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Voluntary task switching in children

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

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25   **Abstract**

26   Emerging cognitive control supports increasingly efficient goal-directed behaviors.

27   With age, children are increasingly expected to decide autonomously and with little external

28   aid which goals to attain. However, little is known about how children engage cognitive

29   control in such a self-directed fashion. The present study examines self-directed control

30   development by adapting the voluntary task switching paradigm—the gold standard measure

31   of this control form in adults—for use with 5-6 year-old and 9-10 year-old children. Overall,

32   p(switch) suggests that even younger children can engage self-directed control successfully.

33   However, other measures showed they struggled with task selection. Specifically, compared

34   with older children and adults, they relied more on systematic strategies which reduced the

35   cost of task selection, even when the strategy involved switching more often. Like externally

36   driven control, self-directed control relies critically on task selection processes. These two

37   forms of control likely form a continuum rather than two discrete categories.

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

40   control, cognitive development

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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

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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,

117   He, Bode, & Haynes, 2013). Thus, due to higher task selection demands, VTS is more

118   demanding than other task switching paradigms.

119   Having enough time to prepare for the next trial is crucial to engage the cognitive

120   control processes needed to select and execute a task, as evidenced by a smaller repetition

121   bias and higher p(switch) when participants are given a longer preparation time (i.e., response

122   to stimulus interval, RSI) before stimulus onset (Arrington & Logan, 2005; Butler, Arrington,

123   & Weywadt, 2011; Butler & Weywadt, 2013; Liefooghe, Demanet, & Vandierendonck,

124   2009; Yeung, 2010). Adults may benefit from longer preparation time because they need time

125   to adaptively select the task they want to perform next through the representativeness

126   heuristic, that is, selecting a task after maintaining a sequence of recently performed tasks in

127   working memory and comparing it with an internal sequence of randomness before stimulus

128   onset). Alternatively, the task to be performed next can be selected via the availability

129   heuristic, which consists in selecting after stimulus onset the task that has just been done,

130   which has had less time to decay in working memory and is thus easier to reactivate than the

131   other task. Unlike the representativeness heuristic, the availability heuristic requires no

132   preparation time to operate but it leads to more task repetitions (Arrington & Logan, 2005).

133   Long preparation times may allow adults to anticipate and prepare in advance for the

134   upcoming task, hence encouraging the representativeness heuristic over the availability

135   heuristic. Interestingly, these two heuristics map onto the distinction between proactive

136   control (i.e., engagement of control in anticipation of upcoming demands) and reactive

137   control (i.e., engagement of control in the moment it is needed; Braver, 2012), respectively.

138   Concurrent working memory load leads to more task repetitions in VTS (Liefooghe,

139   Demanet, & Vandierendonck, 2010; Weaver & Arrington, 2010), perhaps because it prevents

140   proactive control, which heavily relies on working memory for the sustained maintenance of

141   goal-relevant information (Marklund & Persson, 2012). Unlike adults and older children,

142   younger children tend to be biased towards reactive control, rarely engaging proactive control

143   (Chevalier, Martis, Curran, & Munakata, 2015; Doebel et al., 2017; Munakata, Snyder, &

144   Chatham, 2012). They may therefore rely more on the availability than the representativeness

145   heuristic in VTS, and thus show a greater repetition bias than adults, even with long

146   preparation times.

147   However, the repetition bias or p(switch), which is the unique measure of task

148   selection processes in most prior studies in adults, may fail to capture important aspects of

149   VTS performance, such as the need to perform both tasks equally often and in random

150   fashion. Specifically, a participant could show a p(switch) equal to .5, which is considered as

151   a perfect score of randomness, but nevertheless use a non-random strategy such as

152   systematically switching every two trials (e.g., Task A, Task A, Task B, Task B, Task A,

153   Task A, etc.). Indeed, there are individual differences in self-organized strategies in VTS,

154   with a majority of adults adaptively engaging in both task repetitions and task switches (i.e.,

155   *alternaters*), but also a minority using more basic non-random strategies such as constantly

156   switching between the tasks (i.e., *switchers*) or constantly repeating the task they have just

157   done on a previous trial (i.e., *blockers*; Reissland & Manzey, 2016). This heterogeneity in the

158   use of strategies in VTS echoes developmental research showing great heterogeneity

159   regarding the use of strategies in externally driven task switching situations in children (e.g.,

160   Blakey, Visser, & Carroll, 2016; Dauvier, Chevalier, & Blaye, 2012). Consequently, a full

161   account of task selection processes involved in VTS should at least report measures of (a)

162   task transition, assessing how often participants repeat or switch tasks, (b) task selection

163   equality, indexing how well they perform the two (or more) tasks equally often and (c) task

164   randomness, indicating how often participants use non-random strategies.

165   VTS has never been used with children, despite its prominent role in the adult

166   literature and potential to shed light on self-directed control development. The present study

167   adapted this paradigm for children to investigate age-related changes in task selection

168   processes when no external aid is provided. We targeted 5- to 6- and 9- to 10-year-olds (in

169   addition to adults), given the now well-established transition from reactive to proactive

170   control during that age range (Chevalier et al., 2015; Munakata et al., 2012). We used three

171   different measures to comprehensively capture three main aspects of task selection processes:

172   (a) task transition through p(switch); (b) task selection equality through the relative difference

173   between the proportion of trials in which each of the two tasks was selected; and (c) task

174   randomness through occurrences of non-random strategies. In addition, we examined the role

175   of reactive and proactive control in VTS by varying preparation time duration using a short

176   (600 ms) and a long (2,000 ms) preparation times. Given that younger children engage

177   proactive control less than adults, we expected them to show a lower p(switch) and to be

178   worse at performing the two tasks equally often and be less sensitive to preparation time

179   variations than other age groups, who should show a higher p(switch) and perform the two

180   tasks more equally often especially with the longer preparation time. Importantly, we

181   expected younger children to struggle particularly with task selection and therefore rely more

182   on non-random strategies than older children and adults.

183   **Methods**

184   *Participants*

185   Participants included 29 5- and 6-year-old children (M_{age} = 6.07 years, SD_{age} = .46,

186   range: 5.25 – 6.67, 14 females), 31 9- and 10-year-old children (M_{age}= 10.01 years, SD_{age} =

187   .52, range: 9.08 – 10.92, 13 females), and 31 adults (M_{age} = 21.76 years, SD_{age} = 3.36, range:

188   18.75 – 30.75, 15 females). Two additional 5-6-year-olds were excluded, because they either

189   failed the practice (see Methods section hereafter) and or fell outside the targeted age range.

190   Data collection stopped when the sample size of each age group reached 31 participants,

191   which is comparable to prior developmental studies comparing 5- and 6-year-old children and

192 9- and 10-year-old children (e.g., Chevalier, Jackson, Roux, Moriguchi, & Auyeung, 2019) or

193 to adult studies using VTS (e.g., Fröber, Pfister & Dreisbach, 2019). Children were recruited

194 from one private preschool and one private primary school and adults were all students

195 enrolling at the University of Edinburgh. Informed written consent was obtained from

196 children's parents and from adult participants and all children provided signed assent.

