Dauvier et al., 2012). For instance, children with the poorest working memory capacities may have used the strategy of repeating always the same task, as this pattern does not require strong maintenance of previous tasks and contextual information updating while also dropping switching demands. Conversely, children with higher working memory capacities may have used more demanding strategies such as switching on every two trials or may have used less strategies overall. Indeed, their working memory capacities might have been strong enough to manage the higher costs of context-tracking without external aids. Nevertheless, this claim remains a speculation at this stage, as we did not test working memory capacity, however, it offers an interesting venue for future research to explore the link between working memory capacities and context-tracking.

In addition to working memory, age-related gains in context-tracking may relate to increasing abstract representation capacity, which has been argued to support successful self-directed control development (Snyder & Munakata, 2010, 2013). This capacity allows the formation and maintenance of task representations, which may be critical to context-tracking. More specifically, previous studies on self-directed control development have typically used fluency tasks, in which children were asked to name as many items from a particular category (e.g., animals) as possible in a short amount of time. Younger children were found to struggle to form short clusters of items from the same sub-category (e.g., lion, tiger, zebra etc.) but also to repeat the same items throughout the task (Snyder & Munakata, 2010, 2013). While this behaviour may be explained by failure to form abstract representations of different categories and sub-categories, this might be also due to difficulties with context-tracking, namely with manipulating these abstract representations to keep track of which items have already been chosen and from which specific sub-category. However, at this point, it remains an open question whether gains in context-tracking relate to increasingly abstract representations and/or greater working memory capacity with age. This question should be directly addressed in future research.

Interestingly, the manipulation targeting context-tracking and task selection negatively affected task balance (Study 1) and task unpredictability (Study 2), respectively. This pattern of findings raises the possibility that task balance is mostly sensitive to context tracking and task unpredictability primarily captures task selection. However, we need to be cautious about such assumption for two reasons, our manipulations also positively affected the other measure (albeit to a lesser extent), indicating that each measure was somewhat sensitive to both manipulations. Nevertheless, the extent to which task balance and task unpredictability maps onto context-tracking and task selection should be explored further in the future.

Finally, one limitation common to our two studies is the presence of a cue (i.e., a "thief elf") appearing on the monitor when a participant used a non-random task unpredictability. This particular point differs from traditional adult studies using the VTS, in which no such cues appear informing the participant about their use or non-use of predictable pattern. The presence of this cue may provide support for task unpredictability and may, to some extent, encourage the use of context tracking to follow a pseudo-random sequence of tasks (as opposed to adopting a genuinely random task selection approach). Although, we believe that these two versions tap the same processes given that the instructions (i.e., performing the two tasks equally often and in random manner) and the design (i.e., absence of task cues) are similar, this needs to be established in future research by directly comparing both versions. We also acknowledge that the two studies presented may forcibly dichotomise complex cognitive processes, whose complex interactions will need to be further examined in future research. Furthermore, beyond the traditional version of the VTS, it will be important to examine the extent to which the present findings generalise to more ecological contexts in order to better understand the interplay between context tracking and task selection in the development of self-directed control and develop efficient interventions aimed at promoting autonomous behaviours in children. That said, the present findings provide important initial evidence that both context-tracking and task selection contribute to self-directed control performance, but age-related gains during children are mostly driven by progress in context-tracking.

## ACKNOWLEDGMENTS

We thank Helen Wright for proof-reading the current paper and helpful comments made on previous versions of this paper. This research was funded by a doctoral scholarship from Suor Orsola Benincasa University and Research Grant Support from the University of Edinburgh awarded to Aurélien Frick.

## CONFLICT OF INTEREST

We declare no conflict of interest.

## ETHICS

This study has received approvals from the Ethic Committee of the University of Edinburgh.

## PERMISSION

We allow to reproduce material from other sources.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

## ORCID

*Aurélien Frick* https://orcid.org/0000-0002-3702-5186

## ENDNOTES

[1] The interaction age group × condition was marginally significant, $p = 0.065$. Although 5-6 year-olds and adults used predictable strategies equally often in the two conditions, $ps > 0.759$, 9–10 year-olds used these strategies significantly more often when contextual support was provided than when no contextual support was provided ($M = 0.26$ vs. $M = 0.14$; $p = 0.028$).

