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Voluntary task switching in children: Switching more reduces the cost of task selection

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Abstract

Emerging cognitive control supports increasingly efficient goal-directed behaviors. With age, children are increasingly expected to decide autonomously and with little external aid which goals to attain. However, little is known about how children engage cognitive control in such a self-directed fashion. The present study examines self-directed control development by adapting the voluntary task switching paradigm—the gold standard measure of this control form in adults—for use with 5-6 year-old and 9-10 year-old children. Overall, *p*(switch) suggests that even younger children can engage self-directed control successfully. However, other measures showed they struggled with task selection. Specifically, compared with older children and adults, they relied more on systematic strategies which reduced the cost of task selection, even when the strategy involved switching more often. Like externally driven control, self-directed control relies critically on task selection processes. These two forms of control likely form a continuum rather than two discrete categories.

Key words: self-directed control, cognitive control, voluntary task switching, endogenous control, cognitive development

Introduction

Gaining autonomy is a key aspect of growing up. As children grow older, they are increasingly expected to behave autonomously with little or no aids regarding what to do, how to do it and when to do it. For instance, most of the personal work required to prepare for a school test is less explicitly guided by teachers or parents as children move up across school grades, hence leading to greater demands on what particular course materials to study and when and how to study them. To complete such tasks, children engage cognitive control to regulate their thoughts and actions in a goal-directed manner in a self-directed manner. Although self-directed control engagement is bound to substantially impact on children's lives, including academic achievement, little is known about its development. So far, cognitive control development has been studied almost exclusively in situations where its engagement is externally driven by cues, reminders or clear instructions about the goal to attain. In contrast, the current study examined how children self-directedly engage control when no external support is provided.

Even in situations in which cognitive control is externally driven, the ability to select the relevant tasks or actions to perform (or identity goals to pursue) is key to efficient cognitive control (Broeker et al., 2018) and its development across childhood (Chevalier, 2015). In particular, task selection (goal identification) is often inferred through cues that guide relevant behavior selection and engagement (Miller & Cohen, 2001). Indeed, frontoparietal activation while engaging cognitive control is largely related to cue processing in adolescents and adults (Chatham et al., 2012; Church, Bunge, Petersen, & Schlaggar, 2017). Yet, children struggle to process cues and use this info to select the most relevant task in situations where they have to switch between multiple tasks (Chevalier & Blaye, 2009; Chevalier, Huber, Wiebe, & Espy, 2013). They are better at switching tasks after practicing cue detection (Chevalier, Chatham, & Munakata, 2014; Kray, Gaspard, Karbach, & Blaye, 2013) or when cues are easier to process (Chevalier & Blaye, 2009). Cue processing progressively improves with age, resulting in increasingly successful task selection and, more broadly, cognitive control (Chevalier, 2015). As task selection is central, even in situations in which cognitive control is externally driven, children may particularly struggle when cognitive control is self-directed, as there is no external support to drive what to do and when.

To date, however, very little is known about how children engage cognitive control in self-directed situations, as only a handful of developmental studies have explored this question, probably because of the difficulty of running less controlled tasks in which control must be engaged in a self-directed manner (Barker & Munakata, 2015). These studies have essentially used the semantic verbal fluency task (Troyer, Moscovitch, & Winocur, 1997), in which children must name as many items from a specific category (e.g., animals) as they can, (Barker et al., 2014; Snyder & Munakata, 2010, 2013). Although younger children spontaneously generate only a couple of items from one subcategory (e.g., cat, dog, rabbit, bird), they generate more items and switch more often between subcategories when given pre-task reminders (e.g., ‘a cat is a pet’ or ‘a lion is a zoo animal’), that reduce high task selection demands (i.e., choices between multiple competing subcategories; Snyder & Munakata, 2010, 2013). Therefore, reducing task selection demands seems critical for successful task performance in young children, perhaps even more so than switching per se. However, it remains unknown how children engage self-directed control in non-linguistic situations, what task selection strategies they use to achieve a goal and how this use of strategies changes with age, and to what extent becoming increasingly self-directed may relate to adaptive use of different control modes. These questions may not be easily answered using the verbal fluency task as this task leaves little room for experimental manipulations (Isacoff & Stromswold, 2014).

A promising paradigm to chart out the development of self-directed control is the voluntary task switching (VTS; Arrington & Logan, 2004) procedure, which is considered the gold standard assessment of self-directed control in adults (for a review, see Arrington, Reiman, & Weaver, 2014). Unlike other externally driven task switching paradigms, VTS requires individuals to freely choose which task to perform between two simple tasks on each trial, with the constraints to select the tasks equally often and in a random fashion. But, similar to other task switching paradigms (e.g., Meiran, 1996), task performance is worse in task switch trials than in task repetition trials, and therefore a switch cost is observed, especially in terms of reaction times (RTs, for review see Kiesel et al., 2010; Vandierendonck, Liefooghe, & Verbruggen, 2010). In addition, adults are asked to choose both tasks equally often in a random order, which should result in an equal number of task repetitions and task switches. They nevertheless show a robust repetition bias (i.e., repeating the task they have just done more often than switching to the other task), quantified by a probability of switching (noted *p*(switch) and ranging from 0 to 1) lower than the optimal score of .5 (around .44), indicating that task selection is particularly effortful (e.g., Arrington & Logan, 2005; Mittelstädt, Dignath, Schmidt-Ott, & Kiesel, 2018). Interestingly, the repetition bias seems to follow a U shape pattern with age, as adolescents and elderly people show a stronger repetition bias than adults (Butler & Weywadt, 2013; Poljac, Haartsen, van der Cruijsen, Kiesel, & Poljac, 2018; Terry & Sliwinski, 2012). In line with these findings, VTS performance is associated with greater frontal and prefrontal activation than cued task switching (in which the relevant task on each trial is externally signaled by a task cue). Specifically, enhanced activation in the rostral and dorsal anterior cingulate cortex may reflect voluntary control of action and free choice between competitive alternatives (Demanet, De Baene, Arrington, & Brass, 2013; Marsh, Blair, Vythilingam, Busis & Blair, 2007), while activation in the posterior cingulate may support self-chosen intentions (Soon, He, Bode, & Haynes, 2013). Thus, due to higher task selection demands, VTS is more demanding than other task switching paradigms.

Having enough time to prepare for the next trial is crucial to engage the cognitive control processes needed to select and execute a task, as evidenced by a smaller repetition bias and higher *p*(switch) when participants are given a longer preparation time (i.e., response to stimulus interval, RSI) before stimulus onset (Arrington & Logan, 2005; Butler, Arrington, & Weywadt, 2011; Butler & Weywadt, 2013; Liefooghe, Demanet, & Vandierendonck, 2009; Yeung, 2010). Adults may benefit from longer preparation time because they need time to adaptively select the task they want to perform next through the representativeness heuristic, that is, selecting a task after maintaining a sequence of recently performed tasks in working memory and comparing it with an internal sequence of randomness before stimulus onset). Alternatively, the task to be performed next can be selected via the availability heuristic, which consists in selecting after stimulus onset the task that has just been done, which has had less time to decay in working memory and is thus easier to reactivate than the other task. Unlike the representativeness heuristic, the availability heuristic requires no preparation time to operate but it leads to more task repetitions (Arrington & Logan, 2005). Long preparation times may allow adults to anticipate and prepare in advance for the upcoming task, hence encouraging the representativeness heuristic over the availability heuristic. Interestingly, these two heuristics map onto the distinction between proactive control (i.e., engagement of control in anticipation of upcoming demands) and reactive control (i.e., engagement of control in the moment it is needed; Braver, 2012), respectively. Concurrent working memory load leads to more task repetitions in VTS (Liefooghe, Demanet, & Vandierendonck, 2010; Weaver & Arrington, 2010), perhaps because it prevents proactive control, which heavily relies on working memory for the sustained maintenance of goal-relevant information (Marklund & Persson, 2012). Unlike adults and older children, younger children tend to be biased towards reactive control, rarely engaging proactive control (Chevalier, Martis, Curran, & Munakata, 2015; Doebel et al., 2017; Munakata, Snyder, & Chatham, 2012). They may therefore rely more on the availability than the representativeness heuristic in VTS, and thus show a greater repetition bias than adults, even with long preparation times.