197 Children received a small age-appropriate prize (e.g., stickers) and adults received either

198 course credits or £5 for their participation. The research project and protocols were approved

199 by the Ethics Committee from the University of Edinburgh (Study title: Role of time-

200 preparation in voluntary task switching in children and adults, Ref No. 23-1718/2,) as well as

201 all participating schools.

202 *Material and procedure*

203   All participants were tested individually in a 30-minute session either in a quiet room

204 at school (children) or in the laboratory (adults). They completed a child-friendly, voluntary

205 task switching paradigm adapted from a similar paradigm in adults (Arrington & Logan,

206 2004) and presented with E-Prime 2 (Psychology Software Tools, Pittsburgh, PA). It was

207 introduced to participants as 'Santa Claus and Mitch the Bad Elf Game.' Participants were

208 instructed to help Santa sort toys in two bags for Christmas, while watching out for Mitch, an

209 elf toy-thief. Participants were instructed to switch voluntarily between sorting bidimensional

210 targets (e.g., a blue teddy) by color and shape. If they played the color game, they had to

211 place the target in the Color bag by pressing the response box button matching the target's

212 color, whereas they had to place the target in the Shape bag if they played the shape game, by

213 pressing the button matching the matching the target's shape. Participants were given two

214 additional instructions (modelled after Arrington & Logan, 2004), corresponding to two main

215 features of the adult version of voluntary task switching paradigm. First, participants had to

216 put roughly as many toys in each of the two bags. Second, they had to play the two tasks

217 randomly, which was conveyed by asking participants to make sure Mitch could not predict

218 how they would sort the toys. Otherwise, Mitch would show up and steal the toy inside the

219 present box (the now empty present box would still be moved into the selected bag).
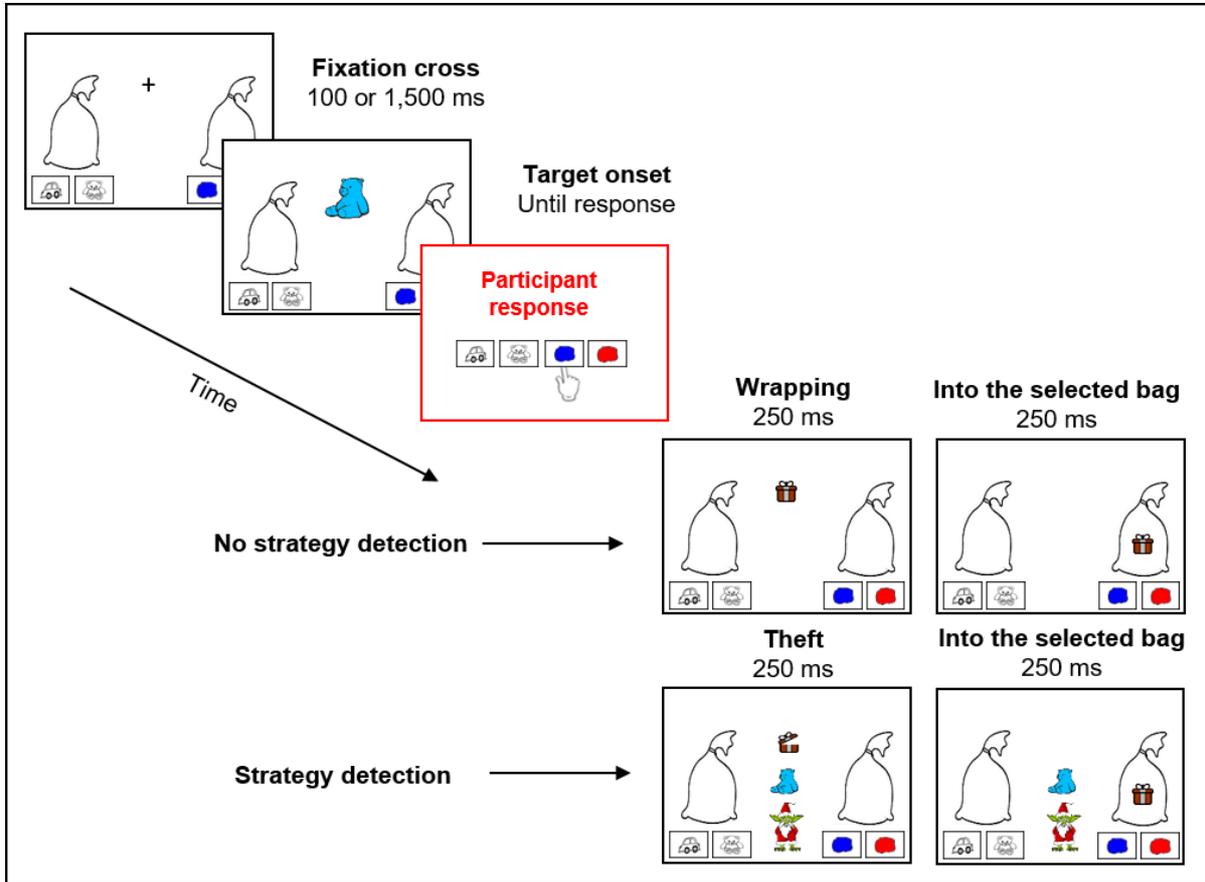
220
221 Figure 1. Child-friendly voluntary task-switching paradigm. Participants had to decide

222 whether to sort the toys in the Color or Shape bags according to the general instructions of

223 filling the two bags with about the same number of toys in a no-predictable fashion to avoid

224 the theft of the toys.

225

226   Each trial started with a central fixation cross alongside the two bags with two

227   responses pictures below each bag (i.e., a blue and red patch under the Color bag, a car and

228   teddy-bear under the Shape bag; Figure 1). The bags were constantly visible on the right- and

229   left-hand sides of the monitor but the locations of the bags and responses pictures were

230   counter-balanced across participants. After 1,500 ms (in the long preparation time condition)

231   or 100 ms (in the short preparation time condition), the fixation cross disappeared and was

232   replaced with the target that remained on the screen until a response was entered by pressing

233   one of the four buttons on a response box. After the response, the target was replaced by a

234   closed present box that remained at the center of the screen for 250 ms before being moved to

235   the selected bag for 250 ms. If a predictable strategy was used and detected by the program

236   (for details on the different strategies implemented in the program and how many trials in a

237   row of a particular strategy would trigger Mitch the thief elf, see Data processing and analysis

238   section), the target was replaced by an opened present box with a small version of the toy

239   alongside Mitch the thief elf for 250 ms and the sound effect 'ah-ah'. Then the same present

240   box was closed and moved into the bag chosen by the participants while the small version of

241   the toy and Mitch remained on the screen for 250 ms. Whether or not the elf showed up, the

242   present box inside the bag was no longer visible during the following trial.

243   All participants completed the task in two conditions (order counterbalanced across

244   participants). In the short preparation time condition, the fixation cross was visible only for

245   100 ms, leaving a total of 600 ms (cross fixation duration = 100 ms + present moving or

246   Mitch appearing duration = 500 ms) for participant to prepare for the upcoming trial. In

247   contrast, in the long preparation time condition, the fixation cross was visible for 1,500 ms,

248   providing a total of 2,000 ms (cross fixation duration = 1,500 ms + present moving or Mitch

249   appearing duration = 500 ms) for participant to prepare for the upcoming trial. Different

250 combinations of colors and shapes were used in each condition (either car-teddy-blue-red or

251 doll-plane-green-pink).

