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Citation for published version:
Frick, A, Brandimonte, MA & Chevalier, N 2020, 'Disentangling the respective contribution of task selection and task execution in self-directed cognitive control development', *Child Development*.
https://doi.org/10.1111/cdev.13479

Digital Object Identifier (DOI):
10.1111/cdev.13479

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Child Development

Publisher Rights Statement:
This is the peer reviewed version of the following article: Frick, A., Brandimonte, M.A. and Chevalier, N. (2021), Disentangling the Respective Contribution of Task Selection and Task Execution to SelfDirected Cognitive Control Development. Child Dev. https://doi.org/10.1111/cdev.13479, which has been published in final form at https://srcd.onlinelibrary.wiley.com/doi/10.1111/cdev.13479. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Self-Archiving.

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Download date: 23. Feb. 2022

In press, *Child Development*

Disentangling the respective contribution of task selection and task execution in self-directed cognitive control development

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Acknowledgements

This research was part of Aurélien Frick's doctoral dissertation and funded by a doctoral scholarship from Suor Orsola Benincasa University and a Research Grant Support from the University of Edinburgh to Aurélien Frick. We thank all participating schools, children and parents. We also thank Helen Wright for proof-reading, commenting and discussing earlier versions of the manuscript.

Ethic approval

The research project and protocol were approved by an Ethics Committee from the University of Edinburgh as well as participating schools.

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Abstract

Task selection and task execution are key constructs in cognitive control development. Yet, little is known about how separable they are and how each contributes to task switching performance. Here, 60 4-5, 61 7-8 and 60 10-11-years-olds completed the double registration procedure, which dissociates these two processes. Task selection yielded both mixing and switch costs, especially in younger children, and task execution mostly yielded switch costs at all age, suggesting that task selection is costlier than task execution. Moreover, both task selection and execution varied with task self-directedness (i.e., to what extent the task is driven by external aids) demands. Whereas task selection and task execution are dissociated regarding performance costs, they nevertheless both contribute to self-directed control.

Key words: cognitive control development, double registration procedure, task selection, task execution, self-directed control, self-directedness, mixing costs, switch costs

At school, children need to engage cognitive control – the goal-directed regulation of thoughts and actions – to follow different teaching instructions, raise their hands before talking or take turns in shared activities. To do so efficiently, they must identify what the goal is and what actions should be taken in order to reach it. In other words, they first need to select the relevant task goal or the appropriate actions before executing them. Although both task selection and task execution are involved when cognitive control is engaged, their respective contributions to children's performance, especially the costs associated with task mixing and switching, have ever been disentangled. The current study aimed to temporally separate task selection and task execution (also referred to as task performance), examined how these processes contribute to both task mixing and switching costs, and how they are differentially affected by task self-directedness demands from early to late childhood.

As one of the best predictors of later life success such as academic achievement, income, and health (e.g., Daly, Delaney, Egan, & Baumeister, 2015; Moffitt et al., 2011), childhood cognitive control has attracted growing scientific interest over the last two decades (Best & Miller, 2010; Moriguchi, Chevalier, & Zelazo, 2016). Importantly, the ability to select the relevant tasks or actions (also referred to as goal identification) has emerged as a key process for efficient cognitive control engagement in adults (Broeker et al., 2018). Task selection is also a major force driving the development of cognitive control across childhood (Chevalier, 2015). For instance, when children have to switch between multiple tasks as a function of task cues, they perform better when the demands on task selection are reduced through cues that are easier to process, after practicing cue detection, or by scaffolding task selection strategies (e.g., Chevalier & Blaye, 2009; Chevalier, Chatham, & Munakata, 2014; Kray, Gaspard, Karbach, & Blaye, 2013; Lucenet & Blaye, 2019).

Task selection is conceptually distinct from task execution. Tasks, which refer to the activity of matching stimuli with responses according to specific rules (i.e., color and shape matching or parity and magnitude judgments), may be represented on two different representation levels, a task level in which instructions and rules guide a specific task (task selection) and a parameter level specifying the stimulus-response association leading to task completion (task execution; Logan & Gordon, 2001). This dissociation has been empirically supported in adult task switching studies reporting either weak or no correlation between task selection measures such as the probability of self-directly deciding (i.e., decide freely), to switch tasks (i.e., *p*(switch)) and task execution measures such as the cost associated with the performance drop when individuals need to switch from one task to another (i.e., switch costs; Arrington & Yates, 2009; Butler, Arrington, & Weywadt, 2011; Mayr & Bell, 2006), hence speaking to the separability of these two processes. However, a drawback of these studies is that they do not disentangle task selection from task execution as both processes are simultaneously captured in one response on each trial. As a consequence, it is unclear how these processes contribute (whether similarly or differently) to performance.