However, the repetition bias or *p*(switch), which is the unique measure of task selection processes in most prior studies in adults, may fail to capture important aspects of VTS performance, such as the need to perform both tasks equally often and in random fashion. Specifically, a participant could show a *p*(switch) equal to .5, which is considered as a perfect score of randomness, but nevertheless use a non-random strategy such as systematically switching every two trials (e.g., Task A, Task A, Task B, Task B, Task A, Task A, etc.). Indeed, there are individual differences in self-organized strategies in VTS, with a majority of adults adaptively engaging in both task repetitions and task switches (i.e., *alternaters*), but also a minority using more basic non-random strategies such as constantly switching between the tasks (i.e., *switchers*) or constantly repeating the task they have just done on a previous trial (i.e., *blockers*; Reissland & Manzey, 2016). This heterogeneity in the use of strategies in VTS echoes developmental research showing great heterogeneity regarding the use of strategies in externally driven task switching situations in children (e.g., Blakey, Visser, & Carroll, 2016; Dauvier, Chevalier, & Blaye, 2012). Consequently, a full account of task selection processes involved in VTS should at least report measures of (a) task transition, assessing how often participants repeat or switch tasks, (b) task selection equality, indexing how well they perform the two (or more) tasks equally often and (c) task randomness, indicating how often participants use non-random strategies.

VTS has never been used with children, despite its prominent role in the adult literature and potential to shed light on self-directed control development. The present study adapted this paradigm for children to investigate age-related changes in task selection processes when no external aid is provided. We targeted 5- to 6- and 9- to 10-year-olds (in addition to adults), given the now well-established transition from reactive to proactive control during that age range (Chevalier et al., 2015; Munakata et al., 2012). We used three different measures to comprehensively capture three main aspects of task selection processes: (a) task transition through *p*(switch); (b) task selection equality through the relative difference between the proportion of trials in which each of the two tasks was selected; and (c) task randomness through occurrences of non-random strategies. In addition, we examined the role of reactive and proactive control in VTS by varying preparation time duration using a short (600 ms) and a long (2,000 ms) preparation times. Given that younger children engage proactive control less than adults, we expected them to show a lower *p*(switch) and to be worse at performing the two tasks equally often and be less sensitive to preparation time variations than other age groups, who should show a higher *p*(switch) and perform the two tasks more equally often especially with the longer preparation time. Importantly, we expected younger children to struggle particularly with task selection and therefore rely more on non-random strategies than older children and adults.

Methods

Participants

Participants included 29 5- and 6-year-old children (M_{age} = 6.07 years, SD_{age} = .46, range: 5.25 – 6.67, 14 females), 31 9- and 10-year-old children (M_{age}= 10.01 years, SD_{age} = .52, range: 9.08 – 10.92, 13 females), and 31 adults (M_{age} = 21.76 years, SD_{age} = 3.36, range: 18.75 – 30.75, 15 females). Two additional 5-6-year-olds were excluded, because they either failed the practice (see Methods section hereafter) and or fell outside the targeted age range. Data collection stopped when the sample size of each age group reached 31 participants, which is comparable to prior developmental studies comparing 5- and 6-year-old children and

9- and 10-year-old children (e.g., Chevalier, Jackson, Roux, Moriguchi, & Auyeung, 2019) or to adult studies using VTS (e.g., Fröber, Pfister & Dreisbach, 2019). Children were recruited from one private preschool and one private primary school and adults were all students enrolling at the University of Edinburgh. Informed written consent was obtained from children's parents and from adult participants and all children provided signed assent. Children received a small age-appropriate prize (e.g., stickers) and adults received either course credits or £5 for their participation. The research project and protocols were approved by the Ethics Committee from the University of Edinburgh (Study title: Role of time-preparation in voluntary task switching in children and adults, Ref No. 23-1718/2,) as well as all participating schools.

Material and procedure

All participants were tested individually in a 30-minute session either in a quiet room at school (children) or in the laboratory (adults). They completed a child-friendly, voluntary task switching paradigm adapted from a similar paradigm in adults (Arrington & Logan, 2004) and presented with E-Prime 2 (Psychology Software Tools, Pittsburgh, PA). It was introduced to participants as 'Santa Claus and Mitch the Bad Elf Game.' Participants were instructed to help Santa sort toys in two bags for Christmas, while watching out for Mitch, an elf toy-thief. Participants were instructed to switch voluntarily between sorting bidimensional targets (e.g., a blue teddy) by color and shape. If they played the color game, they had to place the target in the Color bag by pressing the response box button matching the target's color, whereas they had to place the target in the Shape bag if they played the shape game, by pressing the button matching the matching the target's shape. Participants were given two additional instructions (modelled after Arrington & Logan, 2004), corresponding to two main features of the adult version of voluntary task switching paradigm. First, participants had to put roughly as many toys in each of the two bags. Second, they had to play the two tasks randomly, which was conveyed by asking participants to make sure Mitch could not predict how they would sort the toys. Otherwise, Mitch would show up and steal the toy inside the present box (the now empty present box would still be moved into the selected bag).