252 In both conditions, participants first completed two single-task blocks in which they

253 were instructed to always sort toys by either color or shape, in order to get familiar with each

254 task. Each single-task block comprised four warm-up trials (repeated up to two timed if

255 participants made more than two errors) followed by 16 test trials. The order of the color and

256 shape-matching tasks was counterbalanced across participants. Participants then completed

257 two mixed-task blocks in which they were instructed to switch voluntarily between the two

258 tasks with the two constraints of filling the two bags equally often and tricking Mitch as

259 much as they could. To make sure all participants understood the instructions, the

260 experimenter performed two demonstration trials. In the first demonstration, participants

261 observed the experimenter alternate systematically between the two bags (i.e., two tasks) on

262 seven trials ('color-shape-color-shape-color-shape-color' or 'shape-color-shape-color-shape-

263 color-shape' with order counter-balanced across participants and conditions), which resulted

264 in the next target being stolen by Mitch. In the second demonstration, participants were

265 shown one of two potential ways of successfully sorting the toys ('color-color-shape-color-

266 shape-shape-shape-color-color-shape-color-color' or 'shape-shape-color-shape-color-color-

267 color-shape-shape-color-shape-shape' with order counter-balanced across participants and

268 conditions), putting the same number of toys into each bag and avoiding the theft of toys by

269 Mitch. Participants then completed 16 practice trials. Practice trials were repeated (maximum

270 three times) if one bag contained more than 10 toys (62.5%), Mitch stole a toy (i.e., detection

271 of a predictable strategy), or more than eight errors (50%) were made. Critically, participants

272 first performed the practice trials on their own but if these trials needed to be repeated, they

273 received help from the experimenter. Participants who failed to pass the practice trials after

274 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

300   separately for trials from single blocks, and repeat and switch trials from mixed blocks) or

301   10,000 ms, resulting in the removal of 1.71% of the remaining trials.

302   Task selection was measured via three indices. (1) *Task transition* was calculated

303   based on whether the task was repeated or switched on a given trial *n*. This measure, often

304   considered as the main outcome variable in studies using the voluntary task-switching,

305   corresponds to *p*(switch), and was calculated by dividing the number of task switch trials by

306   the total number of task switch and task repetition trials (i.e., 78). This score ranges between

307   0 and 1 with .5 corresponding to a perfectly equal number of task repetitions and task

308   switches. (2) *Task selection equality* corresponds to a task selection measure of the ability to

309   perform each task equally often in the mixed blocks. This index consisted in the relative

310   difference between the proportion of trials in which the Shape bag was selected and the

311   proportion of trials in which the Color bag was selected. As such, the closer this index was to

312   0, the more equally frequently the two tasks were performed. (3) *Task randomness* was via

313   occurrences of ten different systematic strategies. These strategies ranged from five basic to

314   complex patterns as follows:

315   - *Repetition Only (detected over seven trials)*:

316   o Task A, Task A, Task A, Task A, Task A, Task A, Task A.

317   o Task B, Task B, Task B, Task B, Task B, Task B, Task B.

318   - *Switch Only (detected over seven trials):*

319   o Task A, Task B, Task A, Task B, Task A, Task B, Task A.

320   o Task B, Task A, Task B, Task A, Task B, Task A, Task B.

321   - *One Repetition and Switch (detected over nine trials)*:

322   o Task A, Task A, Task B, Task B, Task A, Task A, Task B, Task B, Task

323   A.

324   o Task B, Task B, Task A, Task A, Task B, Task B, Task A, Task A, Task

325   B.

326 - *Two Repetitions and Switch (detected over eleven trials)*:

327   o Task A, Task A, Task A, Task B, Task B, Task B, Task A, Task A, Task

328   A, Task B, Task B.

329   o Task B, Task B, Task B, Task A, Task A, Task A, Task B, Task B, Task

330   B, Task A, Task A.

331 - *Three Repetitions and Switch (detected over thirteen trials)*:

332   o Task A, Task A, Task A, Task A, Task B, Task B, Task B, Task B, Task

333   A, Task A, Task A, Task A, Task B.

334   o Task B, Task B, Task B, Task B, Task A, Task A, Task A, Task A, Task

335   B, Task B, Task B, Task B, Task A.

336   If participants used one of these patterns, the corresponding strategy was

337 automatically detected by the program and triggered Mitch the thief elf. The frequency of

338 these strategies was used during the game (i.e., when Mitch showed up) as provided an

339 indication of randomness. Moreover, our analyses also focused on the qualitative type of

340 strategies (e.g., simple repetition of one task for seven trials or more complex alternation with

341 a switch every third repetition for thirteen trials).

342   Task performance and task selection measures were analyzed with mixed analyses of

343 variance (ANOVAs) with age as a between-subjects variable, and preparation time and/or

344 trial type as within subject variables, Bonferroni-corrected post hoc tests, and *t*-tests. When

345 appropriate, the Greenhouse-Geisser (Greenhouse & Geisser, 1959) correction was applied

346 for violation of the assumption of sphericity. Finally, the type of strategies used across age

347 groups and preparation time durations was analyzed with a multivariate analysis of

348 covariance (MANCOVA).

349 **Results**

350 ***Task performance***

351 *Accuracy rates*

352   A 3 (age group: 5-6 years, 9-10 years, adults) X 2 (preparation time: short, long) X 3

353 (trial type: single, task repetition, task switch) mixed ANOVA was performed on accuracy

354 rates. The analysis showed main effects of age, $F(2, 88) = 10.56$, $p < .001$, $\eta^2_p = .19$, trial

355 type, $F(2, 176) = 3.80$, $p = .038$, $\eta^2_p = .04$, and preparation time, $F(1, 88) = 8.681$, $p = .004$,

356 $\eta^2_p = .09$, and these effects were qualified by a significant two-way interaction between age

357 and preparation time, $F(2, 176) = 4.30$, $p = .017$, $\eta^2_p = .09$, and a significant three-way

358 interaction, $F(4, 176) = 3.57$, $p = .014$, $\eta^2_p = .07$. Preparation time differentially affected trial

359 type across age groups (Figure 2). More specifically, while 5-6 year-olds were significantly

360 less accurate with the short than the long preparation time ($M_{short} = 88.86\%$ vs. $M_{long} =$

361 93.04%), $p = .008$, no such difference was observed in 9-10 year-olds and adults (9-10 year-

362 olds: $M_{short} = 94.32\%$ vs. $M_{long} = 94.87\%$; adults: $M_{short} = 97.15\%$ vs. $M_{long} = 97.59\%$),

363 respectively $p = .574$ and $p = .209$. Moreover, for the 5-6 year-olds, only the difference

364 between single trials and task repetition trials in the long preparation time condition ($M_{single} =$

365 96.09%, vs. $M_{task\ repetition} = 91.25\%$) was significant, $p = .012$, revealing significant mixing

366 costs. Conversely, 9-10 year-olds showed significant mixing costs in the short preparation

367 time condition ($M_{single} = 96.67\%$ vs. $M_{task\ repetition} = 92.82\ \%$), $p = .014$. For adults, accuracy

368 rates across trial types and preparation time revealed no significant mixing or switch costs, all

369 *ps* > .079.