In contrast, the double registration procedure disentangles task selection and task execution by using a task selection prompt (e.g., a question mark) preceding the task execution target (Arrington and Logan, 2005). Therefore, individuals make two responses on each trial, first they enter a response just to select the task and then they enter a second response to execute it. The handful of studies using the double registration procedure with adults, did so in the voluntary task switching paradigm, in which participants freely choose which tasks to perform between two, following the general instructions of performing them equally often and in a random manner. They found that task selection and task execution are distinct processes, differently affected by individual and contextual factors. For instance, working memory capacity and reward influence task execution switch costs but not *p*(switch)—an index of task selection in the voluntary task switching paradigm (Butler et al., 2011; Fröber, Pfister, & Dreisbach, 2019). But other research has highlighted a more complex relation between task selection and task execution. That is, higher *p*(switch) is associated with smaller task execution switch costs (Mittelstädt, Dignath, Schmidt-Ott, & Kiesel, 2018). Further, task difficulty differently affects task selection and task execution, with greater task selection switch costs observed when switching to the harder tasks whereas greater task execution switch costs are found when switching to the easier task (Millington, Poljac, & Yeung, 2013). Moreover, consistent with the conflict monitoring model predicting that a task is more highly activated in working memory following the experience of response conflict (e.g., Botvinick, Carter, Braver, Barch, & Cohen, 2001; Brown, Reynolds, & Braver, 2007), previous congruency influences both task selection and task execution, with higher *p*(switch) associated with better task performance after incongruent trials than congruent trials, but contrary to the predictions of this model, previous accuracy affects *p*(switch) but no task performance, with higher *p*(switch) and less (not more) accurate responses after incorrect responses (Orr, Carp, & Weissman, 2012). However, although these studies indicate that task selection and task execution are dissociated, they are nevertheless both sensitive to between-task inference and congruency effects (Millington et al., 2013; Orr et al., 2012), revealing a more complex picture about their relation and potential relatedness.

Of particular interest, it is unknown whether task selection and/or task execution gives rise to greater mixing costs or switch costs. Specifically, mixing costs were not investigated in the studies using the double registration procedure with adults. Yet, mixing costs capture a critical performance drop associated with repeating a task in blocks where it is mixed with another task (i.e., high task uncertainty), relative to repeating a task in a block where the same task is always relevant (i.e., low task uncertainty). Switch costs, as stated previously, correspond to the additional performance drop on trials where participants actually need to switch tasks relative to task repeat trials within mixed-task blocks (Peng, Kirkham, & Mareschal, 2018; Rubin & Meiran, 2005). As task uncertainty, which affects task selection, is high on both switch and repeat trials within mixed blocks, mixing costs may mostly reflect the difficulty of task selection (e.g., Kikumoto & Mayr, 2017). Further, as task uncertainty may be similar on both switch and repeat trials within mixed blocks (at least when both trial types are equally frequent), switch costs may mostly reflect the greater difficulty of task execution when one needs to reorient attention to information that has been previously ignored (e.g., Courtemanche et al., 2019).

Previous developmental investigations of cognitive control have used different task-switching paradigms in which performance indistinctly reflects both task selection and task execution (e.g., Doebel & Zelazo, 2015; Gonthier, Zira, Colé, & Blaye, 2019), but never with the double registration procedure. It is therefore unknown how these two processes develop across childhood and whether their separability holds during childhood as it does during adulthood (Demanet & Liefooghe, 2014; Dignath, Kiesel, & Eder, 2015; Fröber et al., 2019; Millington et al., 2013; Mittelstädt et al., 2018; Orr et al., 2012a; Poljac, Poljac, & Yeung, 2012). Indeed, recent research has shown that task selection becomes easier with age (e.g., Frick, Brandimonte, & Chevalier, 2019), but it is still unclear whether this is also the case for task execution. For instance, different developmental trajectories between task selection and task execution (e.g., if task execution was mastered earlier in the development than task selection) would speak to the separability of the two processes.

Further, the separability of task selection and execution can be complementarily probed by investigating to what extent these two processes are influenced by distinct factors (e.g., Fröber et al., 2019; Millington et al., 2013; Orr et al., 2012; Poljac et al., 2012). One such factor is the self-directedness demand of cognitive control engagement, which ranges from being externally driven (e.g., forced task choices driven by environmental cues on each trial such as in cued task switching paradigm) to being self-directed (e.g., free task choices on each trial with the global instructions to perform each task equally often and randomly such as in the voluntary task switching paradigm). Self-directedness demand affects the difficulty of task selection, as selecting the most appropriate task is especially challenging for children in self-directed situations in which no external aids guide what tasks/actions to perform and when. Indeed, in such contexts, children perform better when strategies reducing task selection demands are prompted before the task (Barker et al., 2014; Snyder & Munakata, 2010, 2013; but for a review, see Barker & Munakata, 2015). In contrast, there is no *a priori* reason to expect self-directedness demand to affect task execution, as the task should similarly difficult to execute once it has been selected (Butler et al., 2011; Fröber et al., 2019; Millington et al., 2013). Alternatively, one may argue that self-directedness demand may still have an indirect influence on task execution through task selection if the difficulty of task execution is dependent on the difficulty of task selection, which would speak for a less dissociable aspect regarding these two processes.

The current study aimed to disentangle the respective contribution of task selection and task execution to childhood cognitive control by investigating (1) how they give rise to mixing and switch costs and (2) whether or not the self-directedness demand affects these processes. To this end, 4-5, 7-8 and 10-11-years-old children completed alternating-runs task switching paradigm in which the double registration procedure was used. The alternating-runs task switching paradigm requires participants to follow a predictable task-rule sequence such as switching on every other trial (e.g., task A, task A, task B, task B, etc.) without external (environmental) cues as the task has to be performed on *n* trial, which therefore taps more self-directed than on externally-driven engagement of control (Rogers & Monsell, 1995). Self-directedness demand was manipulated by either explicitly teaching children the alternating rule (low self-directedness demand) or letting them infer it from feedback (i.e., high self-directedness demand). Indeed, while children can already follow an alternating task rule without external cues relatively efficiently at around 5 years-old (Dauvier, Chevalier, &

Blaye, 2012), inferring a task rule from feedback largely improves from 7 years-old only before reaching an adult-like performance around 10 years of age (e.g., Chelune & Baer, 1986; Rosselli & Ardila, 1993; Shu, Tien, Lung, & Chang, 2000). Consequently, targeting 4-5-, 7-8- and 10-11-year-olds ensured varying levels of rule-inference ability, hence potentially revealing age-related change in how self-directedness may affect task selection and task execution.