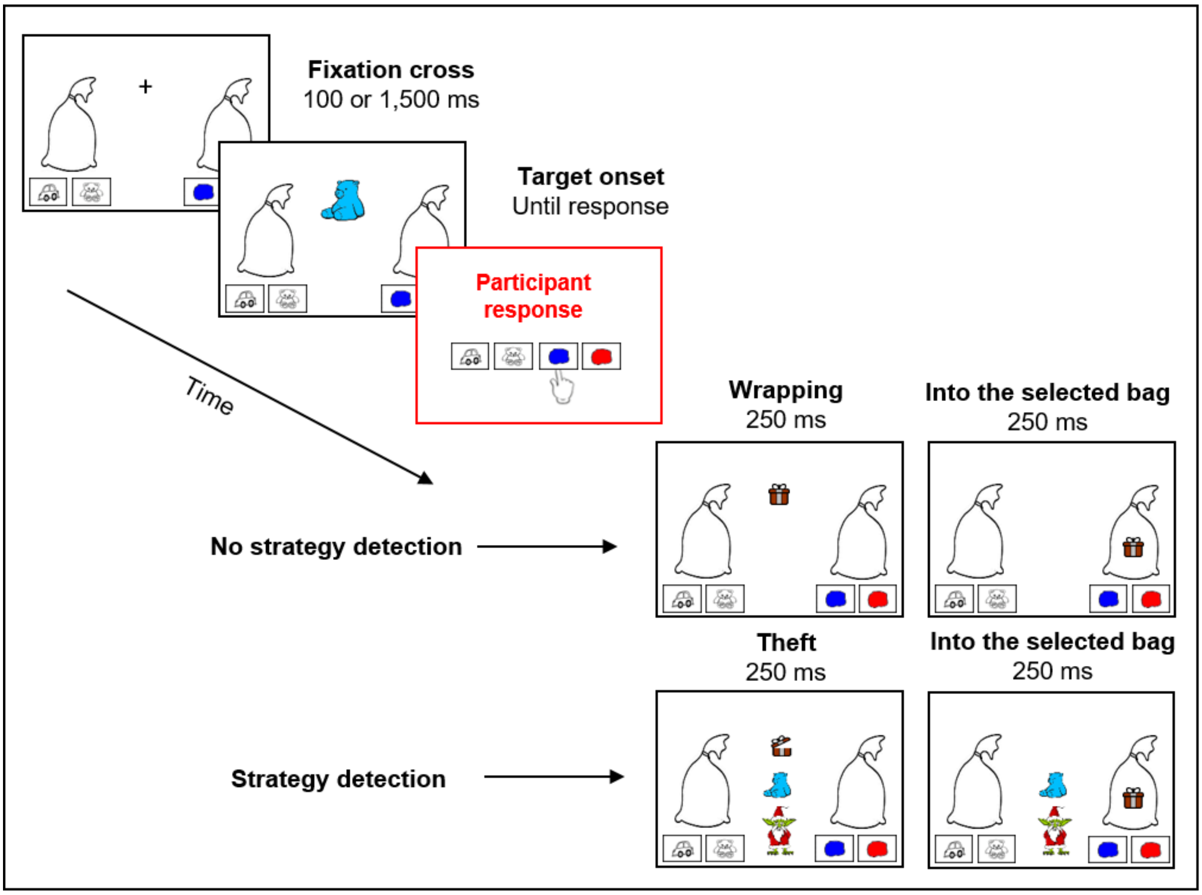

Figure 1. Child-friendly voluntary task-switching paradigm. Participants had to decide whether to sort the toys in the Color or Shape bags according to the general instructions of filling the two bags with about the same number of toys in a no-predictable fashion to avoid the theft of the toys.

Each trial started with a central fixation cross alongside the two bags with two responses pictures below each bag (i.e., a blue and red patch under the Color bag, a car and teddy-bear under the Shape bag; Figure 1). The bags were constantly visible on the right- and left-hand sides of the monitor but the locations of the bags and responses pictures were counter-balanced across participants. After 1,500 ms (in the long preparation time condition) or 100 ms (in the short preparation time condition), the fixation cross disappeared and was replaced with the target that remained on the screen until a response was entered by pressing one of the four buttons on a response box. After the response, the target was replaced by a closed present box that remained at the center of the screen for 250 ms before being moved to the selected bag for 250 ms. If a predictable strategy was used and detected by the program (for details on the different strategies implemented in the program and how many trials in a row of a particular strategy would trigger Mitch the thief elf, see Data processing and analysis section), the target was replaced by an opened present box with a small version of the toy alongside Mitch the thief elf for 250 ms and the sound effect ‘ah-ah’. Then the same present box was closed and moved into the bag chosen by the participants while the small version of the toy and Mitch remained on the screen for 250 ms. Whether or not the elf showed up, the present box inside the bag was no longer visible during the following trial.

All participants completed the task in two conditions (order counterbalanced across participants). In the short preparation time condition, the fixation cross was visible only for 100 ms, leaving a total of 600 ms (cross fixation duration = 100 ms + present moving or Mitch appearing duration = 500 ms) for participant to prepare for the upcoming trial. In contrast, in the long preparation time condition, the fixation cross was visible for 1,500 ms, providing a total of 2,000 ms (cross fixation duration = 1,500 ms + present moving or Mitch appearing duration = 500 ms) for participant to prepare for the upcoming trial. Different combinations of colors and shapes were used in each condition (either car-teddy-blue-red or doll-plane-green-pink).

In both conditions, participants first completed two single-task blocks in which they were instructed to always sort toys by either color or shape, in order to get familiar with each task. Each single-task block comprised four warm-up trials (repeated up to two timed if participants made more than two errors) followed by 16 test trials. The order of the color and shape-matching tasks was counterbalanced across participants. Participants then completed two mixed-task blocks in which they were instructed to switch voluntarily between the two tasks with the two constraints of filling the two bags equally often and tricking Mitch as much as they could. To make sure all participants understood the instructions, the experimenter performed two demonstration trials. In the first demonstration, participants observed the experimenter alternate systematically between the two bags (i.e., two tasks) on seven trials (‘color-shape-color-shape-color-shape-color’ or ‘shape-color-shape-color-shape-color-shape’ with order counter-balanced across participants and conditions), which resulted in the next target being stolen by Mitch. In the second demonstration, participants were shown one of two potential ways of successfully sorting the toys (‘color-color-shape-color-shape-shape-shape-color-color-shape-color-color’ or ‘shape-shape-color-shape-color-color-color-shape-shape-color-shape-shape’ with order counter-balanced across participants and conditions), putting the same number of toys into each bag and avoiding the theft of toys by Mitch. Participants then completed 16 practice trials. Practice trials were repeated (maximum three times) if one bag contained more than 10 toys (62.5%), Mitch stole a toy (i.e., detection of a predictable strategy), or more than eight errors (50%) were made. Critically, participants first performed the practice trials on their own but if these trials needed to be repeated, they received help from the experimenter. Participants who failed to pass the practice trials after three repetitions were excluded (*n* = 1). Participants then completed two mixed-task blocks of

40 test trials separated by a short break. At the end of each mixed-task block (practice trials and test trials), feedback was provided to encourage participants to respond accurately and follow the instructions of preforming the two tasks equally often and in a random fashion. Feedback conveyed the number of errors, whether one bag contained more toys than the other (more than 62.5% of the toys), and the number of toys stolen by Mitch. Although no feedback regarding response times was given, participants were instructed to respond as quickly as possible before each block.

Data processing and analysis

Trial type was determined as follows: if the task (color or shape) performed on trial *n* repeated from the trial *n*-1, this trial was coded as a 'task repetition' trial, if, conversely, the task on trial *n* was different from trial *n*-1, this trial was coded as a 'task switch' trial. Task performance, task choice and task transition measures, and the use of strategies were analyzed. Task performance was indexed by mean response times (RTs) and accuracy for each trial type (single, task repetition and task switch), which allowed estimating mixing costs (contrasting between single trials and task repetition trials) and switch costs (contrasting between task repetition trials and task switch trials. Mixing costs index the difficulty of selecting the relevant task when tasks are mixed and switch costs index the difficulty of switching from one task to another per se. These analyses were performed after discarding the first trial of each block. Moreover, only RTs for correct responses immediately preceded by another correct response were kept in the analyses, resulting in the removal of 13.56% of the trials in total (a rate in line with previous studies using VTS in adults, e.g., Arrington & Weaver, 2015). RTs on trials following the appearance of the bad elf were also removed as their latencies were longer than on normal trials representing 1.14% of the remaining trials. Finally, RTs were trimmed out if they were under 200 ms, to account for accidental button presses, or greater than 3 standard deviations above the mean of each participant (computed separately for trials from single blocks, and repeat and switch trials from mixed blocks) or 10,000 ms, resulting in the removal of 1.71% of the remaining trials.

Task selection was measured via three indices. (1) *Task transition* was calculated based on whether the task was repeated or switched on a given trial *n*. This measure, often considered as the main outcome variable in studies using the voluntary task-switching, corresponds to *p*(switch), and was calculated by dividing the number of task switch trials by the total number of task switch and task repetition trials (i.e., 78). This score ranges between 0 and 1 with.5 corresponding to a perfectly equal number of task repetitions and task switches. (2) *Task selection equality* corresponds to a task selection measure of the ability to perform each task equally often in the mixed blocks. This index consisted in the relative difference between the proportion of trials in which the Shape bag was selected and the proportion of trials in which the Color bag was selected. As such, the closer this index was to 0, the more equally frequently the two tasks were performed. (3) *Task randomness* was via occurrences of ten different systematic strategies. These strategies ranged from five basic to complex patterns as follows:

- *Repetition Only (detected over seven trials)*:
    - Task A, Task A, Task A, Task A, Task A, Task A, Task A.
    - Task B, Task B, Task B, Task B, Task B, Task B, Task B.
- *Switch Only (detected over seven trials):*
    - Task A, Task B, Task A, Task B, Task A, Task B, Task A.
    - Task B, Task A, Task B, Task A, Task B, Task A, Task B.
- *One Repetition and Switch (detected over nine trials)*:
    - Task A, Task A, Task B, Task B, Task A, Task A, Task B, Task B, Task A.

