Cognitive resource limitations shift effort trade-offs across the lifespan

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Keywords: Lifespan development, opportunity costs, cognitive control, cognitive effort

Conflict of Interest: The authors declare no conflict of interest.

Acknowledgements: This work was supported by a grant from the German Research Foundation (DFG) [SFB 940/2 B7] as well as the Natural Sciences and Engineering Research Council of Canada (NSERC), [funding reference number N01882]. Furthermore, this research was undertaken, in part, thanks to funding from the Canada Research Chairs program. The authors thank Annekathrin Rätsch, David Reindel, Theresa Kolb, Noemi Holz, Johanna Dicke, Alexander Nitsch, Lion Schulz, and Niclas Lemmer for their assistance with data collection, as well as all participants and parents for taking part in the study.

Abstract

Previous work suggests that lifespan developmental differences in cognitive control abilities reflect maturational and aging-related changes in prefrontal cortex functioning. However, complementary explanations exist: 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 test whether the degree of cognitive effort expenditure depends on the opportunity cost of time (average reward rate per unit time): if the average reward rate is high, participants should withhold cognitive effort whereas if it is low, they should invest more. In Experiment 1, we examine this hypothesis in children, adolescents, younger, and older adults, by applying a reward rate manipulation in two well-established cognitive control tasks: a modified Erikson Flanker and a task-switching paradigm. We found that young adults and adolescents reflexively withheld effort when the opportunity cost of time was high, whereas older adults invested *more* resources to accumulate reward as quickly as possible. We interpret these results to suggest age- and process-specific differences in the processing of the opportunity cost of time. We qualify our findings in a second experiment in younger adults and conclude that there may exist developmental "sweet spots" for the role of the opportunity cost of time in modulating cognitive effort expenditure.

Taken together, the current study suggests a potential computational mechanism that older adults (and possibly children) use to strategically adapt to cognitive control demands in their environment: the opportunity cost of time.

Introduction

Despite the fact that humans possess an impressive arsenal of cognitive abilities in a variety of domains, our ability to perform multiple tasks in parallel and to flexibly switch between cognitive tasks is remarkably limited (Feng et al., 2014; Musslick & Cohen, 2019). This can be seen when trying to navigate in a busy city while also trying to read messages on a smartphone. Trying to accomplish both tasks is demanding because it requires that we flexibly adapt our actions to changing circumstances (e.g., looking away from the phone when taking a corner). The set of processes necessary to (re-)configure behaviour to changes in internal and external demands is often referred to as cognitive control (Botvinick et al., 2001). Engaging in cognitive control is effortful. Nevertheless we engage in these processes, because they seem to offer something of value (e.g., texting while walking gives us excitement, information, etc.). As a consequence, we face trade-offs between the cost (i.e., effort required) of engaging in a certain behavior and its potential benefits. Whether and how we manage such trade-offs then depends on both our *ability* to complete these tasks—our available cognitive resources—as well as our *motivation* to do so—based on the value of the outcomes.

Yet, individuals differ in their ability to succeed in these tasks. A substantial body of literature suggests that children and older adults have limitations in cognitive control abilities (e.g., Eppinger et al., 2007; Li et al., 2009; Munakata et al., 2012; Craik & Bialystok, 2006). On the behavioral level these age-related limitations are reflected in reduced performance and slower reaction times in cognitive control tasks (Cepeda, Kramer, Gonzalez de Sather, 2001; Zelazo, Craik, & Booth, 2004; Kray, Eber, & Lindenberger, 2004). On the neurobiological levels age differences in cognitive control abilities have been associated with developmental and aging-related changes in the function and structure of the prefrontal cortex (Fjell & Walhovd, 2010; Braver & Barch, 2002; Kievit et al., 2014; Nyberg et al., 2010; Bunge et al., 2002). Taken together, the current research suggests an inverted U-shaped pattern of the development of cognitive control across the lifespan: Control abilities increase during childhood development into early adulthood and then diminish in old age (e.g., Li et al., 2009).

While this “deficit-based” interpretation dominates the current literature, there also exist other, complimentary, explanations for age-related differences in cognitive control. One such interpretation relies on children and older adults’ motivation, rather than ability alone. For example, it could be argued that performance differences between age groups in demanding cognitive tasks may reflect differences in cost-benefit analyses rather than limitations in cognitive abilities *per se*. That is, children and older adults might differ from younger adults not only in the cognitive and neurobiological mechanisms underlying cognitive control, but also in how they balance “cognitive labour” and “cognitive leisure” (Kool & Botvinick, 2014). In both the case of children and older adults, this seems plausible. From a young age, children use cognitive effort assessments to guide their decisions and make metacognitive choices about effort investments (Chevalier, 2015; 2018). However, they seem to make such choices differently than young adults and focus more on their interest in the task rather than their estimate of task difficulty (Chevalier, 2018). Older adults also make metacognitive decisions about effort expenditure. While both young and older adults perceive cognitive effort as aversive, older adults are more sensitive to the costs effort entails, which tends to exaggerate their aversion to expending effort (Hess, Smith, & Sharifian, 2016; Westbrook et al., 2013). Importantly, a certain degree of cognitive abilities seems necessary as a prerequisite for such effort-reward balancing. For instance, in order to engage in metacognitive decisions about effort allocation children have to be cognitively able to perform the task to begin with (Niebaum et al., 2019; Blackwell & Munakata, 2013). The same might be said for older adults. Aging is characterized by deficits in various cognitive abilities (Bishop, Lu, & Yankner, 2010), which may affect their ability to perform a cognitive task and therefore shifts their effort-reward trade-offs (cf. Lieder & Griffiths, 2017). To summarise, limitations in cognitive abilities in children and older adults may themselves lead to particular patterns of effort allocation. Thus, it could be argued that children and older adults may differ from younger adults not only in their *capacity* for cognitive control, but also in how they balance the effort of engaging in control against its potential benefits.

In the present study, we investigate this latter explanation. Specifically, we explore how the moment-to-moment allocation of cognitive effort affects cognitive control and changes across the lifespan. To do so, we leverage current theories of cognitive control and focus on two processes that are central to most of these theories: conflict processing and task-switching (Botvinick et al., 2015; Miller & Cohen, 2001).

Conflict processing refers to the ability to monitor task-appropriate behaviour, evaluate current levels of conflict, and exert top-down control to resolve these conflicts (Botvinick et al., 2001; Yeung, 2015). Experimental paradigms that assess conflict processing require participants to inhibit distracting or dominant information in order to successfully perform the task. For instance, in the traditional Eriksen Flanker task (Eriksen & Eriksen, 1974), participants are asked to identify a central letter (e.g., H) while ignoring flanking items (e.g., Ss). Incongruent Flanker trials involve crosstalk between task-relevant (respond to “H”) and task-irrelevant processing pathways (respond to “S”). This conflict is assumed to trigger effortful, strategic, adjustments in cognitive control in order to optimize performance and prevent errors.

Task-switching requires a different, more complex set of control processes. While it also requires the exertion of top-down control, it involves implementing, maintaining, and updating task-relevant information while switching between two or more tasks (Ridderinkhof et al., 2004; Smith & Jonides, 1999; Monsell, 2003). In a typical task-switching experiment (cf. Monsell, 2003), participants are asked to keep two task rules in mind (e.g., to judge whether numbers are even/odd or small/big using a key press). On each trial, they are told which rule they should use to complete this trial. These rules then either switch or repeat from trial-to-trial. The ability to update and maintain task-relevant information in order to be able to switch between tasks is assessed as switch costs that is, the difference in RT and accuracy between switch and repeat trials (Monsell, 2003).

To operationalize cognitive effort, we draw on Otto and Daw’s (2019) recent work, which elucidates cost-benefit decision-making concerning cognitive effort investment by manipulating the opportunity cost of expending cognitive effort. In line with their work, we refer to opportunity costs as the cost of using cognitive resources in service of some goal while forgoing the benefits of using those resources for some other goal (Kurzban et al., 2013). Following Niv’s et al. (2007) work on physical effort, we formalize a parallel cognitive trade-off between two costs: the harder work necessary to emit more correct actions and the opportunity cost inherent in acting more slowly to do so. In tasks that have a limited time horizon, opportunity costs can be thought of as the average reward per unit time. When average reward is high—when rewards are easy to come by—people tend to withdraw effort, which is reflected in higher error rates (Otto & Daw, 2019; Guitart-Masip et al., 2011; Beierholm et al., 2013). Under this framework, accuracy can be thought of as the principal index of effort, whereas reward-induced differences in response times arise as an epiphenomenon of these effort assessments (Otto & Daw, 2019).

With these operationalizations in mind, we hypothesized that differences in cognitive control abilities across the lifespan would be reflected in different sensitivities to the opportunity cost of time. To study this hypothesis we ran two experiments. In Experiment 1, we studied age differences in opportunity costs across the human lifespan using two cognitive control tasks: a Flanker task (Eriksen & Eriksen, 1974) and a task-switching paradigm (Jersild, 1927; Monsell, 2003), with a reward rate manipulation (for a similar procedure see Otto & Daw, 2019). We found that young adults and adolescents withheld effort when the opportunity cost of time was high, whereas older adults and (possibly) children invested *more* resources to accumulate reward. We interpreted these findings in terms of developmental "sweet spots" in cognitive control. That is, we assume that the opportunity cost effects depend on the control demands in a given task as well as the process-specific limitations of a given age group.