We predicted that mixing costs should arise mostly from task selection and switch costs from task execution, as such we should observe greater mixing costs than switch costs for task selection and greater switch costs than mixing costs for task execution. Moreover, if the difficulties of task selection and task execution are independent of each other as previous research has showed that they are separable processes, we predicted that self-directedness demand should affect task selection performance but not task execution performance. Yet, it remained possible that the higher difficulty of task selection due to greater self-directedness demand may indirectly influence task execution. Finally, as self-directedness demand should be especially costly for younger children, we expected its effect on task selection to decrease with age, and more rapidly under low self-directedness demand than high self-directedness demand. The first and third hypotheses were confirmatory whereas the second hypothesis was exploratory.

Methods

Participants

Participants included 60 4- and 5-year-old children (M_{age} = 5.21 years, SD_{age} = .45, range: 4.25 – 5.98, 27 females), 60 7- and 8-year-old children (M_{age} = 7.92 years, SD_{age} = .30, range: 7.40 – 8.42, 26 females) and 60 10- and 11-year-old children (M_{age} = 10.77 years, SD_{age} = .40, range: 10.00 – 11.73, 34 females). Thirteen additional children were excluded from the analysis: eight children due to an experimental error in the program and four children because they fell outside the targeted age range.

All children were tested at school and prior to data collection, a power analysis was conducted with the program GPOWER (Erdfelder, Faul, & Buchner, 1996) which indicated that a minimum sample size of 30 children was needed per age group in each instruction condition to obtain a statistical power at the recommended .80 level (Cohen, 1988) with a medium effect size of .25 based on previous studies using a similar paradigm to the present study (e.g., Hung, Huang, Tsai, Chang, & Hung, 2016). Therefore, data collection stopped when the sample size for each age group reached at least 60 children, with 30 children in each instruction condition. Informed written consent was obtained from children's parents and all children provided signed assent and received a small age-appropriate prize (e.g., stickers) at the end of the experiment. Children were mostly Caucasian, monolingual and attended the same school, although socio-demographic information was not systematically collected as we did not have specific hypotheses about SES. All children were drawn from the same school catchment area, suggesting similar socio-economic backgrounds. Age and sex did not differ between conditions in any of the age groups (Table 1). The research project and protocol were approved by an Ethics Committee as well as participating schools. Data collection took place between May 2018 and March 2019.

[Insert Table 1 around here]

Material and procedure

All children were tested individually in a 20-minute session in a quiet room at school. They completed a child-friendly alternating-run task-switching paradigm presented with E-Prime 2 (Psychology Software Tools, Pittsburgh, PA) in which a monkey needed help to clean up his room. Toys needed to be sorted by colour or shape in two corresponding toy chests, the Colour toy chest and the Shape toy chest.

Each trial started with a question mark alongside the two closed toy chests with two response pictures below each toy chest (i.e., a blue and red patch under the Colour toy chest, a car and teddy-bear patch under the Shape toy chest) (Figure 1). The toy chests were constantly visible on the right- and left-hand sides of the monitor but their locations and corresponding response pictures were counter-balanced across participants. After children selected one of the two closed toy chests by pressing one of two keys ('w' and 'i' on a QWERTY keyboard), the question mark was replaced by a happy monkey face if they selected the correct toy chest or a sad monkey face if they selected the incorrect toy chest. Additionally, the selected toy chest opened and the two response pictures under the other toy chest disappeared. After 500 ms, the monkey face was replaced by the target and children had to match this target with one of the response pictures below the selected toy chest (i.e., the 'car' or 'teddy bear' buttons if the Shape toy chest was selected or the 'red or 'blue' buttons if the Colour toy chest was selected) by pressing the corresponding key on the keyboard ('a', 'd', 'j' or 'l'). As such, when children selected a task, whatever this selection was correct or incorrect based on the alternating rule, they had a chance to nevertheless execute it as we wanted to see if the difficulties of task selection were related to task execution. After the response, the target was replaced by an entire yellow banana if both task selection and task execution was correct, half of a yellow banana if only task selection or task execution was correct, or an entire green banana if both task selection chest and task execution was incorrect.