    - Task B, Task B, Task A, Task A, Task B, Task B, Task A, Task A, Task B.
- *Two Repetitions and Switch (detected over eleven trials)*:
    - Task A, Task A, Task A, Task B, Task B, Task B, Task A, Task A, Task A, Task B, Task B.
    - Task B, Task B, Task B, Task A, Task A, Task A, Task B, Task B, Task B, Task A, Task A.
- *Three Repetitions and Switch (detected over thirteen trials)*:
    - Task A, Task A, Task A, Task A, Task B, Task B, Task B, Task B, Task A, Task A, Task A, Task A, Task B.
    - Task B, Task B, Task B, Task B, Task A, Task A, Task A, Task A, Task B, Task B, Task B, Task B, Task A.

If participants used one of these patterns, the corresponding strategy was automatically detected by the program and triggered Mitch the thief elf. The frequency of these strategies was used during the game (i.e., when Mitch showed up) as provided an indication of randomness. Moreover, our analyses also focused on the qualitative type of strategies (e.g., simple repetition of one task for seven trials or more complex alternation with a switch every third repetition for thirteen trials).

Task performance and task selection measures were analyzed with mixed analyses of variance (ANOVAs) with age as a between-subjects variable, and preparation time and/or trial type as within subject variables, Bonferroni-corrected post hoc tests, and *t*-tests. When appropriate, the Greenhouse-Geisser (Greenhouse & Geisser, 1959) correction was applied for violation of the assumption of sphericity. Finally, the type of strategies used across age groups and preparation time durations was analyzed with a multivariate analysis of covariance (MANCOVA).

Results

Task performance

Accuracy rates

A 3 (age group: 5-6 years, 9-10 years, adults) X 2 (preparation time: short, long) X 3 (trial type: single, task repetition, task switch) mixed ANOVA was performed on accuracy rates. The analysis showed main effects of age, $F(2, 88) = 10.56$, $p < .001$, $\eta^2_p = .19$, trial type, $F(2, 176) = 3.80$, $p = .038$, $\eta^2_p = .04$, and preparation time, $F(1, 88) = 8.681$, $p = .004$, $\eta^2_p = .09$, and these effects were qualified by a significant two-way interaction between age and preparation time, $F(2, 176) = 4.30$, $p = .017$, $\eta^2_p = .09$, and a significant three-way interaction, $F(4, 176) = 3.57$, $p = .014$, $\eta^2_p = .07$. Preparation time differentially affected trial type across age groups (Figure 2). More specifically, while 5-6 year-olds were significantly less accurate with the short than the long preparation time ($M_{\text{short}} = 88.86\%$ vs. $M_{\text{long}} = 93.04\%$), $p = .008$, no such difference was observed in 9-10 year-olds and adults (9-10 year-olds: $M_{\text{short}} = 94.32\%$ vs. $M_{\text{long}} = 94.87\%$; adults: $M_{\text{short}} = 97.15\%$ vs. $M_{\text{long}} = 97.59\%$), respectively $p = .574$ and $p = .209$. Moreover, for the 5-6 year-olds, only the difference between single trials and task repetition trials in the long preparation time condition ($M_{\text{single}} = 96.09\%$, vs. $M_{\text{task repetition}} = 91.25\%$) was significant, $p = .012$, revealing significant mixing costs. Conversely, 9-10 year-olds showed significant mixing costs in the short preparation time condition ($M_{\text{single}} = 96.67\%$ vs. $M_{\text{task repetition}} = 92.82$ %), $p = .014$. For adults, accuracy rates across trial types and preparation time revealed no significant mixing or switch costs, all *ps* > .079.

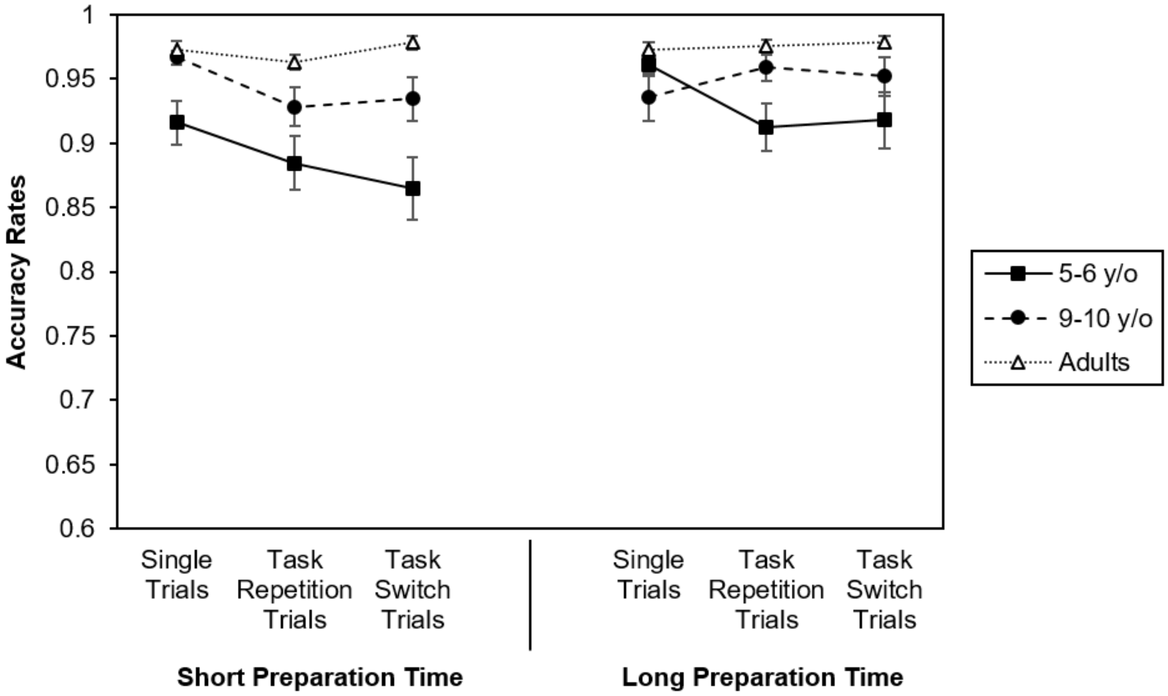

Figure 2. Accuracy rates by trial type (single, task repetition, task switch) for 5-6 year olds, 9-10 year olds and adults as a function of preparation time. Error bars represent standard errors.