370
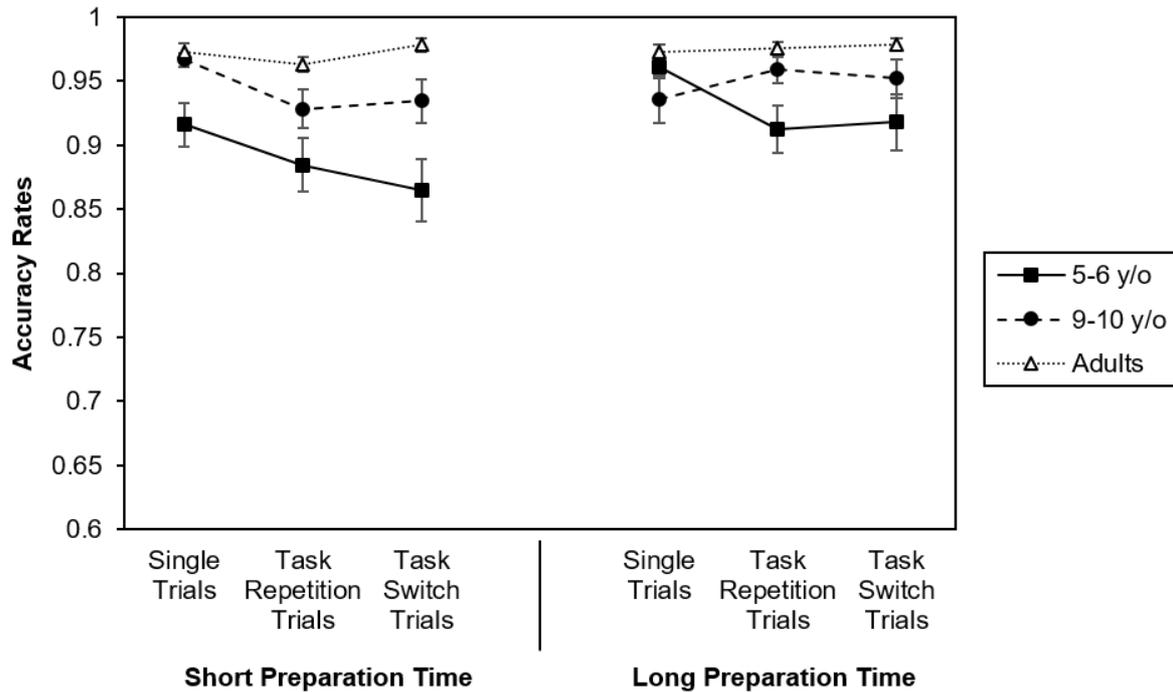
371   Figure 2. Accuracy rates by trial type (single, task repetition, task switch) for 5-6 year olds, 9-

372   10 year olds and adults as a function of preparation time. Error bars represent standard errors.

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374   *Reaction times (RTs)*

375   On RTs, a 3 (age group: 5-6 years, 9-10 years, adults) X 3 (trial type: single, task

376   repetition, task switch) X 2 (preparation time: short, long) mixed ANOVA was performed.

377   There were main effects of age, $F(2, 88) = 159.89$, $p < .001$, $\eta^2_p = .78$, trial type, $F(2, 176) =$

378   351.86, $p < .001$, $\eta^2_p = .80$ but not of preparation time, $p = .231$, and these effects were

379   qualified by two-way interactions between age and trial type, $F(4, 176) = 8.09$, $p < .001$, $\eta^2_p =$

380    $.15$, and trial type and preparation time, $F(2, 176) = 21.87$, $p < .001$, $\eta^2_p = .20$, and a three-

381   way interaction between all these factors, $F(4, 176) = 2.84$, $p = .038$, $\eta^2_p = .06$. Although each

382   age group showed significant mixing and switching costs, all $ps <. 001$, these costs were

383   overall higher for 5-6 year-olds ($M_{single} = 1261.29$ ms, $M_{task\ repetition} = 1870.23$ ms and M_{task}

384    $_{switch} = 2614.53$ ms) than for 9-10 year-olds ($M_{single} = 724.02$ ms, $M_{task\ repetition} = 1018.97$ ms

385   and $M_{task\ switch} = 1219.19$ ms) and adults ($M_{single} = 488.02$ ms, $M_{task\ repetition} = 662.70$ ms and

386    $M_{\text{task switch}}$ = 762.33 ms). Moreover, preparation times did not affect mixing costs in children

387   (5-6 year-olds: M_{short} = 559.55 ms vs. M_{long} = 658.31 ms; 9-10 year-olds: M_{short} = 291.39 ms

388   vs. M_{long} = 298.51 ms), all ps > .629, but it did in adults (M_{short} = 191.78 ms vs. M_{long} = 157.58

389   ms), p = .049. Conversely, switching costs were higher with short than long preparation times

390   in each age group, and this difference was largest for 5-6 year-olds (5-6 year-olds: M_{short} =

391   1034.47 ms vs. M_{long} = 454.12 ms; 9-10 year-olds: M_{short} = 281.25 ms vs. M_{long} = 119.20 ms;

392   adults: M_{short} = 129.35 ms vs. M_{long} = 69.92 ms), all ps < .005 (Figure 3).
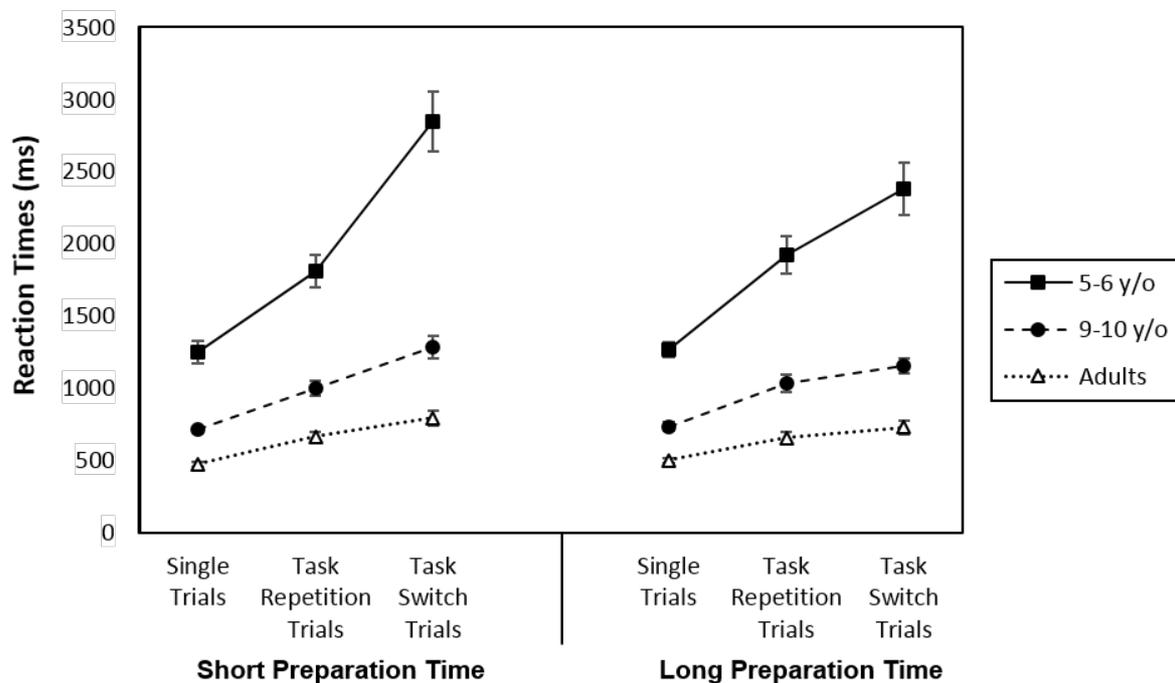
393
394   Figure 3. Response times (RTs) in milliseconds for 5-6 year olds, 9-10 year olds and adults as

395   a function of preparation time. Error bars represent standard errors.