[Insert Figure 1 around here]

All children first completed two single-task blocks in which they consistently filled the Colour toy chest or the Shape toy chest (order counter-balanced). Each single-task block contained 4 practice trials (repeated if more than two errors were committed) followed by 16 test trials. The experimenter helped children on practice trials if necessary but not on test trials. Then, children were told they would fill the two toy chests at the same time and proceeded to the mixed-task blocks. Children were assigned to one of the two experimental conditions. In the rule instruction condition, they were instructed to start with one dimension (counter-balanced across children) and then change dimension on every second trial. This rule was explained as follows: '*Kiki wants you to fill both the Color and Shape toy chests. He wants you to start with the Color toy chest. He also wants you to sort the toys in a specific order: two toys in the Color toy chest, two toys in the Shape toy chest, two toys in the Color toy chest again, two toys in the Shape toy chest again and so on'*. In the no rule instruction condition, they were instructed to start with a specific dimension, but were not told about the alternation between the two dimensions on every second trial, as they had to guess this rule from the feedback. This was explained as follows: '*Kiki wants you to fill both the Color and Shape toy chests. He wants you to start with the Color toy chest. He also wants you to sort the toys in a specific order and it is your job to guess in which toy chest he wants you to sort the toys. Be careful, it will not be always the same toy chest'*. Importantly, in both conditions, children were also instructed that they would have to restart from the start of the sorting rule if they did not select the correct toy chest and/or match correctly the target with the response button. Children completed a familiarization block of six practice trials before performing two mixed blocks of 32 test trials each separated by a short break. During the break, children were reminded of the instructions according to the instruction conditions they were assigned to, and they were told to start the second block with the same dimension than in the first block.

Data analyses

The double registration procedure (Arrington & Logan, 2005) allowed for the distinction between task selection and task execution processes. Accuracy and RTs were separately examined for each process to better isolate the effects of the fixed factors, but also because RTs for task selection and task execution were not comparable because children could prepare in advance their response before prompt onset (for task selection) whereas they could not do so before stimulus onset (for task execution). Prior to analyses, RTs were log-transformed (to correct for skewness and minimize baseline differences between ages; Meiran, 1996). Log RTs were examined after discarding the first trial of each block, which were neither a task repetition trial nor task switch trial, which resulted in the removal of 4.17% of the total trials. Moreover, for task selection, only correct task selection trials and task selection trials preceded by correct task execution trials were kept, resulting in the removal of 17.91% of the total trials and RTs above 10,000 milliseconds (ms) or 3 standard deviations above the mean for each participant were also removed (1.59% of the total trials). For task execution, a similar trimming procedure was performed with the difference that this time, we kept RTs of correct task execution trials and task execution trials preceded by correct task selection trials, which corresponded to the removal of 17.92% of the total trials. Finally, RTs below 200 ms and above 10,000 ms or 3 standard deviations above the mean for each participant were also removed, which resulted in the removal of 1.72% trials.

Mixed analysis of variances (ANOVAs) were run on accuracy and log RTs to examine the effect of age group (4-5 year-olds, 7-8 year-olds and 10-11 year-olds) as a between-subjects variable, and instruction condition (rule instruction, no rule instruction), and trial type (single task, task repetition, task switch) as within subject variables. When appropriate and evidenced by Mauchly's tests (Mauchly, 1940), the Greenhouse-Geisser (Greenhouse & Geisser, 1959) correction was applied for violation of the assumption of sphericity. Tukey's post hoc tests were used for pairwise comparisons resulting from these anovas when there were multiplicities issues. These analyses were performed on R version 3.6.3 (R Core Team, 2020) using *afex* and *emmeans* packages (Lenth, 2020; Singmann, Bolker, Westfall, Aust, & Ben-Shachar, 2020). Mixing costs were examined by contrasting trials in single-task blocks (simply referred to as single trials below) with task repetition trials in mixed-task blocks (referred to as task repetition trials), while switch costs were examined by contrasting task repetition trials and task switch trials within mixed-task blocks (Rubin & Meiran, 2005). Rank-based methods with the Holm adjustment (Holm, 1979) to control for type I error (i.e., known as a false positive finding or conclusion) were used for multiple comparisons of costs with the *nparcomp* package (Konietschke, Placzek, Schaarschmidt, & Hothorn, 2015) and more specifically with the *gao_cs* function (Gao, Alvo, Chen, & Li, 2008).

Results

Task selection accuracy

Task selection accuracy was significantly affected by age group, $F(2, 174) = 14.98$, $p < .001$, $\eta^2_p = .15$, instruction condition, $F(1, 174) = 63.30$, $p < .001$, $\eta^2_p = .27$, and trial type, $F(2, 348) = 244.97$, $p < .001$, $\eta^2_p = .58$. As illustrated in Figure 2, overall, 4-5 and 7-8-year-olds did not differ, $p = .079$, but these two age groups were significantly less accurate than 10-11 year-old children ($M_{\text{4-5 year-olds}} = .86$ *vs.* $M_{\text{7-8 year-olds}} = .89$ *vs.* $M_{\text{10-11 year-olds}} = .93$; *ps* < .004). Accuracy was significantly higher with than without rule instruction ($M_{\text{rule instruction condition}} = .94$ *vs.* $M_{\text{no rule instruction condition}} = .85$; $p < .001$) and decreased significantly across single, task repetition, and task switch trials ($M_{\text{single trials}} = 1$ *vs.* $M_{\text{task repetition trials}} = .86$ *vs.* $M_{\text{task switch trials}} = .82$; *p*s < .001), hence revealing significant mixing and switch costs overall.

Age group and instruction condition significantly interacted, $F(2, 174) = 3.07$, $p = .049$, $\eta^2_p = .03$, 4-5 year-olds were less accurate than 7-8 year-olds and 10-11 year-olds in the rule instruction condition ($M_{\text{4-5 year-olds}} = .89$ *vs.* $M_{\text{7-8 year-olds}} = .95$ *vs.* $M_{\text{10-11 year-olds}} = .96$; *ps* < .007), with no difference between the latter age groups, $p = .694$. Conversely, in the no rule instruction condition, both 4-5 year-olds and 7-8 year-olds showed similar accuracy rates that were significantly lower accurate than 10-11 year-olds ($M_{\text{4-5 year-olds}} = .83$ *vs.* $M_{\text{7-8 year-olds}} = .83$ *vs.* $M_{\text{10-11 year-olds}} = .90$; $ps < .001$).