Reaction times (RTs)

On RTs, a 3 (age group: 5-6 years, 9-10 years, adults) X 3 (trial type: single, task repetition, task switch) X 2 (preparation time: short, long) mixed ANOVA was performed. There were main effects of age, $F(2, 88) = 159.89, p < .001, \eta^2_p = .78$, trial type, $F(2, 176) = 351.86, p < .001, \eta^2_p = .80$ but not of preparation time, $p = .231$, and these effects were qualified by two-way interactions between age and trial type, $F(4, 176) = 8.09, p < .001, \eta^2_p = .15$, and trial type and preparation time, $F(2, 176) = 21.87, p < .001, \eta^2_p = .20$, and a three-way interaction between all these factors, $F(4, 176) = 2.84, p = .038, \eta^2_p = .06$. Although each age group showed significant mixing and switching costs, all *ps* <. 001, these costs were overall higher for 5-6 year-olds (M_{single} = 1261.29 ms, $M_{\text{task repetition}}$ = 1870.23 ms and $M_{\text{task switch}}$ = 2614.53 ms) than for 9-10 year-olds (M_{single} = 724.02 ms, $M_{\text{task repetition}}$ = 1018.97 ms and $M_{\text{task switch}}$ = 1219.19 ms) and adults (M_{single} = 488.02 ms, $M_{\text{task repetition}}$ = 662.70 ms and

$M_{\text{task switch}}$ = 762.33 ms). Moreover, preparation times did not affect mixing costs in children (5-6 year-olds: M_{short} = 559.55 ms vs. M_{long} = 658.31 ms; 9-10 year-olds: M_{short} = 291.39 ms vs. M_{long} = 298.51 ms), all *ps* > .629, but it did in adults (M_{short} = 191.78 ms vs. M_{long} = 157.58 ms), *p* = .049. Conversely, switching costs were higher with short than long preparation times in each age group, and this difference was largest for 5-6 year-olds (5-6 year-olds: M_{short} = 1034.47 ms vs. M_{long} = 454.12 ms; 9-10 year-olds: M_{short} = 281.25 ms vs. M_{long} = 119.20 ms; adults: M_{short} = 129.35 ms vs. M_{long} = 69.92 ms), all *ps* < .005 (Figure 3).

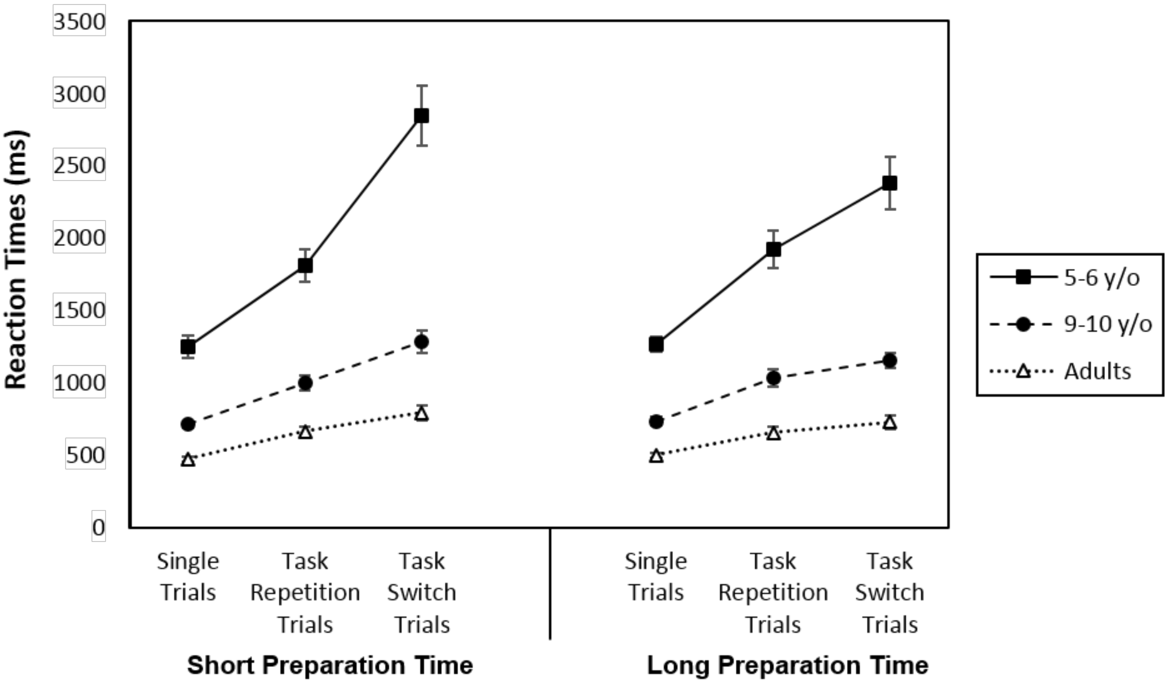

Figure 3. Response times (RTs) in milliseconds for 5-6 year olds, 9-10 year olds and adults as a function of preparation time. Error bars represent standard errors.

Task selection

Task transition – P(switch)

Task transition was examined with a 3 (age group: 5-6 years, 9-10 years, adults) X 2 (preparation time: short, long) mixed ANOVA performed on *p*(switch). The analysis revealed a main effect of preparation time, *F*(1, 88) = 7.90, *p* = .006, η^2_p = .08, but no effect of age, *p* = .353, and no significant interaction between preparation time and age, *p* = .275. Overall, pairwise comparisons indicated that participants switched tasks slightly less often when preparation time was short than long, respectively, $M_{\text{p(switch)}} = 44.78$ % and $M_{\text{p(switch)}} = 48.54$ %, $p = .006$, (Figure 4). However, when comparing *p*(switch) between both conditions for each group, we found that there were significant differences between the short and long preparation time conditions in older children and adults, respectively $p = .015$ and $p = .004$, but no difference in young children, $p = .831$.

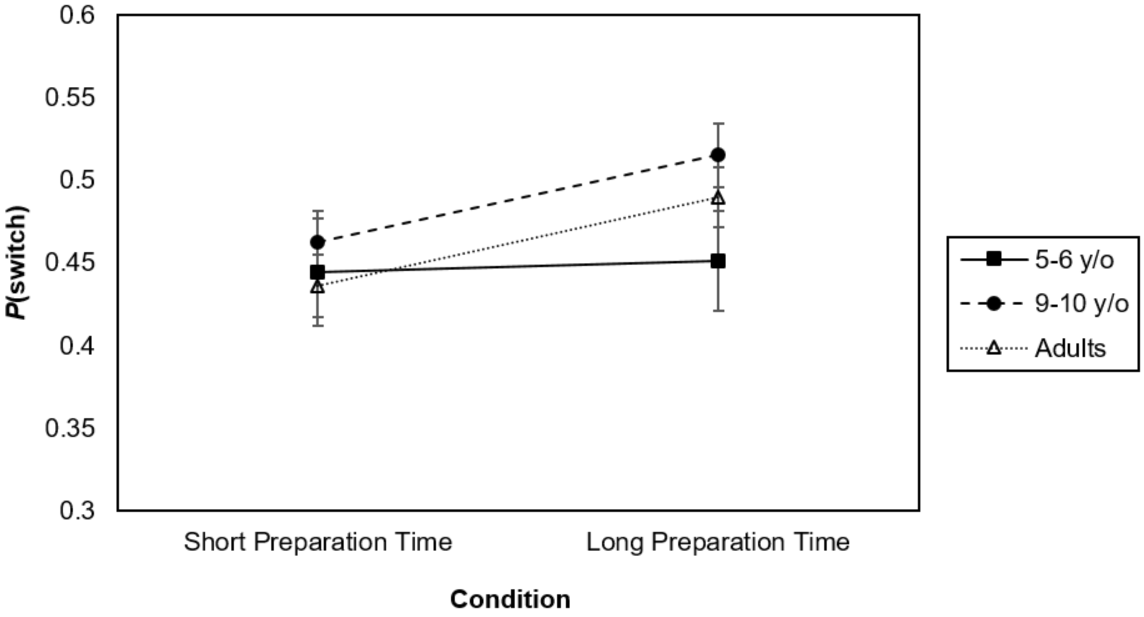

Figure 4. *P*(switch) for 5-6 year olds, 9-10 year olds and adults as a function of preparation time. Error bars represent standard errors.