However, these same results could be argued to be due to differences in perceived task difficulty, rather than age-related processing constraints per se. That is, children and older adults might have perceived the Flanker and task-switching experiments as more challenging than young adults and therefore invested more effort into the task. To rule out this alternative interpretation we performed a follow-up experiment (Experiment 2), in which we manipulated task difficulty across the two paradigms for a new group of young adults. The results of Experiment 2 suggest that task difficulty did not affect young adults' sensitivity to the opportunity cost of time, suggesting that the lifespan age differences in opportunity costs effects in Experiment 1 were not due to differences in task demands between age groups. In short, we take these findings as evidence of age- and process-specific effects of the opportunity cost of time on cognitive control. We conclude by arguing that these data support a view that motivational differences across the lifespan impact cognitive control and situate these findings amidst traditional deficit-based interpretations of lifespan cognitive control differences.

Experiment 1

Method

Participants

We recruited 164 participants through the TU Dresden Lifespan Developmental Neuroscience participant database, who were paid a fixed amount (8.50 €/hour) plus a bonus dependent on their task performance. The sample size was determined based on previous lifespan studies on cognitive abilities (Stoermer, Eppinger, & Li, 2014; Luca et al., 2003; Karbach & Kray, 2009). The age range was constrained by minimal requirements for a separate decision-making task that participants completed as part of a task battery (results of which will be reported elsewhere). Participants (or, in the case of children and adolescents, their parents) underwent a telephone screening prior to participating. We excluded all participants who did not complete both the Flanker and task-switching paradigms (7 participants). To minimize the amount of missing data from timeouts, we also excluded participants who failed to meet the response deadline on a number of trials greater than 3SD from the mean of their respective age group (3 children, 2 adolescents, 1 young adults, 2 older adults). Additionally, 3 older adults were excluded for scoring less than 23 on the Montreal Cognitive Assessment (MOCA; Carson, Leach, & Murphy, 2018). 2 participants (1 older adult, 1 adolescent) reported previous brain surgery when asked for their clinical history and were therefore excluded. The final sample consisted of 144 participants: 49 children (M_{age} = 10.09, SD = 1.33, 21 males), 33 adolescents (M_{age} = 15.29, SD = 1.15, 14 males), 34 young adults (M_{age} = 23.72, SD = 4.48, 16 males), and 28 older adults (M_{age} = 70.66, SD = 5.03, 14 males). Participants/their legal guardians provided written informed consent prior to participation. This study was approved by the TU Dresden ethics committee.

Materials

Flanker task. The Flanker task is a widely used measure of cognitive control (Fan et al., 2002; Eriksen & Eriksen, 1974). It requires participants to classify a target item, while ignoring distracting items that surround it. Distracting items can either suggest the same response as the target item (congruent trials) or a different response (incongruent trials). On incongruent trials, participants must filter-out the distracting information from the flanking items, requiring the use of cognitive control (Enger, 2007).

In our version of the task (see Otto & Daw, 2019 for a similar methodology employing the Simon task [Simon, 1990]), participants had to indicate whether a bee in the center of the display was flying towards the left or to the right (see Figure 1A). All stimuli were presented against a gray background using the software E-Prime (PST Inc., Pittsburgh, PA). Each trial began with a fixation cross presented for 200ms. Then, a reward cue appeared that indicated how many points were at stake on that trial.

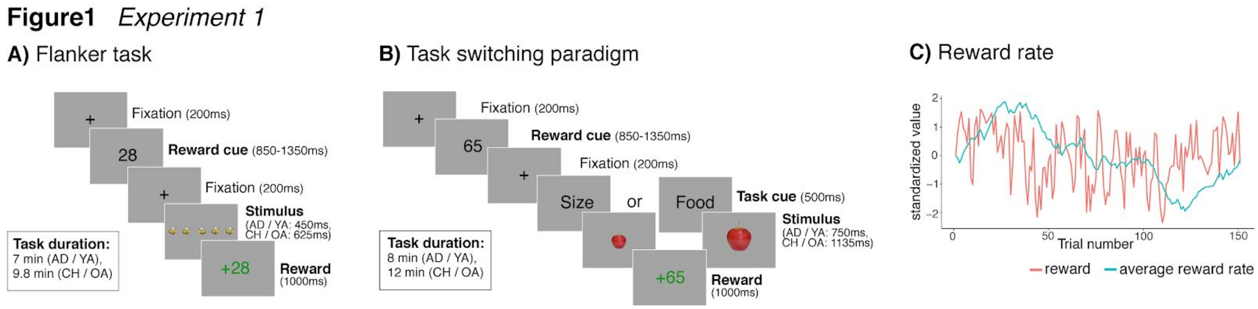

Figure 1. (*A*) In the Flanker task, participants have to indicate whether the bee in the center of the display is flying to the left or the right. On compatible trials the surrounding bees fly into the same direction. On incompatible trials they fly into the opposite direction. To account for slower 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 reward magnitude and reward rate across the experiment for one participant in the Flanker task.

The cue remained on the screen for a random amount of time chosen between the following options: 850 ms, 950 ms, 1050 ms, 1150 ms, 1250 ms, or 1350 ms. The reward on offer was worth between 6 and 96 points on each trial and participants were told beforehand that 100 points were worth 0.03 €. Available rewards were determined randomly using an independent Gaussian random walk with standard deviation 30 and with reflecting boundaries set at 6 and 96 points. After seeing the reward cue, the stimulus appeared. The stimulus display time (and therefore the response deadline) for younger adults was set to 450 ms in order to create some time pressure (Huebner & Schloesser, 2010). To account for generally slower RTs in children and older adults, the stimulus display times were adjusted by a general slowing factor of 1.7. This slowing factor was based on a meta-analysis by Verhaeghen and Cerella (2002). In line with their suggestions, we assumed a peripheral component to the reaction time of 200ms and determined a stimulus presentation time of 200ms + 250ms * 1.7 = 625ms. For the purpose of this study we assumed that children and older adults show a similar degree of the reaction time slowing (see Li et al., 2004). This is clearly an oversimplification and it might be the case that there are process- and task-specific differences in RT slowing in the different age groups. We opted for an adjustment of the stimulus presentation times in children and older adults because a deadline of 450ms (as it was applied in younger adults) would have led to a disproportionate number of time-outs in these two groups, which would have made the results very difficult to compare.

Participants used two response keys to decide which direction the center bee was flying towards. If participants correctly identified which direction the center bee was flying, a green feedback message would appear showing them how many points they earned that trial. If they misidentified the direction, they would receive a red feedback message indicating that they had received no points this trial. This feedback message stayed on the screen for 1000 ms.

To manipulate opportunity costs, participants were told that they would have 7 minutes (for adolescents and young adults) or 9.8 minutes (for children and older adults) to complete as many trials as possible. Each participant had 10 trials to practice the task before beginning the main task. During this practice phase, participants were not under time pressure to respond. These practice trials were not included in the analyses.

Task-switching paradigm. Task-switching paradigms examine the flexibility with which a participant adapts their internal goal settings according to environmental changes. These paradigms require participants to adjust their internal task-rules, or task-sets, to changing task cues on a trial-to-trial basis and respond appropriately, a process which requires the use of cognitive control (Monsell, 2003).

In this version of the paradigm, participants were instructed to perform two tasks: the 'Food task' and the 'Size task' (see Figure 1B). In the Food task, participants had to judge whether the stimulus on-screen was a fruit or a vegetable. In the Size task, they had to judge whether the stimulus on-screen was large or small. The stimulus set of this experimental task consisted of four foods: an apple, a pear, an eggplant, and a cucumber (taken from Moreno-Martinez & Montoro, 2012). Each food could be presented in one of two formats, in each trial: big (300 x 225 bitmap image file) or small (225 x 169 bitmap image file). All stimuli were presented against a white background on a standard PC using the software EPrime (PST Inc., Pittsburgh, PA).

In each trial, participants were presented with a fixation cross at the center of the screen for 200 ms. Then, a reward cue was presented that indicated how many points were at stake that trial. The cue remained on the screen for a randomly determined amount of time (850 ms, 950 ms, 1050 ms, 1150 ms, 1250 ms, or 1350 ms) and was then followed by another 200 ms fixation cross. The task cue (Food or Size) was then presented on the screen for 500 ms. The stimulus was presented on the screen for 750 ms for young adults and adolescents and 1135 ms for children and older adults. Similar to the Flanker task we adjusted the stimulus presentation time to account for developmental and ageing-related differences in overall reaction times using a slowing factor of 1.7 (Verhaeghen & Cerella, 2002). To do so, we assumed a peripheral component to the reaction time of 200ms and determined a stimulus presentation time of 200ms + 550ms * 1.7 = 1135ms. As for the Flanker task, the motivation for adjusting the stimulus presentation times was to avoid disproportionate time pressure in children and older adults.

Participants used two response keys to decide if the stimulus was small/a fruit or big/a vegetable. If participants made the correct choice, a green feedback message appeared showing them how many points they earned that trial. If they misidentified the direction, they would receive a red feedback message indicating that they had received no points this trial. This feedback message stayed on the screen for 1000 ms.

To manipulate opportunity costs, participants were told that they would have 8 minutes (for adolescents and young adults) or 12 minutes (for children and older adults) to complete as many trials as possible. Each participant had 12 trials to practice the task before beginning the testing phase. During the practice phase, there was no time pressure to respond. These practice trials were not included in the data analyses. At the end of the task, participants received 0.03 € for each 100 points they earned.

