Lifespan Developmental Differences in the Effects of Opportunity Costs on Cognitive Effort

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Abstract

Previous work suggests that lifespan developmental differences in cognitive control abilities might be due to maturational and aging-related changes in prefrontal cortex functioning. However, there are also alternative explanations: For example, it could be that children and older adults differ from younger adults in how they balance the effort of engaging in control against its potential benefits. In this work we assume that the degree of engagement in cognitive effort depends on the opportunity cost of time (average reward rate per unit time). If the average reward rate is high, subjects should speed up responding whereas if it is low, they should respond more slowly. Developmental changes in opportunity cost assessments may lead to differences in the sensitivity to changes in reward rate. To examine this hypothesis in children, adolescents, younger, and older adults, we apply a reward rate manipulation in two well-established cognitive control tasks: a modified Erikson Flanker and a task-switching paradigm. Overall, we found a significant interaction between age group and average reward, such that older adults were more sensitive to the average reward rate than the other age groups. However, as task complexity increased (in the task-switching paradigm), children also became sensitive to changes in reward rate. This may suggest that when demands on cognitive load reach capacity limitations, participants engage in strategic behaviour to optimize performance. If this interpretation is correct, increasing the cognitive load in younger adults should lead to similar strategic control allocations. We are currently testing this hypothesis by parametrically manipulating time pressure in the two tasks.

Keywords: Lifespan, Cognitive effort, Opportunity cost, Cognitive control, Reinforcement Learning

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1 Extended Abstract

A large body of literature on cognitive function across the lifespan suggests that children and older adults have limitations in cognitive control abilities, such as the ability to resolve interference between competing actions tendencies as well as the ability to switch between tasks (e.g. Eppinger et al., 2007; Li et al., 2009; Munakata et al., 2012). These limitations are commonly attributed to maturational and ageing-related functional changes in the prefrontal cortex (PFC; Braver & Barch, 2002; Bunge et al., 2002).

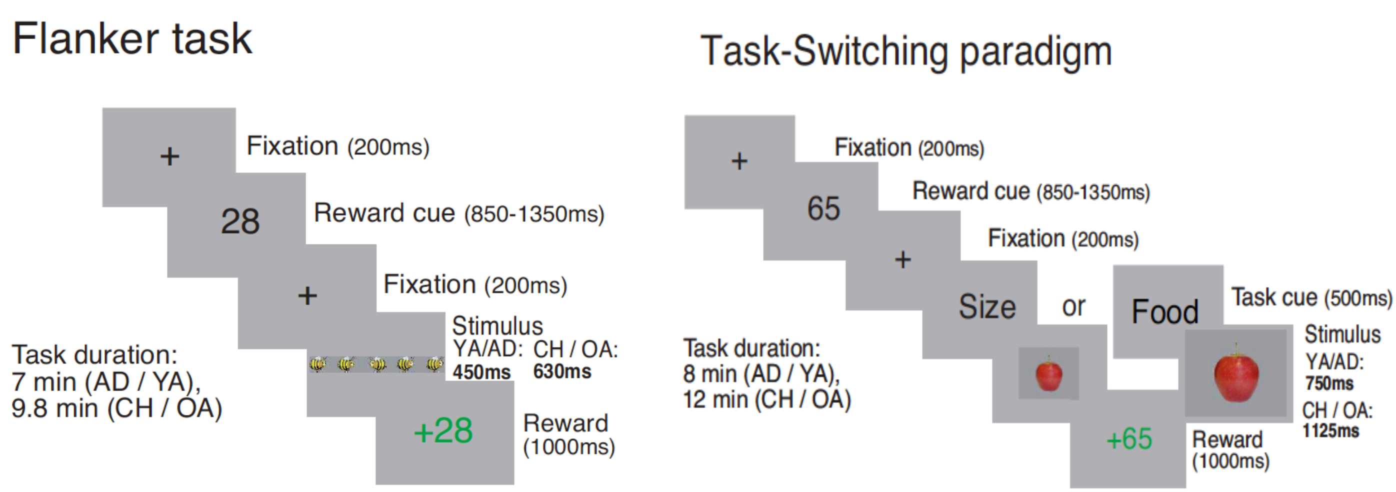
However, there are also alternative explanations: For example, it could be argued that performance differences between groups in demanding cognitive tasks may reflect differences in cost benefit analyses rather than limitations in cognitive abilities per se. From this perspective, it could be argued that children and older adults differ from younger adults not necessarily in their *capacity* for cognitive control, but in how they balance the effort of engaging in control against its potential benefits.