396

397   ***Task selection***

398   *Task transition – P(switch)*

399   Task transition was examined with a 3 (age group: 5-6 years, 9-10 years, adults) X 2

400   (preparation time: short, long) mixed ANOVA performed on p(switch). The analysis revealed

401   a main effect of preparation time, $F(1, 88)$ = 7.90, p = .006, η^2_p = .08, but no effect of age, p

402   = .353, and no significant interaction between preparation time and age, p = .275. Overall,

403   pairwise comparisons indicated that participants switched tasks slightly less often when

404   preparation time was short than long, respectively, $M_{p(switch)}$ = 44.78 % and $M_{p(switch)}$ = 48.54

405   %, p = .006, (Figure 4). However, when comparing p(switch) between both conditions for

406   each group, we found that there were significant differences between the short and long

407   preparation time conditions in older children and adults, respectively p = .015 and p = .004,

408   but no difference in young children, p = .831.

409
410   Figure 4. P(switch) for 5-6 year olds, 9-10 year olds and adults as a function of preparation

411   time. Error bars represent standard errors.

412

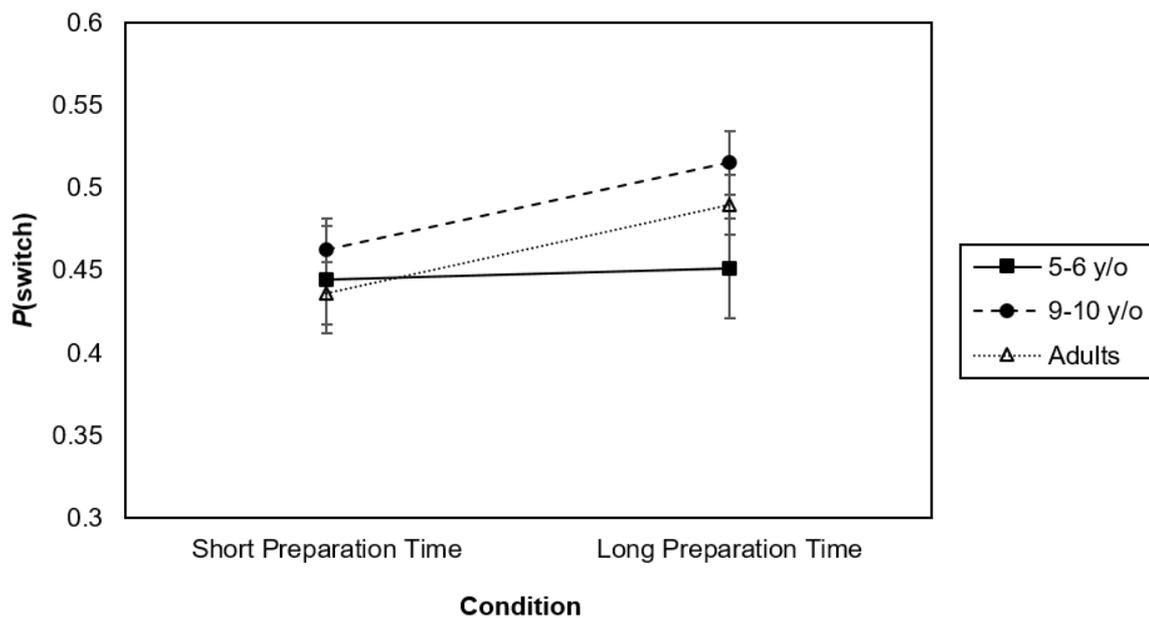413   *Task selection equality – Relative difference between the frequency of each task*

414   Task selection equality was analyzed with a 3 (age group: 5-6 years, 9-10 years,

415   adults) X 2 (preparation time: short, long) mixed ANOVA performed on the relative

416   difference between the two tasks. The ANOVA showed a main effect of age, $F(2, 88)$ = 8.19,

417   p = .001, η^2_p = .16 but no effect of preparation time, p = .720, and no interaction, p = .871.

418   Pairwise comparisons indicated that 5-6 year-olds did not perform the two tasks as equally

419   often ($M_{\text{difference}}$ = 10.30 %) as 9-10 year olds ($M_{\text{difference}}$ = 5.28 %) and adults ($M_{\text{difference}}$ = 5.32

420   %), regardless of the preparation time (Figure 5), all $ps > .003$.