Age group also interacted with trial type, $F(4, 348) = 15.97$, $p < .001$, $\eta^2_p = .15$. There were significant mixing costs for all ages and significant switch costs for 7-8 year-olds and 10-11 year-olds, but not for 4-5 year-olds for whom non-significant reversed switch costs were observed (4-5 year-olds: $M_{\text{single trials}} = 1$ *vs.* $M_{\text{task repetition trials}} = .78$ *vs.* $M_{\text{task switch trials}} = .81$; 7-8 year-olds: $M_{\text{single trials}} = 1$ *vs.* $M_{\text{task repetition trials}} = .88$ *vs.* $M_{\text{task switch trials}} = .79$; 10-11 year-olds: $M_{\text{single trials}} = 1$ *vs.* $M_{\text{task repetition trials}} = .92$ *vs.* $M_{\text{task switch trials}} = .87$; $ps < .009$ and $p = .168$). Specifically targeting performance costs, we observed that mixing costs were overall significantly higher than switch costs ($M_{\text{mixing costs}} = .14$ *vs.* $M_{\text{switch costs}} = .03$; $p < .001$). However, this difference was significant for 4-5 year-olds only ($M_{\text{mixing costs}} = .22$ *vs.* $M_{\text{switch costs}} = -.03$; $p < .001$), but not for older children, $ps > .093$. Moreover, 4-5 year-olds showed greater mixing costs than older children ($M_{\text{7-8 year-olds}} = .12$ and $M_{\text{10-11 year-olds}} = .08$; $p < .001$), whereas the latter did not differ, $p = .125$. Conversely, higher switch costs were observed for 7-8 year-olds and 10-11 year-olds ($M_{\text{7-8 year-olds}} = .08$ and $M_{\text{10-11 year-olds}} = .04$; $ps < .032$) than for 4-5 year-olds.

Finally, instruction condition and trial type significantly interacted, $F(2, 348) = 48.20$, $p < .001$, $\eta^2_p = .22$, with significant mixing costs in both instruction conditions but significant switch costs only in the no rule instruction condition (rule instruction condition: $M_{\text{single trials}} = 1$ *vs.* $M_{\text{task repetition trials}} = .90$ *vs.* $M_{\text{task switch trials}} = .91$; no rule instruction condition: $M_{\text{single trials}} = 1$ *vs.* $M_{\text{task repetition trials}} = .82$ *vs.* $M_{\text{task switch trials}} = .74$; $ps < 001$ and $p = .868$). Mixing costs were higher than switch costs in both instruction conditions (rule instruction condition: $M_{\text{mixing costs}} = .10$ *vs.* $M_{\text{switch costs}} = -.01$; no rule instruction condition: $M_{\text{mixing costs}} = .18$ *vs.* $M_{\text{switch costs}} = .07$; $ps < .001$). Finally, mixing and switch costs were higher in the no rule instruction condition than in the rule instruction condition, $ps < .001$.

The three-way interaction between age group, instruction condition and trial type failed to reach significance, $p = .061$.

[Insert Figure 2 around here]

Task selection RTs

On task selection RTs, there were main effects of age, $F(2, 169) = 138.48$, $p < .001$, $\eta^2_p = .62$, trial type, $F(2, 338) = 30.14$, $p < .001$, $\eta^2_p = .26$, but not of instruction condition, $p = .252$ (Figure 3). Overall, task selection RTs decreased across all three age groups ($M_{4\text{-}5 \text{ year-olds}} = 7.27$ log-transformed ms (ln ms) *vs.* $M_{7\text{-}8 \text{ year-olds}} = 6.67$ ln ms *vs.* $M_{10\text{-}11 \text{ year-olds}} = 6.13$ ln ms; *ps* < .001), and from single task trials to task repetition trials, and from the latter trials to task switch trials ($M_{\text{single task trials}} = 6.57$ ln ms *vs.* $M_{\text{task repetition trials}} = 6.65$ ln ms *vs.* $M_{\text{task switch trials}} = 6.80$ ln ms; *ps* < .019), revealing significant mixing and switch costs. But mixing and switch costs did not differ from each other, $p = .283$.

A two-way interaction between age group and trial type, $F(4, 338) = 10.65$, $p < .001$, $\eta^2_p = .11$, further revealed that switch costs were significant for 4-5 year-olds only ($M_{\text{task repetition trials}} = 7.13$ ln ms *vs.* $M_{\text{task switch trials}} = 7.56$ ms; $p < 001$. Switch costs were significantly higher than mixing costs for 4-5 year-olds ($M_{\text{mixing costs}} = .01$ *vs.* $M_{\text{switch costs}} = .43$; $p < .001$), whereas no differences between these costs were observed for older children, *ps* > .277. 4-5 year-olds showed greater switch costs than older children ($M_{7\text{-}8 \text{ year-olds}} = .02$ and $M_{10\text{-}11 \text{ year-olds}} = .00$; *ps* < .001), whereas these costs between the two latter age groups did not differ, $p = 1$. Mixing costs did not vary across age groups, *ps* > .474.