To explore this suggestion, we expanded on Otto and Daw's (2019) recent work, which suggests that such cost-benefit analyses in cognitive control tasks can be assessed in terms of opportunity costs. Opportunity costs in this context means that the cost of using cognitive resources in service of some goal forgoes the benefits of using those resources for some other goal (Niv et al., 2007). With this in mind, we assumed that the degree of exertion of cognitive effort should depend on the opportunity cost of time (average reward rate per unit time). That is, subjects should speed up responding when the reward rate is high – when delayed action is more expensive – and should slow down when the reward rate is low, representing a withholding of cognitive effort. We hypothesized that developmental changes in opportunity cost assessments would in turn lead to differences in the sensitivity to changes in reward rate.

To examine this hypothesis in children (CH; 9-12 years, n = 49), adolescents (AD; 14-16 years, n = 33), younger (YA; 19-34 years, n = 34), and older adults (OA; 68-70 years, n = 28), we used two well-established cognitive control tasks: an Erikson Flanker task (Eriksen & Eriksen, 1974; see Figure 1a) and a task-switching paradigm (Jersild, 1927; Monsell, 2003; see Figure 1b) with a reward rate manipulation (for a similar procedure see Otto & Daw, 2019). Importantly, we assume that the task-switching paradigm is the more complex of the two tasks, as it requires multiple control processes, involving the representation and maintenance of task sets, the flexible reconfiguration of task sets as well as the inhibition of currently irrelevant task sets (Monsell, 2003; Kiesel et al., 2010). In both tasks, subjects first saw a reward cue that represented the points at stake that trial and then had to complete a judgment task. Rewards varied according to a predetermined random walk, which, with subjects' responses, yielded an empirical average reward (see Figure 1c).

Figure 1

a **b**



c

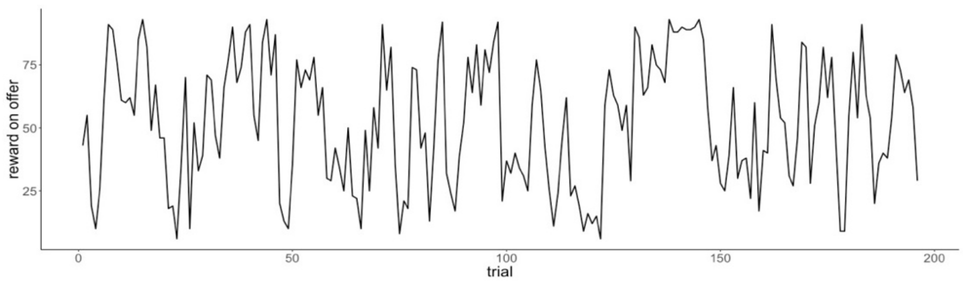


Figure 1. (*a*) In the Flanker task, participants have to indicate whether the bee in the center of the display is flying to the left or the right. On compatible trials the surrounding bees are flying into the same direction. On incompatible trials they fly into the opposite direction. To account for slower RT in children and older adults we adjusted the stimulus display times (max response time). (*b*) In the task-switching paradigm, participants either indicated whether the object was a fruit or a vegetable (Food task) or they indicated whether it was small or large (Size task). To account for slower RT in children and older adults we adjusted the stimulus display times (max response time). (*c*) Example of trial-to-trial fluctuation in reward on offer for one subject.

Following past work, we calculated the average reward, $\bar{r}$, using the following update rule (Otto & Daw, 2019):

$$\bar{r} = (1-a)^T \bar{r}_t + [1-(1-a)^T]\frac{R}{t}$$

where R is the reward obtained on trial t, T is the time elapsed since the last update, and a is the learning rate parameter. The learning rate parameter was estimated by fitting a single-learning rate to the RT of all participants within an age group using a non-linear optimization routine.

To assess the effect of average reward rate on RT, we conducted mixed-effects regressions. All terms were estimated at the fixed-level and as random-effects at the subject-level, except for age group. Continuous variables were within-subject-z-scored. Interactions between age group, average reward, and trial type were computed. Accuracy was examined with a logistic regression that used the same predictors, but where response (correct/error) was taken as a binary outcome variable. Additionally, we divided average reward into high and low reward rate categories. We used these categories to compute difference scores for RT and accuracy by subtracting RT/accuracy on low reward trials from RT/accuracy on high reward trials.