[2] Note that children from Study 1 and Study 2 had overall similar cognitive performance, indexed by accuracy and log RTs in the condition that was the same between studies (no contextual support condition for Study 1 and task difficulty symmetry condition for Study 2), the samples in the two studies are comparable (see Supplemental Information, III).

## REFERENCES

Arrington, C. M., & Logan, G. D. (2004). The cost of a voluntary task switch. *Psychological Science*, *15*(9), 610–615. https://doi.org/10.1111/j.0956-7976.2004.00728.x

Arrington, C. M., Reiman, K. M., & Weaver, S. M. (2014). Voluntary task-switching. In (J. A. Grange & G. Houghton Eds.), *Task switching and cognitive control* (pp. 117–136). Oxford University Press.

Badre, D. (2008). Cognitive control, hierarchy, and the rostro-caudal organization of the frontal lobes. *Trends in Cognitive Sciences*, *12*(5), 193–200. https://doi.org/10.1016/j.tics.2008.02.004

Badre, D., & Nee, D. E. (2018). Frontal cortex and the hierarchical control of behavior. In *Trends in cognitive sciences* (Vol., 22, Issue (2), pp. 170–188). Elsevier Ltd. https://doi.org/10.1016/j.tics.2017.11.005

Barker, J. E., & Munakata, Y. (2015). Developing self-directed executive functioning: Recent findings and future directions. *Mind, Brain, and Education*, *9*(2), 92–99. https://doi.org/10.1111/mbe.12071

Barker, J. E., Semenov, A. D., Michaelson, L., Provan, L. S., Snyder, H. R., & Munakata, Y. (2014). Less-structured time in children's daily lives predicts self-directed executive functioning. *Frontiers in Psychology*, *5*. https://doi.org/10.3389/fpsyg.2014.00593

Bates, D., Mächler, M., & Bolker, B. (2015). Fitting linear mixed-effects models using (lme4). *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Broeker, L., Liepelt, R., Poljac, E., Künzell, S., Ewolds, H., de Oliveira, R. F., & Raab, M. (2018). Multitasking as a choice: A perspective. *Psychological Research*, *82*(1), 12–23. https://doi.org/10.1007/s00426-017-0938-7

Camos, V., & Barrouillet, P. (2018). *Working memory in development*. London, UK: Routledge.

Chatham, C. H., & Badre, D. (2015). Multiple gates on working memory. In *Current opinion in behavioral sciences* (Vol., 1, pp. 23–31). Elsevier Ltd. https://doi.org/10.1016/j.cobeha.2014.08.001

Chatham, C. H., Frank, M. J., & Badre, D. (2014). Corticostriatal output gating during selection from working memory. *Neuron*, *81*(4), 930–942. https://doi.org/10.1016/j.neuron.2014.01.002

Chevalier, N. (2015). Executive function development: Making sense of the environment to behave adaptively. *Current Directions in Psychological Science*, *24*(5), 363–368. https://doi.org/10.1177/0963721415593724

Chevalier, N., & Blaye, A. (2009). Setting goals to switch between tasks: Effect of cue transparency on children's cognitive flexibility. *Developmental Psychology*, *45*(3), 782–797. https://doi.org/10.1037/a0015409

Chevalier, N., Chatham, C. H., & Munakata, Y. (2014). The practice of going helps children to stop: The importance of context monitoring in inhibitory control. *Journal of Experimental Psychology: General*, *143*(3), 959–965. https://doi.org/10.1037/a0035868

Chevalier, N., Dauvier, B., & Blaye, A. (2018). From prioritizing objects to prioritizing cues: A developmental shift for cognitive control. *Developmental Science*, *21*(2), e12534. https://doi.org/10.1111/desc.12534

Craig, F., Margari, F., Legrottaglie, A. R., Palumbi, R., de Giambattista, C., & Margari, L. (2016). A review of executive function deficits in autism spectrum disorder and attention-deficit/hyperactivity disorder. In *Neuropsychiatric disease and treatment* (Vol., 12, pp. 1191–1202). Dove Medical Press Ltd. https://doi.org/10.2147/NDT.S104620