Task selection equality – Relative difference between the frequency of each task

Task selection equality was analyzed with a 3 (age group: 5-6 years, 9-10 years, adults) X 2 (preparation time: short, long) mixed ANOVA performed on the relative difference between the two tasks. The ANOVA showed a main effect of age, $F(2, 88) = 8.19$, $p = .001$, $\eta^2_p = .16$ but no effect of preparation time, $p = .720$, and no interaction, $p = .871$. Pairwise comparisons indicated that 5-6 year-olds did not perform the two tasks as equally often ($M_{\text{difference}}$ = 10.30 %) as 9-10 year olds ($M_{\text{difference}}$ = 5.28 %) and adults ($M_{\text{difference}}$ = 5.32 %), regardless of the preparation time (Figure 5), all *ps* >.003.

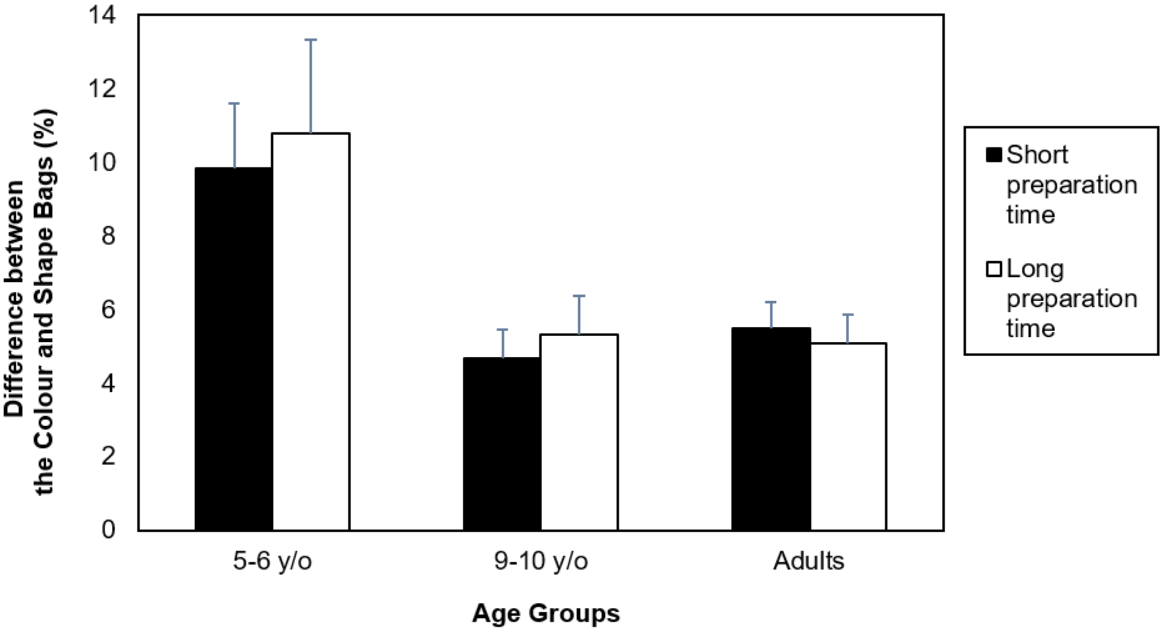

Figure 5. Difference between the two bags for 5-6 year olds, 9-10 year olds and adults as a function of preparation time. Error bars represent standard errors.

Task randomness – Strategy detection and type of strategy used

We examined task randomness with a 3 (age group: 5-6 years, 9-10 years, adults) X 2 (preparation time: short, long) mixed ANOVA to test to what extent participants used predictable strategies, and whether or not it varied according to age and/or preparation time. There were main effects of age, *F*(2, 88) = 38.82, p = <.001 η^2_p = .47, and preparation time, *F*(1, 88) = 6.15, p = .015, η^2_p = .06, while the interaction did not reach significance, p = .113. Overall, pairwise comparisons indicated that younger children used significantly more non-random patterns or strategies (M = 2.59) than older children (M = 0.73) and adults (M = 0.55), all *ps* <.001, and in all age groups, the use of strategies was overall slightly higher in the short preparation time condition than in the long preparation time condition (respectively,

M = 1.49 and M = 1.08; Figure 6). Further analyses revealed that the difference between the two preparation time conditions was not significant for all age groups, all *ps* >.054.

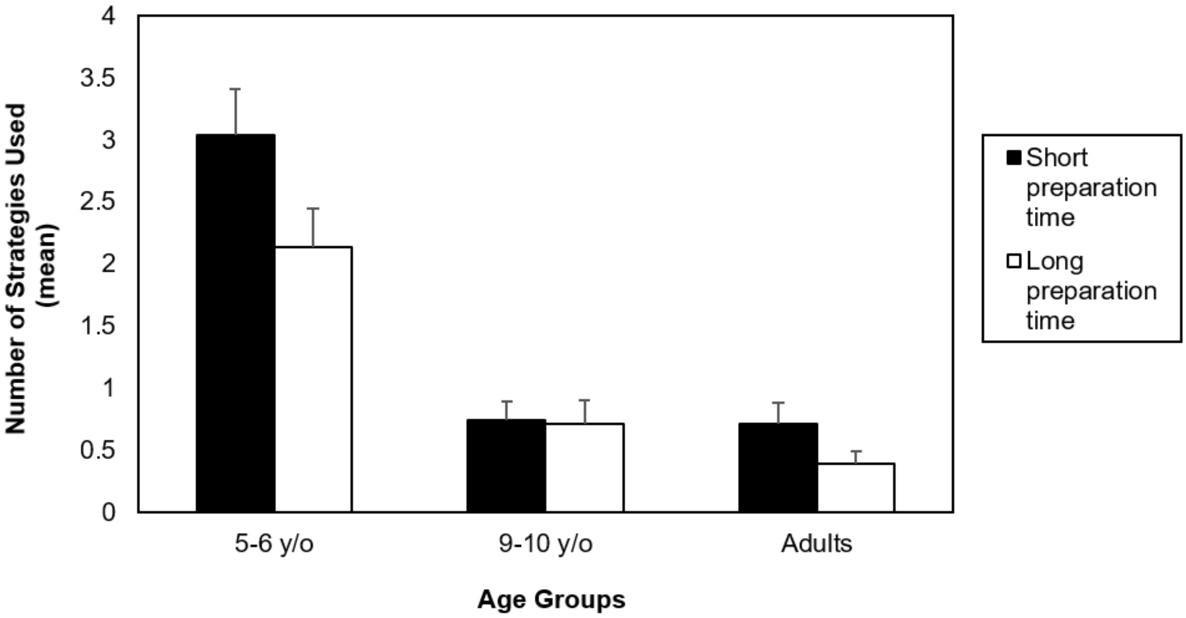

Figure 6. Strategy detection (mean) for 5-6 year olds, 9-10 year olds and adults as a function of preparation time. Error bars represent standard errors.