421
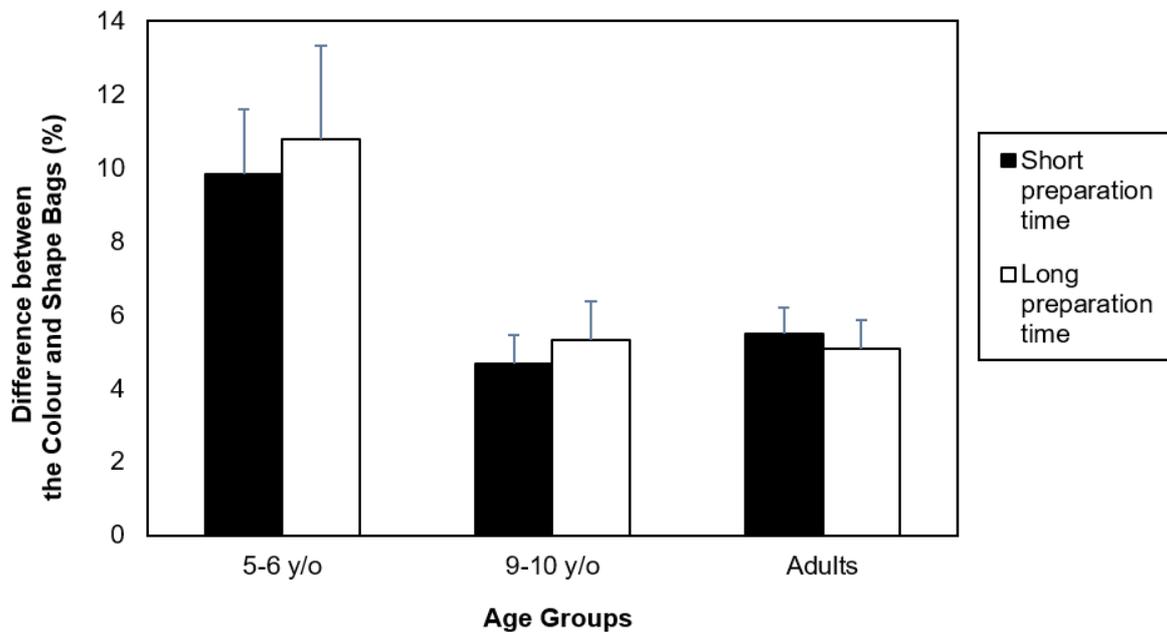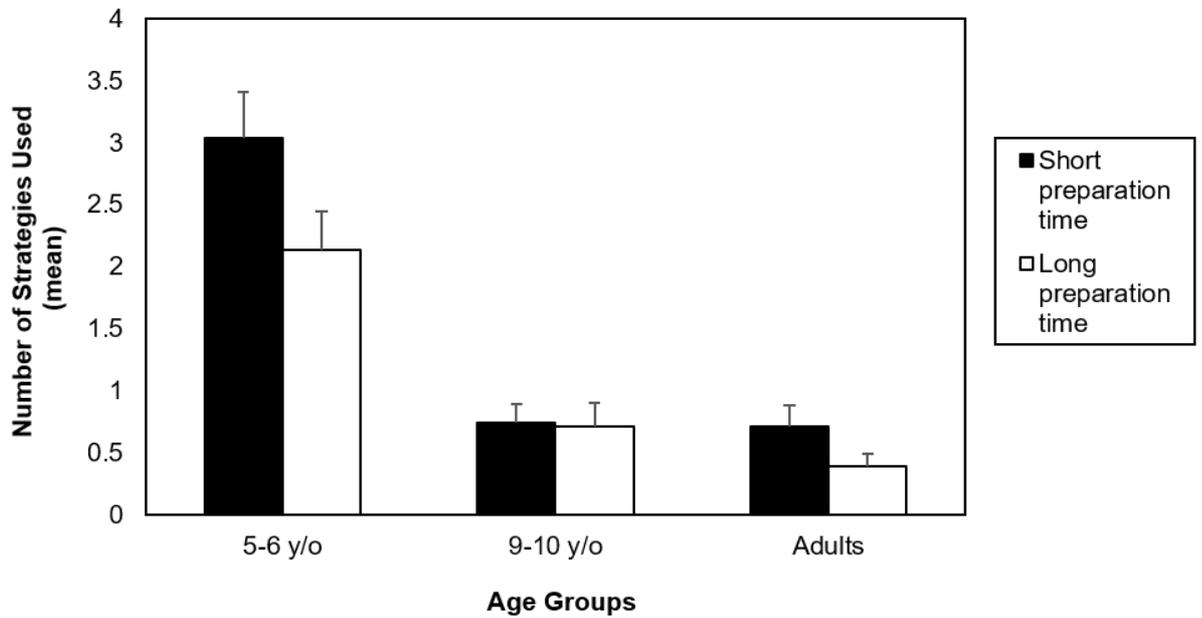422   Figure 5. Difference between the two bags for 5-6 year olds, 9-10 year olds and adults as a

423   function of preparation time. Error bars represent standard errors.

424

425   *Task randomness – Strategy detection and type of strategy used*

426   We examined task randomness with a 3 (age group: 5-6 years, 9-10 years, adults) X 2

427   (preparation time: short, long) mixed ANOVA to test to what extent participants used

428   predictable strategies, and whether or not it varied according to age and/or preparation time.

429   There were main effects of age, $F(2, 88) = 38.82$, $p = < .001$ $\eta^2_p = .47$, and preparation time,

430    $F(1, 88) = 6.15$, $p = .015$, $\eta^2_p = .06$, while the interaction did not reach significance, $p = .113$.

431   Overall, pairwise comparisons indicated that younger children used significantly more non-

432   random patterns or strategies ($M = 2.59$) than older children ($M = 0.73$) and adults ($M =$

433   0.55), all $ps < .001$, and in all age groups, the use of strategies was overall slightly higher in

434   the short preparation time condition than in the long preparation time condition (respectively,

435     $M = 1.49$ and $M = 1.08$; Figure 6). Further analyses revealed that the difference between the

436   two preparation time conditions was not significant for all age groups, all $ps > .054$.

437
438 Figure 6. Strategy detection (mean) for 5-6 year olds, 9-10 year olds and adults as a function

439   of preparation time. Error bars represent standard errors.

440

441   Then, the type of strategies the participants used across age groups and preparation

442   time durations was investigated with a multivariate analysis of variance (MANOVA). It

443   revealed a significant difference in strategy type used based on age, $F(10, 344) = 9.45$, p

444     $< .001$, Wilk's $\Lambda = .62$, $\eta^2_p = .21$, but not based on preparation time, $F(5, 172) = 1.29$, $p =$

445     $.269$, Wilk's $\Lambda = .97$, $\eta^2_p = .04$, with no interaction between these two factors, $p = .340$. In

446   particular, as illustrated in Figure 7, age had a main effect on the strategy 'Repetition Only',

447     $F(2, 88) = 21.34$, $p < .001$, $\eta^2_p = .19$, 'Switch Only', $F(2, 88) = 11.18$, $p < .001$, $\eta^2_p = .11$, and

448   'One Repetition and Switch', $F(2, 88) = 4.55$, $p = .012$, $\eta^2_p = .05$, but not on the two other

449   strategies, all $ps > .441$. Pairwise comparisons indicated that younger children used

450   'Repetition Only' and 'Switch Only' strategies more often than older children and adults

451   ('Repetition Only': $M = 2.31$, $M = .06$ and $M = .29$, respectively, all $ps < .001$; 'Switch Only':

452   *M* = 1.517, *M* = .35 and *M* = .13, respectively, *ps* < .001). Younger children also significantly

453   used more the 'One Repetition and Switch' strategy than adults (*M* = .90 and *M* = .26,

454   respectively), *p* = .011, but not than older children, (*M* = .45), *p* = .123. All other comparisons

455   were not significant, all *ps* >.621. In younger children, the 'Repetition Only' strategy was not

456   significantly used more frequently than the 'Switch Only' strategy, *p* = .232, but more

457   frequently than 'One Repetition and Switch', *p* = .039. No difference was observed between