Procedure

On the testing day, participants underwent a task battery, in fixed-order, consisting of a basic demographic assessment, cognitive/intelligence testing, a measurement of spontaneous eye- blink rate, decision-making tasks, and the Flanker and task-switching paradigms. Participants in the older adult group additionally underwent the Montreal Cognitive Assessment (Carson, Leach & Murphy, 2018). Here, we report data on the Flanker and task-switching paradigms; the data of the decision-making tasks will be reported elsewhere.

Data Analysis

For all of the following analyses, all trials with a RT of less than 200ms were excluded from analysis (based on recommendations from Whelan, 2008 regarding genuine RT minima).

This decision impacted less than 1% of trials in the Flanker task and ~1% of trials in the task-switching paradigm. These proportions did not significantly differ across age groups in either task (Flanker: $F(3, 140) = 1.433$, $p = .2358$; Task-switching: $F(3, 140) = 1.56$, $p = .2024$). All analyses were conducted using R (Version 3.5.3; R Core Team, 2019).

Descriptive analyses. As is common in these types of cognitive control paradigms (Fan et al., 2003; Eppinger et al., 2007), we computed compatibility costs and switch costs for RT and accuracy in both the Flanker task and task-switching paradigm by subtracting RT/accuracy in incongruent/switch trials from RT/accuracy in congruent/repeat trials. To account for differences in response deadlines, we measured performance in points per second for each participant. To explore how participants' overall performance differed across age groups, beyond differences seen in the RT and accuracy analyses, we conducted a one-way ANOVA with points per second as the dependent variable and age group as the independent variable. Statistically significant main effects were then explored using Tukey's honestly significant difference (HSD) post-hoc test. Additionally, we computed descriptive tables of RT and accuracy for each subject, which contained supplemental information regarding each participant's performance, compatibility costs, switch costs, and the effects of high/low reward rate (computed using a tertile split and dropping the middle quantile) on RT and accuracy.

Average reward rate analyses. Following past work, we calculated the average reward, $\overline{r}$, using the following update rule (Otto & Daw, 2019; Constantino & Daw, 2015):

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

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. $\overline{r}$ was initialized as the average reward obtained across an entire session for each subject. From thereon, T relies on both the subject's last RT and the previous ITI such that, everything else being equal, as the amount of time since the last update (T) increases, $\overline{r}$ decreases. Conversely, as the reward obtained, R, increases, $\overline{r}$ increases. However, it is worth noting that average reward values are specific to each participant, thus between-participant differences in RT should not impact participants' sensitivity to them (e.g., such as differences found between age groups). This update rule allows for individual differences in the sensitivity to changes in $\overline{r}$ beyond those seen to R alone (see Figures 1C and 1D).

Following previous work (Otto & Daw, 2019; Beierholm et al., 2013; Guitart-Masip et al., 2011), the learning rate parameter, α, was estimated by fitting a single-learning rate to the RTs of all participants within each age group. The learning rate can be thought of as controlling the degree to which the average reward estimate is updated based on the current outcome (Beierholm et al., 2013). This update rate could range between 0 (equivalent to no learning) and 1 (equivalent to only using the reward obtained in the previous trial). To estimate α, we employed a grid search over the parameter space, estimating subject-specific regressions within each age group in order to determine the value of the a parameter that best minimized total error across the group (average squared residuals):

$$RT = \overline{r} + R + trial\ type + prev\ type + prev\ error + prev\ missed + same\ resp + ITI$$

where $\overline{r}$ is the average reward rate, R is the reward magnitude on each trial, *trial type* is the type of trial the participant is to complete (congruent or incongruent for the Flanker task; repeat or switch for the task-switching), *prev type* is the trial type on the previous trial, *prev error* is a binary variable representing if the participant made an error on the previous trial, *prev missed* is a binary variable representing if the participant timed out (did not respond within the response deadline) in the previous trial, *same resp* is a binary variable representing if the participant repeated their response from the previous trial, and *ITI* represents the time interval between two updates (850 ms-1350 ms in steps of 100 ms).

Using this technique, we found a best-fitting α estimate of .0027 for young adults, which closely approximates the best-fitting a observed by Otto & Daw (2019; α = .0031). For children, adolescents, and older adults, we found best fitting learning rates of .0200, .0010, and .0479 respectively. These values suggest that children and older adults used previous rewards to update current average reward more than adolescents and young adults. This lines up with past work demonstrating that children and older adults adapt their performance in cognitive control tasks to different reward magnitudes (Bolenz et al., 2019; Decker et al., 2015; Nussenbaum & Hartley, 2019).

With these learning rate estimates, we computed average reward rates for each subject. Mean reward rate values per age group were as follows. In the Flanker task, children had a mean average reward rate of 14.10 points per unit time (SE = .039), adolescents one of 15.54 (SE= 0.031), young adults one of 16.93 (SE = .030), and older adults one of 16.78 (SE = .056). In the task-switching paradigm, children had a mean reward rate of 9.93 (SE = .029), adolescents one of 11.27 (SE = .021), young adults one of 12.43 (SE = .018), and older adults one of 10.69 (SE = .056). Unsurprisingly, these values follow the same pattern as group performance levels, since $\overline{r}$ is initialised at the average reward earned for one subject across a whole session. That being said, it is important to note that average reward as computed above and reward magnitude are not equivalent, the two only modestly correlating with each other (r_{Flanker} = .15, r_{TS} = .18; see Figure 1C and 1D). This correlation varies across age groups in accordance with each group's estimated learning rate, with children and older adults having the strongest relationship between reward magnitude and average reward ($r_{\text{Flanker-CH}} = .15$, $r_{\text{Flanker-OA}} = .29$, $r_{\text{TS-CH}} = .25$, $r_{\text{TS-OA}} = .27$) and adolescents and young adults having the weakest ($r_{\text{Flanker-AD}} = .03$, $r_{\text{Flanker-YA}} = .04$, $r_{\text{TS-AD}} = .003$, $r_{\text{TS-YA}} = .02$).

To assess the effect of average reward rate on RT, we estimated mixed-effects regressions using the mixed function from the afex package in R (Version 0.23-0; Singmann et al., 2015). The afex package is built on top of the lme4 package (Bates, Maechler, Bolker, & Walker, 2015), but has the added benefit of providing summary tables for main effects of multi-level (>2) predictors (such as age group in our case) and calculates p-values by using Satterthwaite estimation.

In both tasks, RT was modelled by age group (children, adolescents, young adults, or older adults), trial type (congruent/repeat or incongruent/switch), reward rate, reward magnitude, and all two-way, three-way, and four-way interactions as fixed effects, as well as random intercepts across participants (random effects). The terms of interest were the main effect of age group, trial type, and reward rate, as well as the interactions between the three factors. All continuous variables were scaled and centered, except for RT, which was log-transformed across age groups as is common practice in research across the lifespan (e.g. Kray & Lindenberger, 2000). The effects of age group, trial type, reward rate, and reward were also examined using a logistic mixed-effects regression and the same predictors as for the RT analyses, but with response accuracy (correct/error) as the outcome variable.

Results

Flanker Task

Performance. A one-way analysis of variance (ANOVA) showed a significant effect of age on performance ($F(3, 140) = 12.51$, $p < .0001$), such that older adults ($M_{\text{points/second}} = 1.58$), young adults ($M_{\text{points/second}} = 1.57$), and adolescents ($M_{\text{points/second}} = 1.46$) significantly outperformed children ($M_{\text{points/second}} = 1.33$; $p_{\text{older adults-children}} < .0001$; $p_{\text{young adults-children}} < .0001$; $p_{\text{adolescents-children}} = .043$) on a per-second basis, but differed only numerically from each other ($p_{\text{older adults-young adults}} = .99$; $p_{\text{older adults-adolescents}} = .100$; $p_{\text{young adults-adolescents}} = .998$) (see Figure 2A). These findings suggest that older adults performed at the same level as young adults and adolescents in the Flanker task. All three groups outperformed children.

Compatibility effects. Mirroring past results (Erikson & Erikson, 1974; Ridderinkhof et al., 1999), we found a significant main effect of trial type on RT ($\beta = -0.0132$, SE = 0.0011, $p < .0001$) and accuracy ($\beta = 0.4307$, SE = 0.025, $p < .0001$), such that participants responded more slowly and less accurately on incongruent trials compared to congruent trials. Additionally, we found a significant interaction effect between trial type (congruent or incongruent) and age group on both RT ($F(3, 144.01) = 6.69$, $p = .0003$) and accuracy ($\chi^2(39) = 44.09$, $p < .0001$). That is, all age groups responded more slowly ($\beta_{\text{children}} = -0.0074$, standard error (SE) = 0.0020, $p = .0004$; $\beta_{\text{adolescents}} = -0.0095$, SE = 0.0027, $p = 0.0012$; $\beta_{\text{young adults}} = -0.0188$, SE = 0.0023, $p < .0001$; $\beta_{\text{older adults}} = -0.0173$, SE = 0.00216, $p < .0001$) and less accurately ($\beta_{\text{children}} = 0.2245$, SE = 0.0278, $p < .0001$; $\beta_{\text{adolescents}} = 0.5441$, SE = 0.0523, $p < .0001$; $\beta_{\text{young adults}} = 0.7126$, SE = 0.06813, $p < .0001$; $\beta_{\text{older adults}}$ 0.2968, SE = 0.0653, $p = .0002$) on incongruent trials compared to congruent trials, but the magnitude of the compatibility effects differed across age