Instruction condition also interacted with trial type, $F(2, 338) = 4.51$, $p = .014$, $\eta^2_p = .03$. Significant mixing and switch costs were observed in the no rule instruction condition ($M_{\text{single task trials}} = 6.54$ ln ms *vs.* $M_{\text{task repetition trials}} = 6.72$ ln ms *vs.* $M_{\text{task switch trials}} = 6.85$ ln ms; *ps* < .004), but only significant switch costs were observed in the rule instruction condition

($M_{\text{single task trials}}$ = 6.59 ln ms *vs.* $M_{\text{task repetition trials}}$ = 6.59 ln ms *vs.* $M_{\text{task switch trials}}$ = 6.75 ln ms; $p < .001$). Mixing and switch costs did not differ between the instruction conditions, *ps* > .070.

[Insert Figure 3 around here]

Task execution accuracy

Age group and trial type significantly affected task execution accuracy, $F(2, 174) = 15.91$, $p < .001$, $\eta^2_p = .15$ and $F(2, 348) = 14.83$, $p < .001$, η^2_p = ..08, but not instruction condition, $p = .514$, and none of these factors interacted with each other, *ps* > .171 (Figure 4). Overall, 4-5 year-olds were less accurate than 7-8 year-olds and 10-11 year-olds, but the latter two did not differ from each other ($M_{\text{4-5 year-olds}}$ = .89 *vs.* $M_{\text{7-8 year-olds}}$ = .93 *vs.* $M_{\text{10-11 year-olds}}$ = .94; *p*s < .001 and $p = .391$). Accuracy was lower in both single trials and task repetition trials, which did not differ from each other, relative to switch trials ($M_{\text{single trials}}$ = .92 *vs.* $M_{\text{task repetition trials}}$ = .91 *vs.* $M_{\text{task switch trials}}$ = .94; $p = .508$ and $p < .001$), hence revealing no significant mixing costs and reverse switch costs.

[Insert Figure 4 around here]

Task execution RTs

On task execution RTs, there were main effects of age group, $F(2, 169) = 197.70$, $p < .001$, $\eta^2_p = .70$, and trial type, $F(2, 332) = 378.99$, $p < .001$, $\eta^2_p = .69$, but not of instruction condition, $p = .834$. As illustrated in Figure 5, RTs significantly decreased with age ($M_{\text{4-5 year-olds}}$ = 7.48 ln ms *vs.* $M_{\text{7-8 year-olds}}$ = 7.08 ln ms *vs.* $M_{\text{10-11 year-olds}}$ = 6.67 ln ms; *p*s < .001), and were faster on single trials than on task repetition trials, and on task repetition trials than on task switch trials ($M_{\text{single trials}}$ = .6.88 ln ms *vs.* $M_{\text{task repetition trials}}$ = 7.02 ln ms *vs.* $M_{\text{task switch trials}}$ = 7.30 ln ms; *ps* < .001), hence revealing significant mixing and switch costs. Switch costs were significantly higher than mixing costs overall ($M_{\text{mixing costs}}$ = .13 ln ms *vs.* $M_{\text{switch costs}}$ = .28 ln ms; $p < .001$).

Moreover, age group significantly interacted with trial type, $F(4, 338) = 3.10$, $p = .020$, $\eta^2_p = .03$. Mixing costs were significant for 4-5 year-olds and 7-8 year-olds (4-5 years-old: $M_{\text{single task trials}} = 7.26$ ln ms *vs.* $M_{\text{task repetition trials}} = 7.43$ ln ms; 7-8 years-old: $M_{\text{single task trials}} = 6.90$ ln ms *vs.* $M_{\text{task repetition trials}} = 7.02$ ln ms; *ps* < .024), but not for 10-11 year-olds, $p = .059$. Switch costs were significant for all age groups (4-5 years-old: $M_{\text{single task trials}} = 7.26$ ln ms *vs.* $M_{\text{task repetition trials}} = 7.43$ ln ms *vs.* $M_{\text{task switch trials}} = 7.75$ ln ms; 7-8 years-old: $M_{\text{single task trials}} = 6.90$ ln ms *vs.* $M_{\text{task repetition trials}} = 7.02$ ln ms *vs.* $M_{\text{task switch trials}} = 7.31$ ln ms; 10-11 years-old: $M_{\text{single task trials}} = 6.52$ ln ms *vs.* $M_{\text{task repetition trials}} = 6.62$ ln ms *vs.* $M_{\text{task switch trials}} = 6.87$ ln ms; *ps* < .001). Switch costs were significantly higher than mixing costs for all age group (4-5 year-olds: $M_{\text{mixing costs}} = .18$ ln ms *vs.* $M_{\text{switch costs}} = .31$ ln ms; 7-8 year-olds: $M_{\text{mixing costs}} = .12$ ln ms *vs.* $M_{\text{switch costs}} = .29$ ln ms; 10-11 year-olds: $M_{\text{mixing costs}} = .10$ ln ms *vs.* $M_{\text{switch costs}} = .25$ ln ms; *ps* < .013). Mixing and switch costs did not differ between age groups, *ps* > .280.