458   'Switch Only' and 'One Repetition and Switch', *p* = .164.
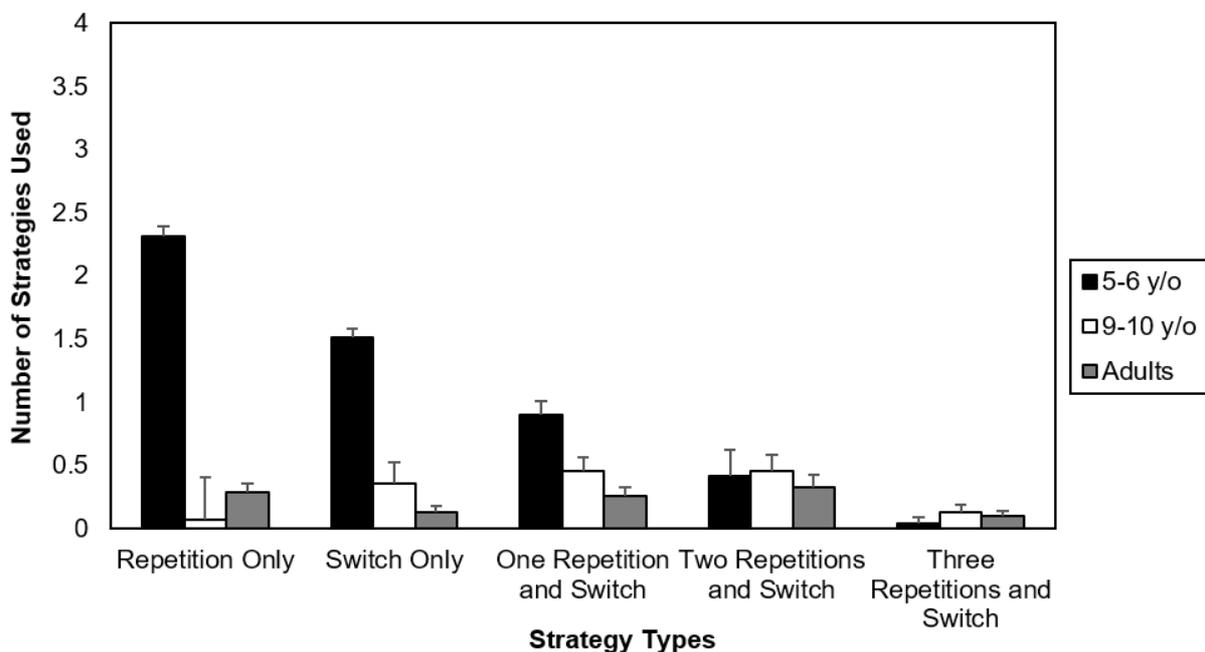
459
460   Figure 7. Use rate (mean) of each strategy from more the more basic to the more complicated

461   (left to right) as a function of age groups (5-6 year olds, 9-10 year olds and adults). Error bars

462   represent standard errors.

463

464   **Discussion**

465   The current study addressed the development of self-directed control by examining

466   how 5- to 6-year-olds, 9- to 10-year-olds, and adults voluntarily switch between tasks. In

467   particular, we explored the role of proactive and reactive control by using a short and a long

468   preparation time. Contrary to our expectations, younger children showed a similar repetition

22

469   bias to older children and adults, with a *p*(switch) value inferior to .5. However, following

470   our predictions, their *p*(switch) was less sensitive to preparation time variations than for older

471   children and adults, suggesting they engaged control more reactively than older groups.

472   Moreover, younger children were significantly worse at performing the two tasks equally

473   often, and used significantly more basic non-random strategies such as repeating

474   systematically the task that had just been done, switching systematically between the two

475   tasks or always switching after one repetition, reducing the cognitive demands of task

476   selection.

477   Mixing and switch costs found in our experiment replicated the trend found in

478   externally driven task switching paradigms in children (e.g., Chevalier & Blaye, 2009;

479   Chevalier, Dauvier, & Blaye, 2018; Dauvier et al., 2012), suggesting that our child-friendly

480   version of VTS appropriately tapped task switching. Furthermore, using for the first time this

481   child-friendly VTS paradigm, we replicated previous findings from VTS studies in adults

482   showing that participants had overall a *p*(switch) lower than .5 which even decreased with

483   shorter preparation time for older children and adults (e.g., Arrington & Logan, 2005; Butler,

484   Arrington, & Weywadt, 2011; Butler & Weywadt, 2013; Liefooghe, Demanet, &

485   Vandierendonck, 2009; Yeung, 2010). This further suggests that our VTS paradigm captured

486   self-directed control processes similar to those measured by classic VTS paradigms in adults,

487   hence speaking to the success of our VTS adaption.

488   Surprisingly, children showed a similar *p*(switch) to adults, against the expectation

489   that the repetition bias would follow a U shape pattern with age, as hinted by prior studies

490   showing a lower *p*(switch) during adolescence and aging than adulthood (Butler & Weywadt,

491   2013; Poljac, Haartsen, van der Cruijsen, Kiesel, & Poljac, 2018; Terry & Sliwinski, 2012).

492   In our study, the similar *p*(switch) across all age groups *seemingly* suggests no major

493   differences between children and adults in the task selection processes involved in VTS.

494   However, although the interaction between age and preparation time was not significant,

495   younger children showed the same p(switch) with both preparation times, whereas p(switch)

496   significantly increased with preparation time in older children and adults. Younger children

497   may have used reactive control (i.e., availability heuristic) in VTS regardless of the amount

498   of preparation time available, while older participants may have engaged proactive control

499   (i.e., representativeness heuristic) when enough time was available. This would corroborate

500   similar trends observed task switching paradigms, but also in other paradigms both tapping

501   externally-driven cognitive control (e.g., Blackwell & Munakata, 2014; Chevalier, James,

502   Wiebe, Nelson, & Espy, 2014; Chevalier et al., 2015; Lucenet & Blaye, 2014). Nevertheless,

503   further research is needed to clarify the role of reactive and proactive control in children's

504   VTS performance. One promising option would be to couple our child-friendly VTS with

505   physiological measurements such as event-related potentials, fMRI and pupil dilation, as they

506   measures have shown sensitivity to reactive and proactive control engagement on other tasks

507   (e.g., Chatham et al., 2012; Chevalier et al., 2015; Church et al., 2017).

508   As mentioned earlier, a drawback of using p(switch) as a unique measure of task

509   selection (Arrington et al., 2014) is that it does not capture all aspects of VTS performance.

510   In our study, the similar p(switch) found across age groups would suggest that children, and

511   younger children in particular, have little difficulty with self-directed control, which would

512   seem at odd with previous research on self-directed control development using different tasks

513   (Barker et al., 2014; Snyder & Munakata, 2010, 2013; White, Burgess, & Hill, 2009).

514   However, when considering measures other than p(switch), a different picture emerged,

515   showing that task selection was particularly costly for younger children. In particular,

516   younger children performed the two tasks less equally often than older children and adults.

517   Besides task selection difficulty, developmental limitations in numerical

518   understanding may contribute to age-related differences in VTS performance. Indeed,

519   learning number magnitudes develops slowly across childhood and although children as

520   young as 5 years-old can compare and add numerical quantities, they do not have adult-like

521   exact number magnitude representations and they do not have much experience with numbers

522   exceeding the 0-10 range (Barth, La Mont, Lipton, & Spelke, 2005, but see Sigler, 2016).

523   Therefore, younger children may therefore have failed to add on from the last number and

524   maintained this representation in working memory, leading them to struggle performing the

525   two tasks equally often. That said, counting strategies may not necessarily consist in counting

526   how many times each task was played throughout the game, but instead counting trials within

527   a run of trials before switching to the other task and starting from 1 again, which would

528   require simpler numerical processing. Helping children more easily keep track how many

529   toys have been put into each bag by letting children see how many toys have been sorted

530   within each bag should reduce age-related differences in future research, if these differences

531   arise from limited numerical processing in younger children.