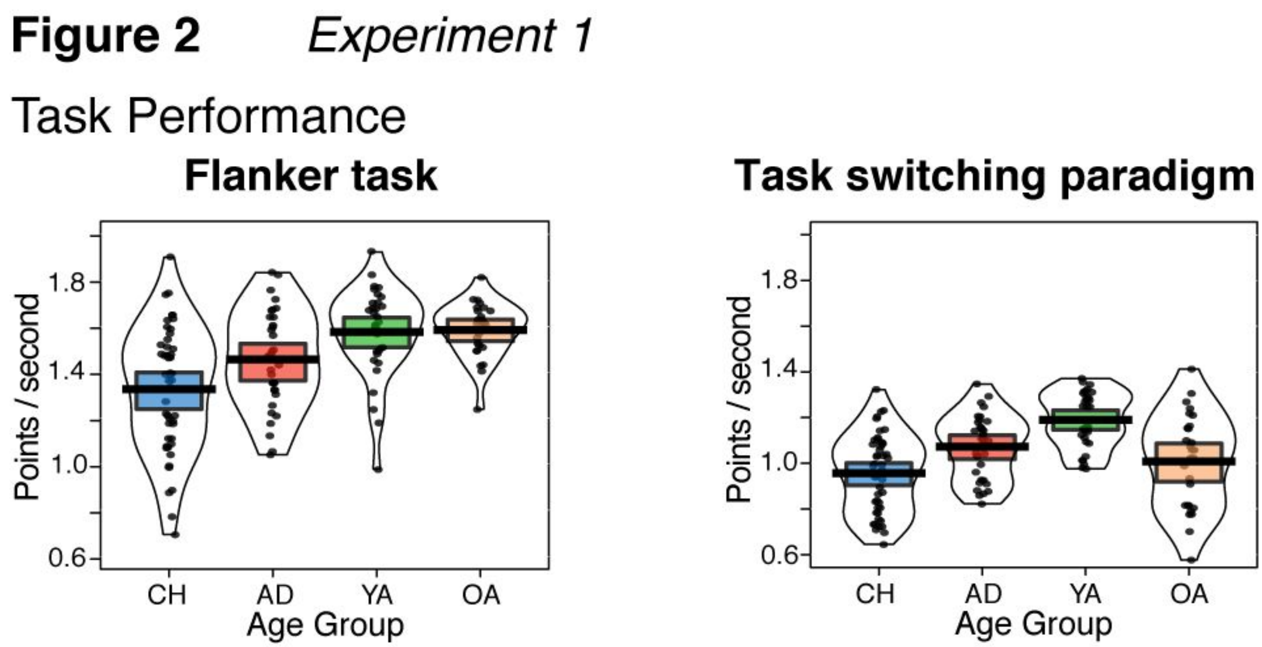

Figure 2. Pirate Plots (Phillips, 2017) of performance across age groups in the Flanker task and task-switching paradigm. Coloured (shaded) boxes represent confidence intervals of the mean, black lines represent mean points per second of each age group, and black points represent individual participants' average points per second.

groups with young adults showing the greatest compatibility costs in RT and adolescents showing the greatest costs on accuracy.

Reward-on-offer effects. We found a significant main effect of reward magnitude on RT (β = -0.0044, SE = 0.0010, p < 0001), such that higher reward on offer engendered quicker RT. However, we found no significant interaction of reward on offer with age group (F(3, 147.26) = 0.72, p = .5442). In line with Otto & Daw's (2019) findings, we found no significant main effect of reward on offer with accuracy (β = 0.0095, SE = 0.0224, p = 0.6698) nor significant interaction with age group (χ^2 (3) = 3.55, p = .3100).

Opportunity cost effects. We found no significant main effect of average reward rate on RT (β = -0.0022, SE = 0.0014, p = .1106) or accuracy (β = 0.0269, SE = 0.0262, p = .3301). However, we found a significant interaction effect between age group and average reward rate

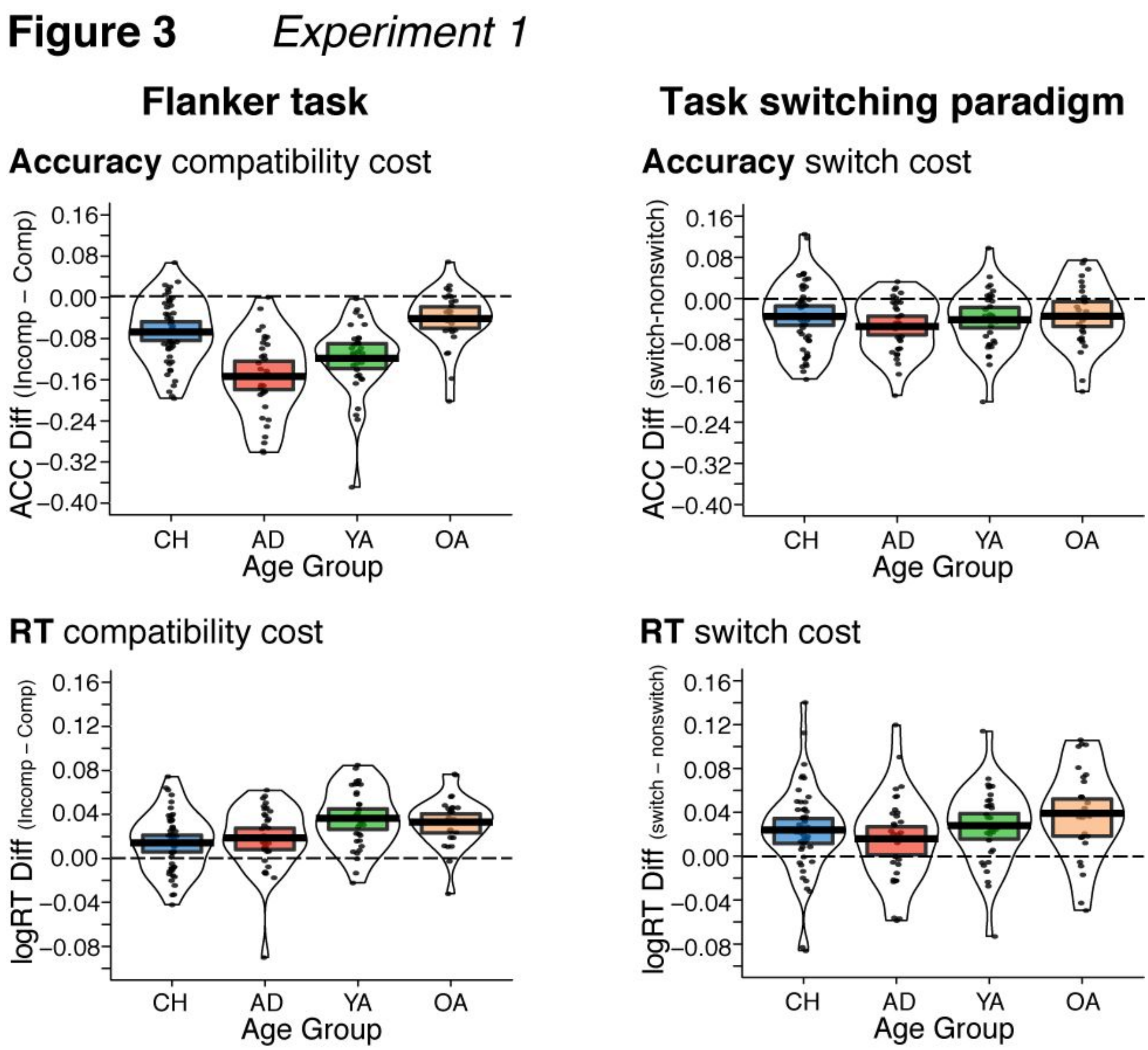

Figure 3. Pirate Plots of difference scores for log-RT and accuracy in (A) the Flanker task and (B) the task-switching paradigms. Differences scores are computed by subtracting log-RT/accuracy in incongruent/switch trails by log-RT/accuracy in congruent/repeat trials. Coloured (shaded) boxes represent confidence intervals of the mean, black lines represent mean costs for each age group, and black points represent individual participants' costs.

on both RT (F(3, 131.80) = 2.88, p = .0386) and accuracy (χ^2(3) = 12.99, p = .0047) (See Figure 4). Follow-up analyses conducted within each age group revealed that average reward rate differentially affected participants' behavior depending on their age. Specifically, changes in reward rate significantly predicted RT in older adults (β = -0.0079, SE = 0.0019, p = 0.0003), such that when average reward was high, older adults responded more quickly. This effect was not found in any other age group.

Average reward rate was also found to significantly predict accuracy scores in older adults ($\beta = 0.1605$, SE = 0.0734, $p = .0287$), such that when average reward rate was high, accuracy increased. In younger adults we found a trend in the opposite direction, such that when average reward was high, young adults became less accurate, but this effect was not statistically significant ($\beta = -0.0903$, SE = 0.0492, p = .0665). We found no statistically significant effect of average reward rate on accuracy in children ($\beta = 0.0652$, SE = 0.0413, $p = .1142$) or adolescents ($\beta = -0.0231$, SE = 0.0387, $p = .5501$).

The current results suggest that in the Flanker task, older adults were more sensitive to changes in average reward rate both in terms of RT and accuracy than any other age group. When the reward rate was high, older adults responded more quickly and more accurately than when it was low.