Results. Accuracy: Older adults outperformed (earned more points per trial than) all other groups in the Flanker task (M_{OA}= 48.95, M_{Rest}= 43.57, p < .001), but their performance dropped below that of young adults in the task-switching paradigm (M_{OA}= 40.18, M_{YA}= 44.44, p = .011)(see Figure 2). In contrast, children and teenagers showed impairments in task performance compared to younger adults in both tasks (Flanker: M_{YA} = 47.39, M_{CH} = 41.02, p < .001, M_{AD} = 43.04, p = .007; Task-Switching: M_{YA} = 44.44, M_{CH} = 37.28, p < .001, M_{AD} = 40.17, p =<.001).

Reward rate effects: We found a significant interaction effect between age group and average reward on RT in both tasks (Flanker: β = -0.09, SE = 0.005, p = .03; Task-Switching: β = -0.02, SE = 0.008, p = .02). Older adults sped up RT more than any other group when average reward was high in both tasks (Flanker: $M_{OA\text{-}RTLow}$ = 498.24, $M_{OA\text{-}RTHigh}$ = 489.53, p < .001; Task-Switching: $M_{OA\text{-}RTLow}$ = 708.96, $M_{OA\text{-}RTHigh}$ = 685.88, p < .001)(see Figure 3a). Interestingly, this speeding up did not come at a significant cost to accuracy in either task (Flanker: $M_{OA\text{-}ACCLow}$ = 0.91, $M_{OA\text{-}ACCHigh}$ = 0.93, p = .003; Task-Switching: $M_{OA\text{-}ACCLow}$ = 0.75, $M_{OA\text{-}ACCHigh}$ = 0.77, p = 0.10)(see Figure 3b). When task complexity increased (in the task-switching paradigm), children began to engage in the same strategy: speeding up RT without sacrificing accuracy ($M_{CH\text{-}RTLow}$ = 678.37, $M_{CH\text{-}RTHigh}$ = 667.26, p = .001; $M_{CH\text{-}ACCLow}$ 0.71, $M_{CH\text{-}ACCHigh}$ = 0.71, p = .99). In adolescents we found no significant differences in reward rate effects compared to younger adults ($M_{AD\text{-}RTlow\text{-}RThigh}$ = - 1.99, $M_{YA\text{-}RTlow\text{-}RThigh}$ = 2.55, p = 0.17; $M_{AD\text{-}ACClow\text{-}ACChigh}$ = 0.02, $M_{YA\text{-}RTlow\text{-}RThigh}$ = 0.03, p = 0.44).

Figure 2

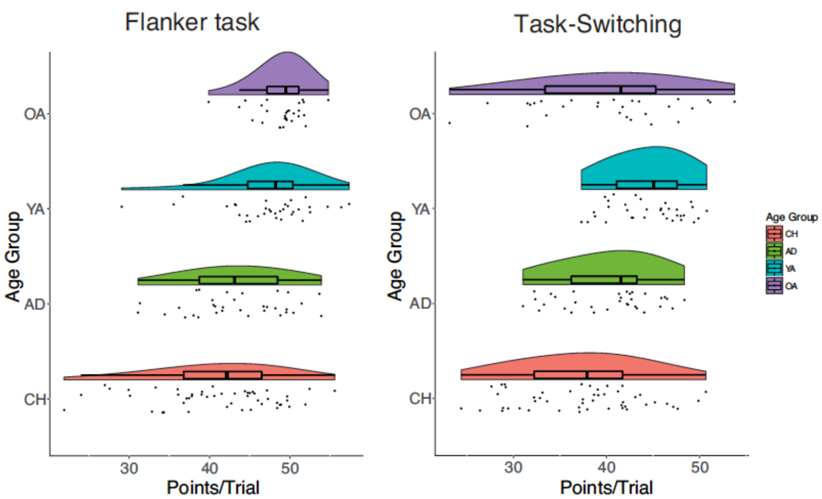
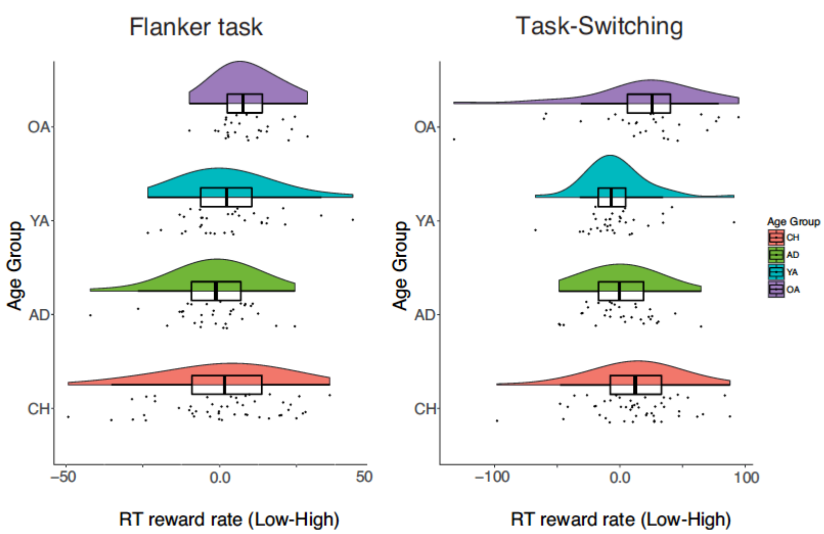