Dauvier, B., Chevalier, N., & Blaye, A. (2012). Using finite mixture of GLMs to explore variability in children's flexibility in a task-switching paradigm. *Cognitive Development*, *27*, 440–454. https://doi.org/10.1016/j.cogdev.2012.07.004

Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*(1), 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Doebel, S., & Zelazo, P. D. (2015). A meta-analysis of the Dimensional Change Card Sort: Implications for developmental theories and the measurement of executive function in children. In *Developmental Review* (Vol., 38, pp. 241–268). Mosby Inc. https://doi.org/10.1016/j.dr.2015.09.001

Freier, L., Cooper, R. P., & Mareschal, D. (2017). Preschool children's control of action outcomes. *Developmental Science*, *20*(2), e12354. https://doi.org/10.1111/desc.12354

Freier, L., Gupta, P., Badre, D., & Amso, D. (2021). The value of proactive goal setting and choice in 3- to 7-year-olds' use of working memory gating strategies in a naturalistic task. *Developmental Science*, *24*(1). https://doi.org/10.1111/desc.13017

Frick, A., Brandimonte, M. A., & Chevalier, N. (2019). Voluntary task switching in children: Switching more reduces the cost of task selection. *Developmental Psychology*, *55*(8), 1615–1625. https://doi.org/10.1037/dev0000757

Frick, A., Brandimonte, M. A., & Chevalier, N. (2021). Disentangling the respective contribution of task selection and task execution to self-directed cognitive control development. *Child Development*, *92*(4), 1309–1324. https://doi.org/10.1111/cdev.13479

Friedman, N. P., & Miyake, A. (2017). Unity and diversity of executive functions: Individual differences as a window on cognitive structure. In *Cortex* (Vol., 86, pp. 186–204). Masson SpA. https://doi.org/10.1016/j.cortex.2016.04.023

Kennerley, S. W., Walton, M. E., Behrens, T. E. J., Buckley, M. J., & Rushworth, M. F. S. (2006). Optimal decision making and the anterior cingulate cortex. *Nature Neuroscience*, *9*(7), 940–947. https://doi.org/10.1038/nn1724

Kray, J., Eber, J., & Karbach, J. (2008). Verbal self-instructions in task switching: A compensatory tool for action-control deficits in childhood and old age? *Developmental Science*, *11*(2), 223–236. https://doi.org/10.1111/j.1467-7687.2008.00673.x

Kray, J., Gaspard, H., Karbach, J., & Blaye, A. (2013). Developmental changes in using verbal self-cueing in task-switching situations: The impact of task practice and task-sequencing demands. *Frontiers in Psychology*, *4*, 940. https://doi.org/10.3389/fpsyg.2013.00940

Lenartowicz, A., & McIntosh, A. R. (2005). The role of anterior cingulate cortex in working memory is shaped by functional connectivity. *Journal of Cognitive Neuroscience*, *17*(7), 1026–1042. https://doi.org/10.1162/0898929054475127

Lenth, R. (2020). emmeans: Estimated Marginal Means, aka Least-Squares Means. Available online at: https://CRAN.R-project.org/package=emmeans

Liefooghe, B., Demanet, J., & Vandierendonck, A. (2010). Persisting activation in voluntary task switching: It all depends on the instructions. *Psychonomic Bulletin & Review*, *17*(3), 381–386. https://doi.org/10.3758/PBR.17.3.381

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *22*(6), 1423–1442. https://doi.org/10.1037/0278-7393.22.6.1423

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, *24*(1), 167–202. https://doi.org/10.1146/annurev.neuro.24.1.167

Millington, R. S., Poljac, E., & Yeung, N. (2013). Between-task competition for intentions and actions. *Quarterly Journal of Experimental Psychology*, *66*(8), 1504–1516. https://doi.org/10.1080/17470218.2012.746381

Mittelstädt, V., Dignath, D., Schmidt-Ott, M., & Kiesel, A. (2018). Exploring the repetition bias in voluntary task switching. *Psychological Research*, *82*(1), 78–91. https://doi.org/10.1007/s00426-017-0911-5

Mostofsky, S. H., & Simmonds, D. J. (2008). Response inhibition and response selection: Two sides of the same coin. *Journal of Cognitive Neuroscience*, *20*(5), 751–761. MIT Press 238 Main St., Suite 500, Cambridge, MA 02142-1046USA journals-info@mit.edu . https://doi.org/10.1162/jocn.2008.20500