Then, the type of strategies the participants used across age groups and preparation time durations was investigated with a multivariate analysis of variance (MANOVA). It revealed a significant difference in strategy type used based on age, $F(10, 344) = 9.45$, $p < .001$, Wilk's $\Lambda = .62$, $\eta^2_p = .21$, but not based on preparation time, $F(5, 172) = 1.29$, $p = .269$, Wilk's $\Lambda = .97$, $\eta^2_p = .04$, with no interaction between these two factors, $p = .340$. In particular, as illustrated in Figure 7, age had a main effect on the strategy ‘Repetition Only’, $F(2, 88) = 21.34$, $p < .001$, $\eta^2_p = .19$, ‘Switch Only’, $F(2, 88) = 11.18$, $p < .001$, $\eta^2_p = .11$, and ‘One Repetition and Switch’, $F(2, 88) = 4.55$, $p = .012$, $\eta^2_p = .05$, but not on the two other strategies, all *ps* > .441. Pairwise comparisons indicated that younger children used ‘Repetition Only’ and ‘Switch Only’ strategies more often than older children and adults (‘Repetition Only’: $M = 2.31$, $M = .06$ and $M = .29$, respectively, all *ps* < .001; ‘Switch Only’:

$M = 1.517$, $M = .35$ and $M = .13$, respectively, $ps < .001$). Younger children also significantly used more the ‘One Repetition and Switch’ strategy than adults ($M = .90$ and $M = .26$, respectively), $p = .011$, but not than older children, ($M = .45$), $p = .123$. All other comparisons were not significant, all $ps > .621$. In younger children, the ‘Repetition Only’ strategy was not significantly used more frequently than the ‘Switch Only’ strategy, $p = .232$, but more frequently than ‘One Repetition and Switch’, $p = .039$. No difference was observed between ‘Switch Only’ and ‘One Repetition and Switch’, $p = .164$.

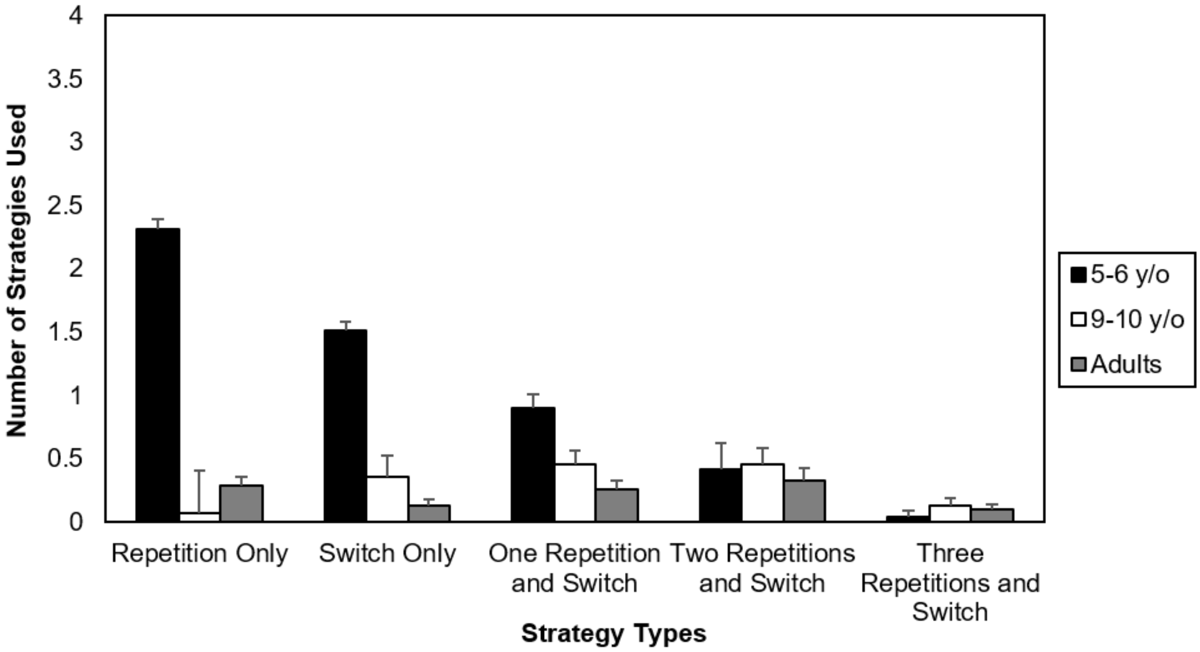

Figure 7. Use rate (mean) of each strategy from more the more basic to the more complicated (left to right) as a function of age groups (5-6 year olds, 9-10 year olds and adults). Error bars represent standard errors.

Discussion

The current study addressed the development of self-directed control by examining how 5- to 6-year-olds, 9- to 10-year-olds, and adults voluntarily switch between tasks. In particular, we explored the role of proactive and reactive control by using a short and a long preparation time. Contrary to our expectations, younger children showed a similar repetition bias to older children and adults, with a *p*(switch) value inferior to .5. However, following our predictions, their *p*(switch) was less sensitive to preparation time variations than for older children and adults, suggesting they engaged control more reactively than older groups. Moreover, younger children were significantly worse at performing the two tasks equally often, and used significantly more basic non-random strategies such as repeating systematically the task that had just been done, switching systematically between the two tasks or always switching after one repetition, reducing the cognitive demands of task selection.

Mixing and switch costs found in our experiment replicated the trend found in externally driven task switching paradigms in children (e.g., Chevalier & Blaye, 2009; Chevalier, Dauvier, & Blaye, 2018; Dauvier et al., 2012), suggesting that our child-friendly version of VTS appropriately tapped task switching. Furthermore, using for the first time this child-friendly VTS paradigm, we replicated previous findings from VTS studies in adults showing that participants had overall a *p*(switch) lower than .5 which even decreased with shorter preparation time for older children and adults (e.g., Arrington & Logan, 2005; Butler, Arrington, & Weywadt, 2011; Butler & Weywadt, 2013; Liefooghe, Demanet, & Vandierendonck, 2009; Yeung, 2010). This further suggests that our VTS paradigm captured self-directed control processes similar to those measured by classic VTS paradigms in adults, hence speaking to the success of our VTS adaption.

Surprisingly, children showed a similar *p*(switch) to adults, against the expectation that the repetition bias would follow a U shape pattern with age, as hinted by prior studies showing a lower *p*(switch) during adolescence and aging than adulthood (Butler & Weywadt, 2013; Poljac, Haartsen, van der Cruijsen, Kiesel, & Poljac, 2018; Terry & Sliwinski, 2012). In our study, the similar *p*(switch) across all age groups *seemingly* suggests no major differences between children and adults in the task selection processes involved in VTS.

However, although the interaction between age and preparation time was not significant, younger children showed the same *p*(switch) with both preparation times, whereas *p*(switch) significantly increased with preparation time in older children and adults. Younger children may have used reactive control (i.e., availability heuristic) in VTS regardless of the amount of preparation time available, while older participants may have engaged proactive control (i.e., representativeness heuristic) when enough time was available. This would corroborate similar trends observed task switching paradigms, but also in other paradigms both tapping externally-driven cognitive control (e.g., Blackwell & Munakata, 2014; Chevalier, James, Wiebe, Nelson, & Espy, 2014; Chevalier et al., 2015; Lucenet & Blaye, 2014). Nevertheless, further research is needed to clarify the role of reactive and proactive control in children's VTS performance. One promising option would be to couple our child-friendly VTS with physiological measurements such as event-related potentials, fMRI and pupil dilation, as they measures have shown sensitivity to reactive and proactive control engagement on other tasks (e.g., Chatham et al., 2012; Chevalier et al., 2015; Church et al., 2017).

As mentioned earlier, a drawback of using *p*(switch) as a unique measure of task selection (Arrington et al., 2014) is that it does not capture all aspects of VTS performance. In our study, the similar *p*(switch) found across age groups would suggest that children, and younger children in particular, have little difficulty with self-directed control, which would seem at odd with previous research on self-directed control development using different tasks (Barker et al., 2014; Snyder & Munakata, 2010, 2013; White, Burgess, & Hill, 2009). However, when considering measures other than *p*(switch), a different picture emerged, showing that task selection was particularly costly for younger children. In particular, younger children performed the two tasks less equally often than older children and adults.