Task-Switching Paradigm

Performance. A one-way ANOVA revealed a significant effect of age on performance ($F(3, 140) = 14.92$, $p < .0001$), such that young adults ($M_{\text{points/second}} = 1.19$) outperformed children ($M_{\text{points/second}} = 0.96$; $p_{\text{young adults-children}} < .0001$), adolescents ($M_{\text{points/second}} = 1.07$; $p_{\text{young adults-adolescents}} = .018$), and older adults ($M_{\text{points/second}} = 1.01$; $p_{\text{young adults-older adults}} = .0001$). Furthermore, adolescents outperformed children ($p = .009$), but did not differ significantly from older adults ($p = .410$). Children and older adults did not differ in terms of performance ($p =$

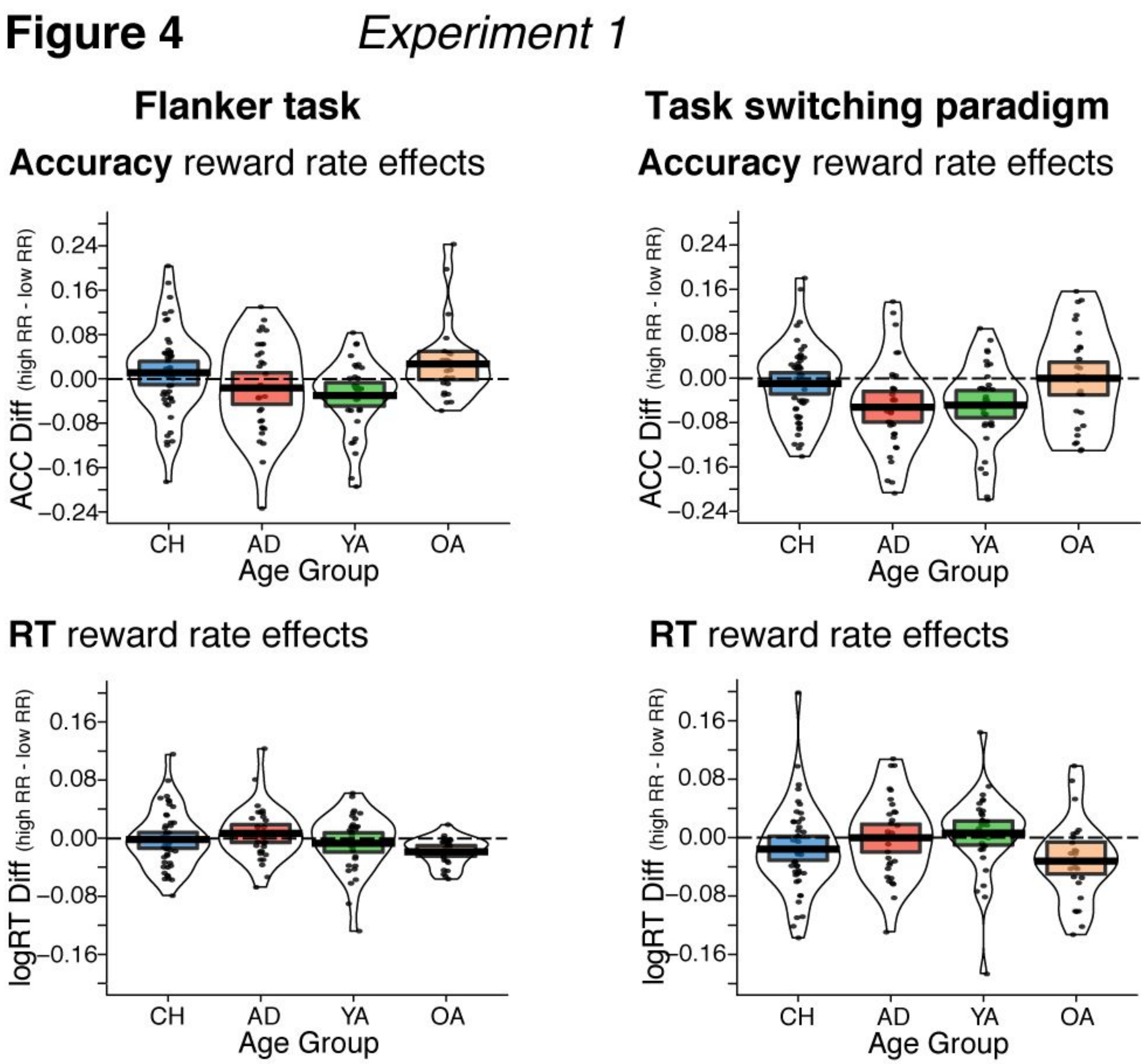

Figure 4. Pirate Plots of difference scores across the two tasks on (A) log-RT and (B) accuracy. Scores were computed by dividing reward rate into tertiles and dropping the middle quantile. Difference scores are represented here as "High - Low", where High represents log RT/accuracy when reward rate is high and Low represents RT/accuracy when reward rate is low. For instance, a negative difference score in log-RT represents a speeding up during high reward rate trials. Coloured (shaded) boxes represent confidence intervals of the mean, black lines represent mean differences for each age group, and black points represent individual participants' reward rate effects.

.520) As shown in Figure 3, performance in the task-switching paradigm followed a U-shape function in performance, where children and older adults performed worse than adolescents and young adults.

Task-switching effects. We observed a significant main effect of trial type on both RT ($\beta = -0.0136$, SE = 0.0017, $p < .0001$) and accuracy ($\beta = 0.1453$, SE = 0.0187, $p < .0001$), such that participants responded more slowly and less accurately on switch trials compared to repeat trials. However, we did not find a significant interaction between age group and trial type on RT ($F(3, 154.09) = 1.79$, $p = .1521$) or accuracy ($\chi^2(3) = 5.04$, $p = .1691$) (see Figure 3).

Reward-on-offer effects. We did not observe a significant main effect of reward on offer on RT ($\beta = 0.0010$, SE = 0.0015, $p = 0.4943$) or accuracy ($\beta = 0.0111$, SE = 0.0197, $p = 0.5737$). Similarly, we observed no significant interaction of reward on offer with age group on RT ($F(3, 777.11) = 0.51$, $p = .6762$) or accuracy ($\chi^2(3) = 0.16$, $p = .9203$).

Opportunity cost effects. The analysis revealed a significant main effect of average reward rate on RT ($\beta = -0.0049$, SE = 0.0022, $p = .03433$) and accuracy ($\beta = 0.0110$, SE = 0.0197, $p = .0007$), such that participants responded more quickly, but less accurately when average reward rate was high compared to when it was low.

Additionally, we found a significant interaction effect between age group and reward rate on both RT ($F(3, 148.76) = 3.94$, $p = .0097$) and accuracy ($\chi^2(3) = 16.25$, $p = .0010$). Follow-up analyses revealed that reward rate differentially affected RT and accuracy in each age group. We found a significant effect of reward rate on RT for older adults ($\beta = -0.0160$, SE = 0.00496, $p = .0032$), such that older adults responded more quickly when reward rate was high compared to when it was low. We also found a trend of reward rate on RT for children in the same direction as older adults, but that failed to reach statistical significance ($\beta = -0.0074$, SE = 0.0038, $p = .05997$). We found no significant effect of reward rate on RT for adolescents ($\beta = 0.0012$, SE =

0.0044, p = .7894) or young adults (β = 0.0038, SE = 0.0042, p = .3757). In terms of accuracy, we did not find a significant effect of reward rate on accuracy in the children (β = 0.0004, SE = 0.0326, p = .9897) or older adults groups (β = 0.0271, SE = 0.072, p = .7049). However, we did observe this effect in adolescents (β = -0.1412, SE = 0.0373, p = .0002) and young adults (β = -0.1957, SE = 0.046, p < .0001), such that—for both of these groups—when average reward was high, accuracy scores decreased (see Figure 5).

In summary, in the task-switching experiment, we found that changes in average reward rate predicted RT in older adults but not in adolescents or young adults. That is, older adults responded faster when the average reward was high compared to when it was low. We also observed a similar trend for this effect in children in the same direction, but it did not reach statistical significance. Conversely, changes in reward rate did not predict response accuracy in children or older adults, but did in adolescents and young adults. That is, adolescents and young adults responded less accurately on high reward rate trials compared to low reward rate trials, which was not the case in the other two age groups.

Discussion

The main goal of this experiment was to explore how lifespan age differences in cognitive control abilities affect the moment-to-moment allocation of cognitive effort. To do so, we used two modified cognitive control tasks, an Erikson Flanker and a task-switching paradigm, in which we manipulated the available reward for correctly responding on each trial. We hypothesized that the degree of effort exertion should depend on the opportunity cost of time—operationalized as the average reward per unit time—whereby participants would respond more quickly and/or less accurately when the reward rate was high, representing a withholding of effort when rewards were easy to come by (Otto & Daw, 2019). We expected that age-related limitations in cognitive control abilities would moderate the degree to which participants engaged in these strategies. Interestingly, we found that the opportunity cost of time affected behaviour differently for children and older adults than it did for adolescents and young adults.

In what follows, we will first discuss the basic cognitive control effects in the Flanker and task-switching paradigms. Then, we will detail how the opportunity cost of time differentially affected behaviour in these cognitive tasks across the lifespan. We will conclude with our interpretation of these data and consider an alternative explanation that acts as the rationale for Experiment 2.