Munakata, Y., Snyder, H. R., & Chatham, C. H. (2012). Developing cognitive control: Three key transitions. *Current Directions in Psychological Science*, *21*(2), 71–77. https://doi.org/10.1177/0963721412436807

O'Reilly, R. C., & Frank, M. J. (2006). Making working memory work: A computational model of learning in the prefrontal cortex and basal ganglia. *Neural Computation*, *18*(2), 283–328. https://doi.org/10.1162/089976606775093909

Peng, A., Kirkham, N. Z., & Mareschal, D. (2018). Task switching costs in preschool children and adults. *Journal of Experimental Child Psychology*, *172*, 59–72. https://doi.org/10.1016/j.jecp.2018.01.019

Poljac, E., Haartsen, R., van der Cruijsen, R., Kiesel, A., & Poljac, E. (2018). Task intentions and their implementation into actions: Cognitive control from adolescence to middle adulthood. *Psychological Research*, *82*(1), 215–229. https://doi.org/10.1007/s00426-017-0927-x

Powell, M. J. D. (2009). The BOBYQA algorithm for bound constrained optimization without derivatives. (Report). Retrieved from http://www.damtp.cam.ac.uk/user/na/NA_papers/NA2009_06.pdf

Rushworth, M. F. S., Hadland, K. A., Gaffan, D., & Passingham, R. E. (2003). The effect of cingulate cortex lesions on task switching and working memory. *Journal of Cognitive Neuroscience*, *15*(3), 338–353. https://doi.org/10.1162/089892903321593072

Singmann, H., Bolker, B., Westfall, J., Aust, F., & Ben-Shachar, S. (2021). afex: Analysis of Factorial Experiments. Available online at: https://CRAN.R-project.org/package=afex

Snyder, H. R., & Munakata, Y. (2010). Becoming self-directed: Abstract representations support endogenous flexibility in children. *Cognition*, *116*(2), 155–167.

Snyder, H. R., & Munakata, Y. (2013). So many options, so little control: Abstract representations can reduce selection demands to increase children's self-directed flexibility. *Journal of Experimental Child Psychology*, *116*(3), 659–673. https://doi.org/10.1016/j.jecp.2013.07.010

Team R Core. (2020). R: A language and environment for statistical computing.

Terry, C. P., & Sliwinski, M. J. (2012). Aging and random task switching: The role of endogenous versus exogenous task selection. *Experimental Aging Research*, *38*(1), 87–109. https://doi.org/10.1080/0361073X.2012.637008

Umemoto, A., HajiHosseini, A., Yates, M. E., & Holroyd, C. B. (2017). Reward-based contextual learning supported by anterior cingulate cortex. *Cognitive, Affective and Behavioral Neuroscience*, *17*(3), 642–651. https://doi.org/10.3758/s13415-017-0502-3

Unger, K., Ackerman, L., Chatham, C. H., Amso, D., & Badre, D. (2016). Working memory gating mechanisms explain developmental change in rule-guided behavior. *Cognition*, *155*, 8–22. https://doi.org/10.1016/j.cognition.2016.05.020

Weaver, S. M., & Arrington, C. M. (2010). What's on your mind: The influence of the contents of working memory on choice. *Quarterly Journal of Experimental Psychology*, *63*(4), 726–737. https://doi.org/10.1080/17470210903137180

White, S. J., Burgess, P. W., & Hill, E. L. (2009). Impairments on "open-ended" executive function tests in autism. *Autism Research*, *2*(3), 138–147. https://doi.org/10.1002/aur.78

Wickham, H. (2016). *ggplot2: Elegant graphics for data analysis*. New York, NY: Springer-Verlag.

Yeung, N. (2010). Bottom-up influences on voluntary task switching: The elusive homunculus escapes. *Journal of Experimental Psychology: Learning Memory and Cognition*, *36*(2), 348–362. https://doi.org/10.1037/a0017894

## SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

**How to cite this article:** Frick, A., Brandimonte, M. A., & Chevalier, N. (2021). Understanding autonomous behaviour development: Exploring the developmental contributions of context-tracking and task selection to self-directed cognitive control. *Developmental Science*, e13222. https://doi.org/10.1111/desc.13222