Finally, instruction condition significantly interacted with trial type, $F(2, 338) = 3.61$, $p = .030$, $\eta^2_p = .03$. Mixing and switch costs were significant in both instruction conditions (rule instruction condition: $M_{\text{single task trials}} = 6.89$ ln ms *vs* $M_{\text{task repetition trials}} = 6.99$ ln ms *vs.* $M_{\text{task switch trials}} = 7.32$ ln ms; no rule instruction condition: $M_{\text{single task trials}} = 6.87$ ln ms *vs* $M_{\text{task repetition trials}} = 7.04$ ln ms *vs.* $M_{\text{task switch trials}} = 7.29$ ln ms; *ps* < .001). Switch costs were higher than mixing costs in both instruction conditions, although this difference was smaller in the no rule instruction condition (rule instruction condition: $M_{\text{mixing costs}} = .09$ ln ms *vs.* $M_{\text{switch costs}} = .32$ ms ls; no rule instruction condition: $M_{\text{mixing costs}} = .17$ ln ms *vs.* $M_{\text{switch costs}} = .25$ ln ms; respectively $p = .007$ and $p = .017$). Mixing costs were higher in the no rule instruction condition than in the rule instruction condition whereas switch costs were higher in the rule instruction condition than in the no rule instruction condition, *ps* < .016.

[Insert Figure 5 around here]

Discussion

The present study temporally separated task selection and task execution to investigate to what extent these processes lead to mixing and switch costs and are affected by the self-directedness demand during childhood. Although mixing costs and switch costs were observed for both processes, task selection gave rise to both mixing and switch costs whereas task execution mostly gave rise to switch costs. Further, the self-directedness demand affected both task selection and task execution. This suggests that although these two processes are relatively independent regarding performance costs with age, they neverthless both contribute to self-directed cognitive control development.

One of the main finding is that task selection was associated with both mixing and switch costs whereas task execution was mostly associated with switch costs. This pattern is not consistent with the proposal that mixing costs mostly reflect task selection and switch costs task execution, but it nevertheless indicates that performance costs are differently associated with these processes, hence speaking for their relative dissociation. However, whereas greater switch costs than mixing costs were observed in task execution RTs for all age groups, these costs differently contributed to task selection with age. Indeed, task selection accuracy mixing costs were significantly greater than task selection switch costs for 4-5 year-olds but were similar for 7-8 year-olds and 10-11 year-olds. This primilarly sugests that mixing costs are more associated with task selection at a young age whereas both mixing and switch costs contribute to this this process in older children.

However, when it came to RTs, task selection switch costs were higher than task selection mixing costs for RTs in 4-5 years-old children, whereas once again no difference was observed between these costs for older children. Thus, identifying when to switch the task was costlier for 4-5 year-olds than for other age groups (see Chevalier, Huber, Wiebe, & Espy, 2013). Interestingly, younger children showed non-significant reversed switch costs for task selection accuracy. This pattern suggests a speed-accuracy trade-off: 4-5 year-olds may have been especially cautious on switch trials, leading to longer but more accurate responses on these trials as compared to task repetition trials, hence the reversed or small switch costs at that age. One possible interpretation for this trade-off is that 4-5 year-olds were easily detected that they needed to switch tasks, but figuring out which task to switch to and/or activating this task in working memory, was especially time consuming for them as compared to older children, potentially because of lower working memory capacities (Camos & Barrouillet, 2018). Similarly, we found similar reversed switch costs for task execution accuracy associated with longer switch costs for task execution RTs for all age groups. This pattern is consistent with potential speed-accuracy trade-offs: taking longer to executive a task seems to ensure greater likelihood of success.

Taken together, these findings on task selection suggest that although both mixing and switch contribute to this process; these costs were higher in 4-5 year-olds than older children, indicating that this process was particularly costly for young children. This potentially shed new light on why children under 7-8 years-old struggle with task selection (Frick et al., 2019; Munakata, Snyder, & Chatham, 2012; Snyder & Munakata, 2010, 2013). Conversely, on task execution, switch costs were greater than mixing costs at all ages and these costs did not differ between age groups, indicating that this pattern is steady across childhood. Besides speaking for the separability of these two processes, the fact that task selection was associated with both performance costs whereas task execution was mostly associated with switch costs seem to indicate that task execution is less costly and master earlier in the development.

Furthemore, there were no significant costs for task execution accuracy, suggesting that task execution was less difficult to achieve than task selection in our paradigm. However, a limitation of this finding is that mixing costs may not have been observed for task execution accuracy because of the specificity of the paradigm used in the current study. Indeed, once the task was selected, only that task remained available for task execution. This procedure is different from what has been done in some adult studies in which response options related to both tasks remained available during task execution (e.g., Demanet & Liefooghe, 2014). Children may have made less errors because they could only perform the task they previously selected, hence reducing accuracy mixing costs. Note however that significant mixing and switch costs were observed for task execution RTs, suggesting that executing the selected task remained demanding even though our setup likely resulted in highly successful outcomes, hence revealing that the difficulties of task selection did influence the difficulties of task execution.

This transfer of difficulty from task selection to task execution was more salient when the self-directedness demand varied as both processes were affected. More specifically, both mixing costs for task selection accuracy and task execution RTs were significantly higher in the no rule instruction condition than in the rule instruction condition. Therefore, the costs associated to the selection of the relevant task when the two tasks are mixed, and more precisely when the relevant task has to be self-inferred, requiring increasingly working memory capacities and efficient abstract representations (Camos & Barrouillet, 2018; Munakata et al., 2012), transferred to when this task has to be executed. As such, although task selection and task execution processes progressively dissociate from each other with age, they are both sensitive to high self-directedness demand (i.e., when control engagement is especially self-directed). This has important implications for our understanding of the supposedly separability of these two processes as shown in the adult literature (e.g., Butler et al., 2011; Fröber et al., 2019; Millington et al., 2013; Mittelstädt et al., 2018; Orr et al., 2012). Indeed, while these studies have shown that factors such as between-task interference or previous congruency both affect task selection and task execution, but in a different ways (see Millington et al., 2013; Orr, Carp, & Weissman, 2012), our study reports that these processes are similarly influenced by self-directedness demand, suggesting their dissociable but relatedness on this aspect and that they both contribute to self-directed control development as this effect hold for all age groups.