Cognitive Control Costs

As shown in Figure 3, we observed cognitive control costs in both the Flanker task and task-switching paradigm. Consistent with past work, we found that under higher demands on cognitive control (incongruent trials in the Flanker task and switch trials in task-switching paradigm) participants responded more slowly and less accurately overall (Fan et al., 2003; Eppinger et al., 2007). Furthermore, in the Flanker task, we found that trial type interacted with age on both RT and accuracy. That is, while all age groups showed the same direction of effects —slower and less accurate responses on incongruent trials—young adults and adolescents were the most affected by compatibility costs in terms of both RT and accuracy respectively. This finding differs from past work that suggests that lifespan differences in conflict processing follow a quadratic function: with compatibility costs being highest in young childhood and late adulthood (Li et al., 2009). One interpretation of this result could be that the average reward rate manipulation pushed older adults to respond more quickly and accurately overall, thus obscuring more extreme compatibility costs. A more extensive discussion of this shift in response strategies is provided below. No significant interaction between age group and trial type was found in the task-switching paradigm.

Opportunity Cost Effects

In the Flanker task, we only found effects of the opportunity cost of time on cognitive control in older adults. That being said, we observed a rather different effect of opportunity cost on behaviour for older adults than we expected. Specifically, we found that older adults responded both *more* quickly and *more* accurately when the opportunity cost of time was high in the Flanker task. These results suggest that older adults processed the opportunity cost of time in the Flanker task differently than as described by Otto & Daw (2019): Rather than to withhold resources when rewards were easy to come by (i.e., while “the getting was good”; the average reward per unit time was high), they invested more resources to accumulate reward as quickly as possible, which was reflected in higher accuracy. Thus, in the Flanker task, older adults seem to have taken a more rational cost-benefit approach to effort exertion, investing the most effort when doing so yielded maximal rewards (cf. Lieder & Griffiths, 2017). This strategy is in contrast to the reflexive, Pavlovian, withdrawal that Otto & Daw (2019) observed in younger adults (Otto & Daw, 2019). However, unlike Otto & Daw (2019) observed in the (different) tasks they used, opportunity cost effects were not observed in younger adults, nor were they seen in children or adolescents, in the Flanker task.

In the task-switching paradigm however, we found that the opportunity cost of time affected behaviour differently for adolescents and young adults compared to the Flanker task and in the expected direction given the findings by Otto and Daw (2019). Again, older adults responded more quickly when the opportunity cost of time was high and were therefore able to maximise the number of points they could earn per unit time. In contrast to the Flanker task, however, they were not able to improve accuracy and operated on the same performance level on high and low reward rate trials. Young adults and adolescents, on the other hand, responded less accurately, but not more quickly, when the opportunity cost of time was high. These findings are in line with the results obtained by Otto and Daw (2019) and their interpretation that the opportunity cost of time modulates effort investment beyond what would be expected of a simple speed-accuracy trade-off. That is, higher opportunity costs invoked a reflexive withdrawal of cognitive effort in adolescents and young adults, reflected in reduced accuracy, but did not lead to faster responses. This could be thought of as a "purer" effort withdrawal than originally observed in Otto & Daw (2019), because the performance differences cannot be explained in terms of a speed-accuracy trade-off.

What about children? In the task-switching paradigm, we found a trend suggesting that children utilised the opportunity cost of time similarly to older adults (faster RT when average reward was high). However, this trend was not statistically significant ($p \approx .06$). After observing this result, we hypothesized that the between group analysis might not be sensitive enough to show developmental changes in opportunity cost effects. Hence, we looked into the relationship between chronological age and opportunity costs on reaction time and accuracy (see Supplemental for these analyses and a more detailed discussion)[1]. Here, we found a trend suggesting that younger children (less than 10 years old) invest more effort when the opportunity

[1] In line with best practices regarding confirmatory hypothesis testing (Hollenback & Wright, 2017), we note that these analyses were exploratory and not based on original hypotheses. Instead, they were motivated by the non-significant trend we observed in the children as a group.

cost of time is high (similarly to older adults) whereas older children and young adults withhold effort when reward rate is high. Clearly more fine-grained research is needed in this area in order to understand the developmental trajectories of effort-reward trade-offs in this age range (see also the limitation section in the General Discussion).

To summarize, the findings of Experiment 1 suggest that children and older adults processed the opportunity cost of time differently than younger adults and adolescents. Whereas young adults and adolescents reflexively withheld effort when the opportunity cost of time was high, older adults and in some cases children invested *more* resources to accumulate reward as quickly as possible.

These age- and process-specific differences in the sensitivity to the opportunity cost of time are particularly interesting when we look at participant performance on the cognitive control tasks we administered. In the Flanker task, older adults unexpectedly performed at the same level as younger adults. In this way, our results differ from what is typically found in studies on ageing-related impairments in cognitive control, which suggest that children and older adults perform worse on these tasks than younger adults (Li et al., 2009). We did observe such an inverted U-shape pattern in performance, however, only in the task-switching paradigm (Craik & Bialystock, 2006). This suggests that the strategic allocation of cognitive resources exhibited by older adults based on the opportunity cost of time may play a beneficial role in some (perhaps more basic) processes underlying cognitive control, like attentional control, but not necessarily in other (maybe more complex) processes, like task-switching (see Otto & Daw's (2019) discussion of speed-accuracy trade-off functions in task-switching).

Limitations and Considerations

An important question that follows from these results is why adolescents and young adults were only sensitive to the opportunity cost of time in the task-switching paradigm but not the Flanker task, whereas older adults were sensitive to these effects in both tasks. Above, we offer the explanation that the opportunity cost of time affects behaviour not only in an age-specific manner (in terms of *how* it affects reaction time and accuracy), but also seems to be process-specific. This interpretation lines up with past work that has shown that older adults differ from young adults both in terms of their overall cognitive control abilities, but also about how they use these limited resources to monitor conflict and flexibly adapt to changes in task contexts (e.g., Eppinger et al., 2007; Kray et al., 2005).

However, there is also an alternative explanation: one might suggest that the age differences we observe are not the result of age-specific sensitivities to the opportunity cost of time in attentional control and/or task-switching, but are due to differences in perceived task difficulty. That is, older adults might have perceived the Flanker and task-switching experiments as more challenging and therefore invested more effort into the task. If this was the case, then different responses to the opportunity cost of time might arise not necessarily as a function of age and demands on specific cognitive control processes, as we contend, but as a result of relative task difficulty. To examine this hypothesis we performed a follow-up experiment (Experiment 2) in younger adults only, in which we aimed to increase task difficulty. We predicted that if younger adults' cognitive control abilities were pushed closer to their limits—as we presumed they were for older adults in both tasks in Experiment 1—then they would exhibit similar opportunity cost effects as older adults.

Experiment 2

Method

We recruited 39 young adults through Concordia University's participant pool and were given participant pool credits plus a bonus depending on their task performance. This sample size was chosen to be able to compare the results to those of young adults in Experiment 1. All participants were English-speaking, free of neurological disorders, and free of any cognitive, motor, visual, or other condition(s) that would impede their performance, including but not limited to a history of head trauma with loss of consciousness, organic brain disorders, seizures, or neurosurgical intervention, to sensory deficits (i.e. deafness, blindness, colour blindness, intellectual disability), or self-reported cognitive impairment. One participant was excluded from the analyses due to failing to meet the response deadline on a number of trials greater than 3SD from the mean in at least one task. The final sample was 38 young adults (M_{age} = 20.63, SD_{age} = 1.82, 33 females). The study protocol was approved by the Concordia Human Research Ethics Committee.

Materials

Flanker task. To manipulate task difficulty in the Flanker Task in Experiment 1, participants were pre-cued with flankers (without the target stimulus) before the presentation of each trial (Hübner & Töbel, 2019). These pre-cue flankers were either compatible (identical direction) or incompatible (opposite direction) to those being presented alongside the target

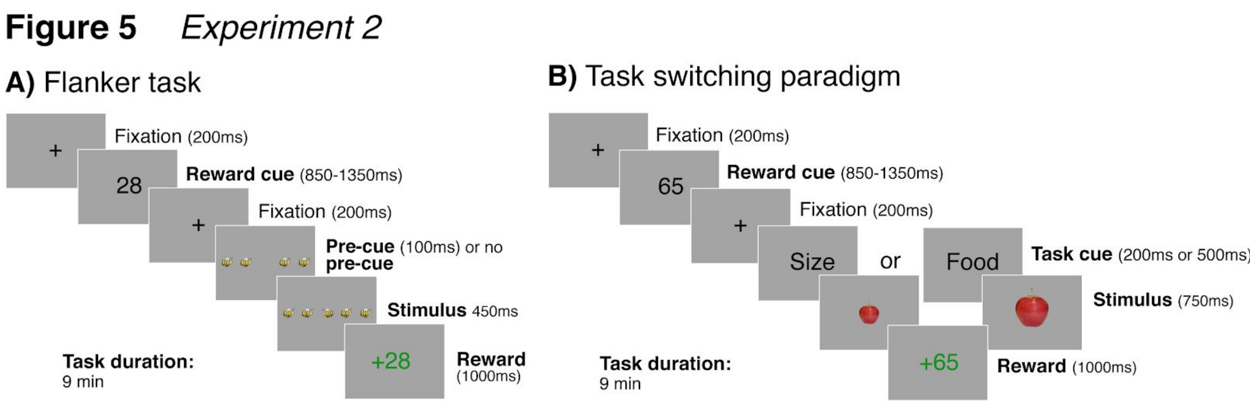

Figure 5. (*A*) In the Flanker task, participants have to indicate whether the bee in the center of the display is flying to the left or the right. On compatible trials the surrounding bees fly into the same direction. On incompatible trials they fly into the opposite direction. In one block we added a pre-cue of the flankers prior to the stimulus presentation. These flankers were either congruent or incongruent to those presented in the stimulus trial. (*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). We manipulated the task cue time (or preparation time) in which participants had 1 block with a 200ms preparation time and 1 block with a 500ms preparation time.

stimulus. By presenting noise (i.e. the flankers) ahead of the target for a sufficient amount of time, we produced greater conflict with the target (Flowers, 1980; Wendt et al., 2014).