Figure 2. Performance in the Flanker and task-switching paradigm across age groups. On the x-axis are the average point for each subject. On the y-axis are the age groups. Median performance for each age group are represented by boxplots over distributions.

Figure 3

a



b

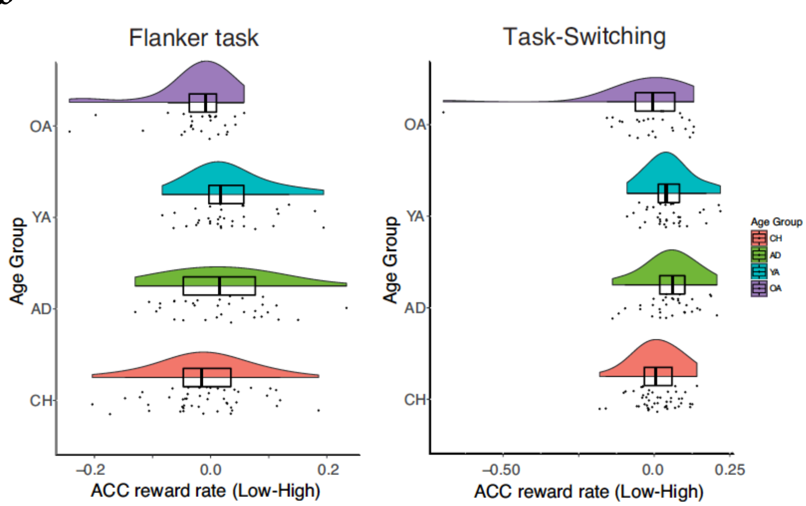


Figure 3. (*a*) Reward rate effects on RT in the Flanker and task-switching paradigm across age groups. (*b*) Reward rate effects on accuracy in the Flanker and task-switching paradigm across age groups.

On the x-axes are difference scores (RT/ACC when reward rate was low minus RT/ACC when reward rate was high). On the y-axis are the age groups. Median reward rate effects for each age group are represented by boxplots over distributions.

Discussion. Our results point to an enhanced sensitivity to reward rate in older adults in both tasks. That is, compared to the other age groups, older adults show the greatest reductions in RT when average reward was high compared to when it was low, with no significant loss in accuracy. This may suggest that when reward rate was high older adults focused more strongly on accuracy than the other age groups, which seems consistent with the previous literature (Starns & Ratcliff, 2010). As task complexity increased (in the task-switching paradigm), children also became sensitive to changes in reward rate. This indicates that when demands on cognitive load reach capacity limitations, children as well as older adults engage in strategic behaviour to optimize performance. In contrast to children and older adults, adolescents showed significant impairments in task performance compared to younger adults but no differences in reward rate effects. This may suggest that factors other than strategic control allocations contribute to the performance deficits in teenagers.

To investigate the hypothesis that trade-offs between effort and reward depend on cognitive load (as suggested by the data in children and older adults) we are currently assessing the impacts of parametric manipulations of time pressure on cognitive control performance in younger adults.

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