532   Another important finding was that, systematic, non-random strategies were more

533   frequent in younger children than older children and adults. To account for this difference,

534   one may argue that younger children simply did not understand the instruction of filling the

535   two bags in a random fashion, even though this instruction was conveyed in a child-friendly

536   manner through a bad elf that could otherwise guess how the target would be sorted and

537   'steal' it. However, during practice, the use of systematic strategies was actively monitored

538   and participants would progress onto the test blocks only if they successfully played

539   randomly, hence ensuring their understanding of this instruction. As younger children

540   required indeed more practice than older children and adults (respectively $M_{number\ of\ practice} =$

541   1.43, $M_{number\ of\ practice} = 1.21$ and $M_{number\ of\ practice} = 1.11$, all $ps < .019$) to master the

542   instructions, one may argue that they may still have struggled to understand this instruction.

543   However, when comparing younger children who needed only one practice round without the

544 help of the experimenter—and therefore showed perfect understanding of the 'randomness'

545 instruction—to younger children who needed more than one practice round with the help of

546 the experimenter, we observed no significant differences regarding how often they resorted to

547 strategies (respectively, $M_{\text{number of strategy}}$ = 4.82 and $M_{\text{number of strategy}}$ = 5.25, p = .693). These

548 findings further suggest that younger children understood the need to sort targets randomly

549 but nevertheless relied on non-random strategies.

550   Young children may have been especially prone to resorting to strategies because of a

551 lack of working memory abilities coupled with a difficulty to keep in mind the instructions of

552 performing the two tasks equally often and in a random manner. Indeed, preschoolers, who

553 have low working memory abilities, are more prone to goal neglect (i.e., failure to maintain a

554 goal although how to achieve it is fully understood; see Marcovitch, Boseovski, & Knapp,

555 2007). Moreover, decrements in task performance when keeping prospective rule instructions

556 in mind have been observed with both adults (e.g., Smith, 2003) and children (e.g., Leigh &

557 Marcovitch, 2014; Smith, Bayen, & Martin, 2010; Nigro, Brandimonte, Cicogna, Cosenza,

558 2014; Smith, Bayen, & Martin, 2010). In our study, younger children may have needed the

559 appearance of the thief elf as a prospective cue to follow the instruction of being non-

560 predictable. It is therefore possible that processes underlying prospective memory abilities

561 also affect task selection processes alongside with task performance processes. Consistently,

562 commonality in processes between cognitive control and prospective memory has been

563 emphasized in childhood (Brandimonte, Filippelo, Coluccia, Altgassen, & Kliegel, 2011;

564 Mahy, Moses, & Kliegel, 2014; Mahy & Munakata, 2015; Spiess, Meier, & Roebers, 2016).

565   Whether intentional or not, use of non-random strategies reduced the high cost of task

566 selection demands specific to VTS for younger children. Having to hold complex rule

567 instructions while performing VTS is particularly costly for younger children, and one way to

568 reduce this cost is to favor the easiest rule instruction (i.e., putting about the same number of

569   toys into each bag) over the most difficult rule instruction (i.e., performing the two tasks

570   randomly). In prior research, removing the instruction of performing the two tasks in a

571   random manner resulted in larger individual differences regarding task selection in adults, as

572   indicated by large standard deviations in p(switch), suggesting that some participants were

573   more likely to repeat tasks whereas others were more likely to switch tasks (Arrington et al.,

574   2014). Of particular interest, one of the two most frequent strategies among the younger

575   children consisted in repeating the same task for long runs of trials, which led to a small

576   p(switch) and would fit with the U shape changes in VTS performance with age, with

577   adolescents and elderly people showing a greater repetition bias than adults (Butler &

578   Weywadt, 2013; Poljac et al., 2018; Terry & Sliwinski, 2012). However, younger children

579   also often used another strategy that consisted in switching systematically on every trial,

580   which led to a very large p(switch) and could explain why the overall p(switch) at the group

581   level was unexpectedly similar to that of older children and adults. Favoring the rule

582   instruction of performing the two tasks equally often over the rule instruction of performing

583   the two tasks randomly effectively reduces the cost of task selection. The selection of the

584   'Repeat Only' and 'Switch Only' as non-random strategies by younger children echoes the

585   study of Arrington et al. (2014), as well as a recent study showing individual preferences in

586   the use of strategies in a modified version of VTS in adults (Reissland & Manzey, 2016), and

587   confirms that in task switching situations, children show higher variability in individual

588   profiles when it comes to strategy selection (Dauvier et al., 2012; Moriguchi & Hiraki, 2011).

589   It is surprising that children systematically switched between tasks on every trial,

590   given that this strategy must have resulted in heavier task switching demands. This finding

591   further suggests that switching per se is not children's main difficulty when it comes to

592   engaging efficient cognitive control. Switch costs were indeed not significant in terms of

593   accuracy, even in younger children, although switching tasks is still more time-consuming

594   than repetitions, as attested by significant switch costs in terms of RTs. Unlike switching per

595   se, selecting the appropriate task appeared particularly demanding as attested by (a)

596   significant mixing costs for both accuracy and RTs, and (b) the use of non-random strategies

597   by young children to reduce its costs. This corroborated studies using externally driven

598   situations showing that task selection might be main young children's difficulty when

599   engaging cognitive control (Chevalier, 2015; Chevalier et al., 2018; Deák, Ray, & Pick,

600   2004; Holt & Deák, 2015).

601   In our experiment, participants showed similar mixing and switch costs on RTs to

602   those observed in externally driven situations. Similar processes may indeed be involved in

603   both externally driven and self-directed control, which may mostly differ in task selection

604   difficulty. Indeed, in VTS, while older children and adults adaptively selected tasks, younger

605   children struggled in their task selection as attested by the fact that they performed the two

606   tasks less equally often and used more non-random strategies. This confirms the recent idea

607   that task selection is key in cognitive control (Broeker et al., 2018) and a major force driving

608   cognitive development (Chevalier, 2015). Further, it also suggests that task selection is

609   crucial when drawing the contrast between externally driven and self-directed control. For

610   instance, consider the Wisconsin Card Sorting Test (WCST; Grant & Berg, 1948) compared

611   to VTS. Both tap self-directed control as in VTS, participants have to decide on their own

612   when to switch and what task to switch to, while in WCST, participants have to infer that the

613   rule has changed and figure out on their own which rule is now relevant. However, WCST

614   taps also externally driven control because the need to switch is externally supported by a

615   short feedback from the experimenter after each choice. This feedback indicates when to

616   switch but not towards what to switch to. These differences shed light on a continuum

617   between externally driven and self-directed control based on the amount of task selection

618   demands rather than a difference in nature, such as between reactive and proactive control.

619   To conclude, when voluntarily switching between tasks in VTS, 5- to 6-year-old

620   children especially struggled to select between the two tasks, in comparison with 9- to 10-

621   year-old children and adults, and used strategies which reduced task selection demands, even

622   if these strategies involved frequent switching. These findings are strikingly similar to what

623   has been previously found in tasks tapping externally driven control in children, speaking to

624   the idea that these two forms of control form a continuum in which task selection demands

625   vary rather than two discrete categories. As a consequence, better understanding task

626   selection processes and their development open up new directions to design efficient

627   interventions for assessing and supporting cognitive control in childhood.

633

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