We tested four different pre-cue durations (100 ms, 200 ms, 300 ms, 400 ms) to determine which would have the greatest effect on performance. Based on these preliminary analyses, the 100 ms pre-cue duration showed the largest decrease in performance as well as the greatest compatibility costs (similar to the results of Hübner & Többel, 2019). Participants each completed two blocks of this task: one with a 100 ms pre-cue and the second with no pre-cue (a control block identical to the Flanker task in Experiment 1). All other materials of the Flanker task were identical to those presented to young adults in the first experiment (see Figure 5).

Task-switching paradigm. To manipulate task difficulty in the task-switching paradigm, we decreased the preparation time (time between the task cue onset and trial stimulus onset; 500 ms in Experiment 1). The logic of doing so is based on past work that demonstrates reduced switch-costs when information is given about the upcoming task—in effect, giving participants time to prepare for the following choice (i.e. preparation effect; Monsell, 2003). Similarly, when preparation time is increased, switch costs are more pronounced (Altmann, 2004; Schneider, 2016).

We tested four different preparation times (200 ms, 300 ms, 400 ms and 500 ms) to determine the one that would have the largest effect on switch costs. Based on these preliminary analyses, a 200 ms preparation time showed the greatest switch costs. Each participant completed two blocks of this task: one with a 200 ms preparation time and the other with a 500 ms preparation time (control block; see Figure 5). All other materials of the task-switching paradigm were identical to those presented to young adults in the first experiment.

Procedure

On testing day, participants underwent a test battery, consisting of a categorization task (as part of another study), the Flanker task, and the task-switching paradigm. Participants completed the Flanker and task-switching paradigms in a counterbalanced order. All participants were given two blocks of each task (Flanker: 100ms pre-cue and no pre-cue; Task-Switching: 200ms and 500ms preparation times), which were also counterbalanced within each task.

Data Analysis

Descriptive analyses. All descriptive analyses were identical to those of Experiment 1, except that the age group variable was replaced by pre-cue duration and/or preparation time (in Flanker and task-switching paradigm respectively) in all analyses. Additionally, we conducted one-way ANOVA with RT and accuracy as dependent variables and pre-cue duration or preparation time as the independent variable to explore overall task performance.

Average reward rate analyses. Average reward rates were calculated in the same as in Experiment 1. In line with the results from Experiment 1 and Otto and Daw (2019), we found a best-fitting *a* estimate of 0.0037 for young adults. The same regression models as in Experiment 1 were used to model the effect of average reward rate on RT and accuracy, substituting age group for task difficulty (pre-cue in flanker and preparation time in task-switching). The terms of interest were the main effect of task difficulty, trial type, and reward rate, as well as the interactions between these predictors on RT and accuracy.

Results

Flanker Task

Performance. A one-way analysis of variance (ANOVA) showed no significant effect of pre-cue on performance calculated as points per second ($F(1,74) = 3.29$, $p = 0.074$; see Figure 5A). However, there was a main effect of pre-cue (0 or 100ms) on RT ($F(1,13127) = 56.74$, $p < .001$; see Figure 6) and accuracy ($F(1,13127) = 27.46$, $p < .001$, see Figure 6), whereby reaction times were longer ($M_{diff} = 8.73$, $p < .001$) and participants were less accurate ($M_{diff} = - 0.016$, $p < .001$) in the 100ms pre-cue block than in the no pre-cue block. This suggests that the 100ms pre-cue block was overall more difficult than the block with no pre-cue.

Compatibility effects. We found a significant main effect of trial type on RT ($\beta = 13.58$, SE = 2.37, $p < .0001$) and accuracy ($\beta = -0.34$, SE = 0.14, $p = .00037$), such that participants responded more slowly and less accurately on incongruent trials compared to congruent trials. Additionally, we found a significant interaction effect between trial type and pre-cue on both RT ($\beta = 18.79$, SE = 2.13, $p < .0001$) and accuracy ($\beta = -0.61$, SE = 0.17, $p < .0001$). That is, there are significant compatibility costs in RT in both conditions (pre-cue, no pre-cue) in the expected

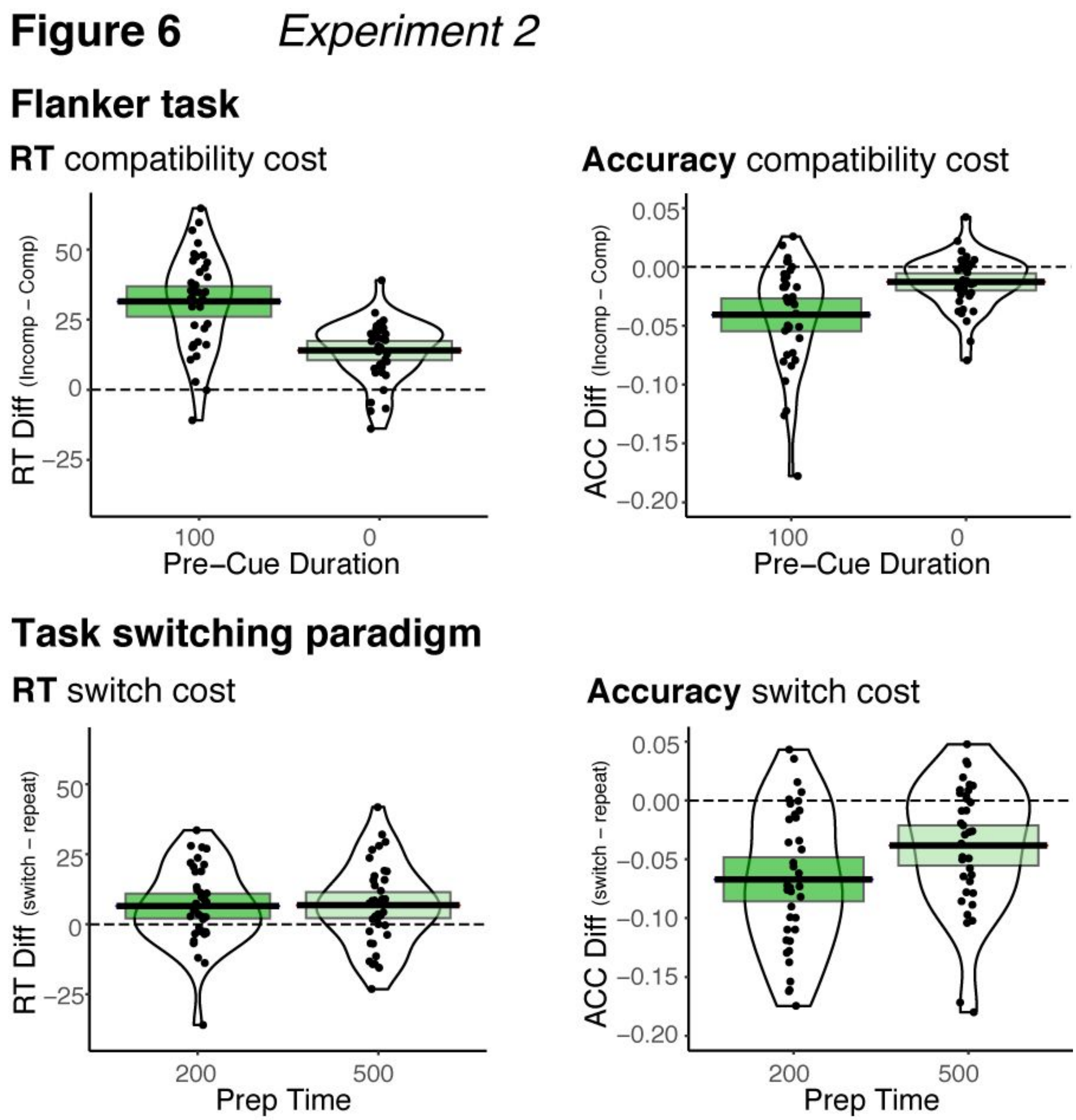

Figure 6. Pirate Plots of difference scores for RT and accuracy in (A) the Flanker task and (B) the task-switching paradigms. Differences scores are computed by subtracting RT/accuracy in incongruent/switch trails by RT/accuracy in congruent/repeat trials. Boxes represent confidence intervals of the mean, coloured lines represent mean costs for each age group, and coloured points represent individual participants' costs.

direction (higher RT on incompatible trials), but that this effect was exaggerated in the 100ms condition (0: $\beta = -13.58$, SE = 2.37, $p < .0001$; 100: $\beta = -32.36$, SE = 2.37, $p < .0001$).

Moreover, there are significant compatibility costs in accuracy in the 100ms condition in the expected direction (lower accuracy on incompatible trials; $\beta = 0.95$, SE = 0.14, $p < .0001$). This effect was less pronounced in the no pre-cue condition ($\beta = 0.34$, SE = 0.14, $p = .087$; see Figure 7). Taken together these results suggest that Flanker pre-cueing increases compatibility costs and thus creates a more difficult task.