Besides task selection difficulty, developmental limitations in numerical understanding may contribute to age-related differences in VTS performance. Indeed, learning number magnitudes develops slowly across childhood and although children as young as 5 years-old can compare and add numerical quantities, they do not have adult-like exact number magnitude representations and they do not have much experience with numbers exceeding the 0-10 range (Barth, La Mont, Lipton, & Spelke, 2005, but see Sigler, 2016). Therefore, younger children may therefore have failed to add on from the last number and maintained this representation in working memory, leading them to struggle performing the two tasks equally often. That said, counting strategies may not necessarily consist in counting how many times each task was played throughout the game, but instead counting trials within a run of trials before switching to the other task and starting from 1 again, which would require simpler numerical processing. Helping children more easily keep track how many toys have been put into each bag by letting children see how many toys have been sorted within each bag should reduce age-related differences in future research, if these differences arise from limited numerical processing in younger children.

Another important finding was that, systematic, non-random strategies were more frequent in younger children than older children and adults. To account for this difference, one may argue that younger children simply did not understand the instruction of filling the two bags in a random fashion, even though this instruction was conveyed in a child-friendly manner through a bad elf that could otherwise guess how the target would be sorted and 'steal' it. However, during practice, the use of systematic strategies was actively monitored and participants would progress onto the test blocks only if they successfully played randomly, hence ensuring their understanding of this instruction. As younger children required indeed more practice than older children and adults (respectively $M_{\text{number of practice}} = 1.43$, $M_{\text{number of practice}} = 1.21$ and $M_{\text{number of practice}} = 1.11$, all $ps < .019$) to master the instructions, one may argue that they may still have struggled to understand this instruction. However, when comparing younger children who needed only one practice round without the help of the experimenter—and therefore showed perfect understanding of the 'randomness' instruction—to younger children who needed more than one practice round with the help of the experimenter, we observed no significant differences regarding how often they resorted to strategies (respectively, $M_{\text{number of strategy}} = 4.82$ and $M_{\text{number of strategy}} = 5.25$, $p = .693$). These findings further suggest that younger children understood the need to sort targets randomly but nevertheless relied on non-random strategies.

Young children may have been especially prone to resorting to strategies because of a lack of working memory abilities coupled with a difficulty to keep in mind the instructions of performing the two tasks equally often and in a random manner. Indeed, preschoolers, who have low working memory abilities, are more prone to goal neglect (i.e., failure to maintain a goal although how to achieve it is fully understood; see Marcovitch, Boseovski, & Knapp, 2007). Moreover, decrements in task performance when keeping prospective rule instructions in mind have been observed with both adults (e.g., Smith, 2003) and children (e.g., Leigh & Marcovitch, 2014; Smith, Bayen, & Martin, 2010; Nigro, Brandimonte, Cicogna, Cosenza, 2014; Smith, Bayen, & Martin, 2010). In our study, younger children may have needed the appearance of the thief elf as a prospective cue to follow the instruction of being non-predictable. It is therefore possible that processes underlying prospective memory abilities also affect task selection processes alongside with task performance processes. Consistently, commonality in processes between cognitive control and prospective memory has been emphasized in childhood (Brandimonte, Filippelo, Coluccia, Altgassen, & Kliegel, 2011; Mahy, Moses, & Kliegel, 2014; Mahy & Munakata, 2015; Spiess, Meier, & Roebers, 2016).

Whether intentional or not, use of non-random strategies reduced the high cost of task selection demands specific to VTS for younger children. Having to hold complex rule instructions while performing VTS is particularly costly for younger children, and one way to reduce this cost is to favor the easiest rule instruction (i.e., putting about the same number of toys into each bag) over the most difficult rule instruction (i.e., performing the two tasks randomly). In prior research, removing the instruction of performing the two tasks in a random manner resulted in larger individual differences regarding task selection in adults, as indicated by large standard deviations in *p*(switch), suggesting that some participants were more likely to repeat tasks whereas others were more likely to switch tasks (Arrington et al., 2014). Of particular interest, one of the two most frequent strategies among the younger children consisted in repeating the same task for long runs of trials, which led to a small *p*(switch) and would fit with the U shape changes in VTS performance with age, with adolescents and elderly people showing a greater repetition bias than adults (Butler & Weywadt, 2013; Poljac et al., 2018; Terry & Sliwinski, 2012). However, younger children also often used another strategy that consisted in switching systematically on every trial, which led to a very large *p*(switch) and could explain why the overall *p*(switch) at the group level was unexpectedly similar to that of older children and adults. Favoring the rule instruction of performing the two tasks equally often over the rule instruction of performing the two tasks randomly effectively reduces the cost of task selection. The selection of the 'Repeat Only' and 'Switch Only' as non-random strategies by younger children echoes the study of Arrington et al. (2014), as well as a recent study showing individual preferences in the use of strategies in a modified version of VTS in adults (Reissland & Manzey, 2016), and confirms that in task switching situations, children show higher variability in individual profiles when it comes to strategy selection (Dauvier et al., 2012; Moriguchi & Hiraki, 2011).

It is surprising that children systematically switched between tasks on every trial, given that this strategy must have resulted in heavier task switching demands. This finding further suggests that switching per se is not children's main difficulty when it comes to engaging efficient cognitive control. Switch costs were indeed not significant in terms of accuracy, even in younger children, although switching tasks is still more time-consuming than repetitions, as attested by significant switch costs in terms of RTs. Unlike switching per se, selecting the appropriate task appeared particularly demanding as attested by (a) significant mixing costs for both accuracy and RTs, and (b) the use of non-random strategies by young children to reduce its costs. This corroborated studies using externally driven situations showing that task selection might be main young children's difficulty when engaging cognitive control (Chevalier, 2015; Chevalier et al., 2018; Deák, Ray, & Pick, 2004; Holt & Deák, 2015).

In our experiment, participants showed similar mixing and switch costs on RTs to those observed in externally driven situations. Similar processes may indeed be involved in both externally driven and self-directed control, which may mostly differ in task selection difficulty. Indeed, in VTS, while older children and adults adaptively selected tasks, younger children struggled in their task selection as attested by the fact that they performed the two tasks less equally often and used more non-random strategies. This confirms the recent idea that task selection is key in cognitive control (Broeker et al., 2018) and a major force driving cognitive development (Chevalier, 2015). Further, it also suggests that task selection is crucial when drawing the contrast between externally driven and self-directed control. For instance, consider the Wisconsin Card Sorting Test (WCST; Grant & Berg, 1948) compared to VTS. Both tap self-directed control as in VTS, participants have to decide on their own when to switch and what task to switch to, while in WCST, participants have to infer that the rule has changed and figure out on their own which rule is now relevant. However, WCST taps also externally driven control because the need to switch is externally supported by a short feedback from the experimenter after each choice. This feedback indicates when to switch but not towards what to switch to. These differences shed light on a continuum between externally driven and self-directed control based on the amount of task selection demands rather than a difference in nature, such as between reactive and proactive control.

To conclude, when voluntarily switching between tasks in VTS, 5- to 6-year-old children especially struggled to select between the two tasks, in comparison with 9- to 10-year-old children and adults, and used strategies which reduced task selection demands, even if these strategies involved frequent switching. These findings are strikingly similar to what has been previously found in tasks tapping externally driven control in children, speaking to the idea that these two forms of control form a continuum in which task selection demands vary rather than two discrete categories. As a consequence, better understanding task selection processes and their development open up new directions to design efficient interventions for assessing and supporting cognitive control in childhood.

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