Note that consistent with our initial hypothesis, task selection accuracy significantly increased from 4-5 years-old to 7-8 years-old, while no difference was observed between 7-8 and 10-11 years-old under low self-directedness demand. Conversely, both 4-5 and 7-8 years-old were significantly less accurate than 10-11 years-old under high self-directedness demand. These findings are in line with Dauvier et al. (2012) who showed that children from 5-6 years-olds can be successful when the task provides alternating rule instructions even without external cues. In contrast, inferring the rule from feedback was challenging for children below 7-8 years-olds (e.g., Chelune & Baer, 1986; Rosselli & Ardila, 1993; Shu et al., 2000). However, this finding does not necessarily mean that children below 7-8 years of age cannot use feedback to infer a rule to guide behaviours. For instance, 4- to 6-years-olds children can successfully infer the relevant tasks based on feedback and switch between task sets, although not as efficiently as older children and adults (e.g., Chevalier, Dauvier, & Blaye, 2009; Cianchetti, Corona, Foscoliano, Contu, & Sannio-Fancello, 2007; Jacques & Zelazo, 2001). But, here, children assigned to the no rule instruction condition did not only need to infer the relevant task, they had to infer a relevant sequence of tasks. This required them to maintain the information conveyed by the feedback but also the information about the tasks they performed over multiple trials before they could actually infer the alternating rule. As such, it was more demanding in terms of working memory and abstract reasoning that what children are asked to do in tasks where after one or two trials children can know which task is now relevant for several further trials once they have inferred the newly relevant task (e.g., Chevalier et al., 2009; Cianchetti et al., 2007; Jacques & Zelazo, 2001). Therefore, improvement in task selection in our paradigm may be linked to increasingly working memory capacities and efficient abstract representations with age (Camos & Barrouillet, 2018; Munakata et al., 2012).

Our study is limited by a potential confound between the self-directedness demand and reinforcement induced in our paradigm. As the task was easier to select with rule instructions, children in this condition received more positive feedback than children in the no rule instruction condition. Importantly, more frequently getting positive feedback may increase positive affect in the rule instruction condition. Research has shown that positive phasic (i.e., inducing an emotion before each trial) and tonic (i.e., inducing a general mood in the long run) affect reducing switch costs (e.g., Liu & Wang, 2014; Müller et al., 2007; Wang, Chen, & Yue, 2017; but for a review, see Goschke & Bolte, 2014). To further investigate this potential confound related to affect and motivation, we conducted further analyses on RTs for task execution to control for the phasic and tonic affect (see Supplemental Material). In short, we found the exact same pattern of findings as in the main analyses, suggesting that switch costs were more related to task execution than mixing costs. Moreover, if phasic and tonic affect had an effect on our initial results, we should have observed greater switch costs in the no rule instruction condition than in the rule instruction condition. However, in our initial analyses and supplemental analyses, we observed that switch costs were greater in the rule instruction condition than in the no rule instruction condition for task execution RTs. This indicates that children who received more negative feedback (in the no rule instruction condition) did not show a more pronounced switch costs that children who received more positive feedback (in the rule instruction condition), but the reverse, and that phasic and tonic affect did not influence this result.

Finally, another limitation relates to the fact that although no precise socioeconomic status (SES) information regarding the children tested in this study was collected, they all came from private schools and therefore our sample was largely homogenous. As such, our results require cautious as they might not be generalizable to the larger population. Indeed, lower SES has been found to be associated with poorer cognitive control in situations where cognitive control is externally driven (Halse, Steinsbekk, Hammar, Belsky, & Wichstrøm, 2019; Lawson, Hook, & Farah, 2018). In contrast, little is known about the influence of SES on self-directed engagement of cognitive control during childhood. Consequently, future research on self-directed control should examine how it may be influenced by SES, especially given that self-directed control likely plays a critical role in children's lives and academic achievement.

To conclude, our findings speak to the separability of task selection and task execution regarding performance costs. Indeed, both mixing and switch costs contributed to task selection, but to a greater extent in younger children than in older children, whereas task execution is mostly associated with switch costs at all age. This suggests that task execution and its underlying mechanism is mastered earlier in the development than task selection. One venue for future research is to explore how different modes of control engagement can account for this difference. For instance, younger children may show both greater performance costs for task selection because they rely more on a reactive form of control whereas older children engage more flexibly a proactive form of control, which potentially reduces these costs more than mixing costs, in task selection. However, so far this assumption remains speculative. Moreover, self-directedness demand variations have a greater effect on mixing costs than on switch costs, especially when this demand is high. But this effect can be seen in both task selection and task execution, suggesting that the difficulties in task selection transfers to some extent to task execution, and therefore that these two processes are related on this aspect. Consequently, although these two processes appear to be dissociated with age regarding performance costs, they are related when it comes to self-directedness, suggesting that these two processes should be targeted if one wants to promote self-directed control development, which is key fostering autonomy in children.

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