Reward-on-offer effects. We did not observe a significant main effect of reward on offer on RT ($\beta = 0.78$, SE = 1.06, $p = 0.07642$) or accuracy ($\beta = 0.052$, SE = 0.096, $p = 0.06274$). Similarly, we observed no significant interaction of reward on offer with pre-cue (none or 100ms) on RT ($\beta = 7.06$, SE = 1.52, $p = 0.7980$) or accuracy ($\beta = 0.016$, SE = 0.14, $p = 0.4626$).

Opportunity cost effects. We found no significant main effect of average reward rate on RT ($\beta = -0.0032$, SE = 1.09, $p = .3044$) or accuracy ($\beta = 0.089$, SE = 0.088, $p = .8176$). We also did not find a significant interaction effect between pre-cue and average reward rate on both RT ($\beta = 0.49$, SE = 1.53, $p = .060$) and accuracy ($\beta = -0.084$, SE = 0.13, $p = .2780$; see Figure 8). The current results suggest that in the Flanker task, young adults were not sensitive to changes in average reward rate both in terms of RT and accuracy similar to what was seen in Experiment 1.

Task-Switching Paradigm

Performance. A one-way analysis of variance (ANOVA) showed no significant effect of preparation time on performance calculated as points per second ($F(1, 74) = 0.30$, $p = 0.59$; see Figure 5B). However, preparation time (200 or 500ms) did have an effect on RT ($F(1,11462) = 170.30$, $p < .001$; see Figure 6) and accuracy ($F(1,11936) = 53.29$, $p < .001$), whereby reaction times were longer ($M_{diff} = 23.32$, $p < .001$) and participants were less less accurate ($M_{diff} = -0.054$, $p < .001$) in the 200ms preparation time block than in the 500ms preparation time block.

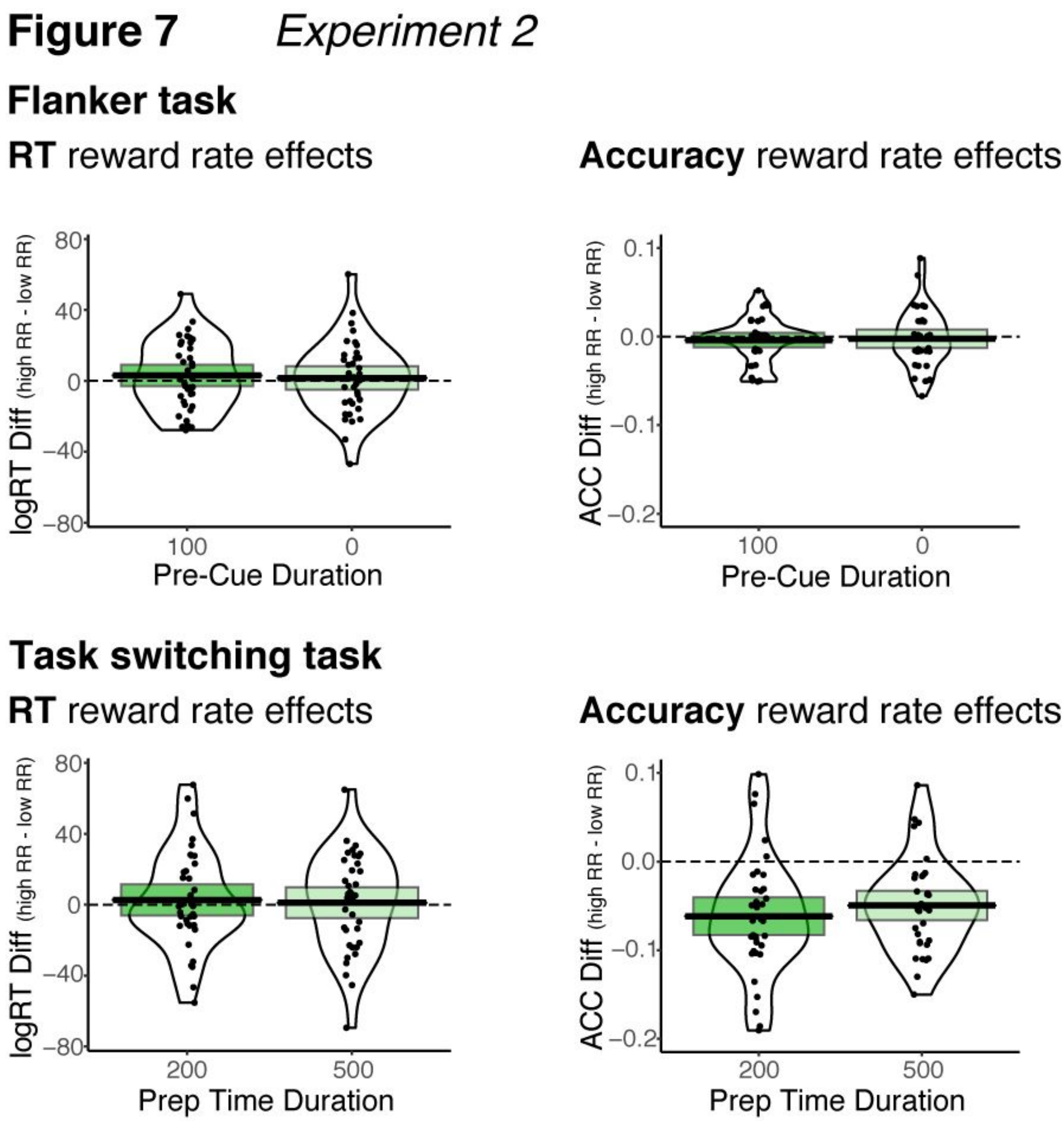

Figure 7. Pirate Plots of difference scores across the two tasks on (A) RT and (B) accuracy. Scores were computed by dividing reward rate into tertiles and dropping the middle quantile. Difference scores are represented here as “High - Low”, where High represents RT/accuracy when reward rate is high and Low represents RT/accuracy when reward rate is low. For instance, a negative difference score in RT represents a speeding up during high reward rate trials. Boxes represent confidence intervals of the mean, coloured lines represent mean differences for each block (pre-cue or preparation time), and coloured points represent individual participants’ reward rate effects.

Task-switching effects. We observed a significant main effect of trial type (switch or repeat) on both RT (β = 6.79, SE = 2.36, $p < .001$) and accuracy (β = -0.38, SE = 0.063, $p < .001$), such that participants responded more slowly and less accurately on switch trials compared to repeat trials. However, we did not find a significant interaction between preparation time and trial type on RT (β = - 0.0056, SE = 3.36, $p = .9611$) or accuracy (β = 0.12, SE = 0.093, $p = .1937$).

Reward-on-offer effects. We did not observe a significant main effect of reward on offer on RT (β = -0.56, SE = 1.65, $p = 0.8819$) or accuracy (β = -0.0030, SE = 0.045, $p = 0.7970$). Similarly, we observed no interaction of reward on offer with preparation time on RT (β = -0.31, SE = 2.37, $p = 0.8689$) and accuracy (β = -0.056, SE = 0.068, $p = 0.5602$).

Opportunity cost effects. We found a significant main effect of average reward rate on RT (β = -4.04, SE = 1.72, $p = .01029$) and accuracy (β = -0.03, SE = 0.047, $p = .03718$), such that participants responded more slowly and less accurately when average reward was high, suggesting a withdrawal of effort. However, it is worth noting that while a statistically significant RT difference was observed overall, this difference was extremely small (average difference between low and high reward rate responses = 0.0543ms; see Figure 8). Furthermore, we found no significant interaction between preparation time and average reward rate on either RT (β = 2.55, SE = 2.43, $p = .9001$) or accuracy (β = 0.035, SE = 0.067, $p = .08588$). The current results suggest that in the task-switching paradigm, young adults were sensitive to changes in average reward rate in terms of accuracy (reduced accuracy when reward rate is high, similar to Experiment 1) and negligibly in terms of RT.

Discussion

The main goal of this experiment was to address a possible alternative explanation to our results in Experiment 1. Namely, that children and older adults experienced the cognitive tasks as more challenging than younger adults and therefore invested more effort.

To test this hypothesis we performed a follow-up experiment in younger adults and manipulated task difficulty. We predicted that if younger adults' cognitive control abilities were pushed closer to their limits, they would show similar opportunity cost effects as older adults in Experiment 1. As before, we hypothesized that the degree of exertion of cognitive effort should depend on the opportunity cost of time—operationalized as the average reward per unit time—whereby young adults would respond less accurately when average reward was high (Otto & Daw, 2019). Additionally, however, we hypothesized that this relationship would be mediated by task difficulty, such that when young adults had less time to prepare (task-switching) or were presented with additional, irrelevant, information (Flanker), they would expend more effort when the opportunity cost of time was high (as older adults did in Experiment 1).

As seen in Figure 6, in both tasks the more difficult conditions elicited slower and less accurate responses overall. Additionally, as shown in Figure 7, we observed costs of cognitive control in both the Flanker task and task-switching paradigm: Under higher demands on cognitive control (incongruent trials in the Flanker task and switch trials in task-switching paradigm) participants responded more slowly and less accurately (Fan et al., 2003; Eppinger et al., 2007). Furthermore, we found an interaction between trial type and pre-cue (no pre-cue vs. 100ms pre-cue blocks) on both RT and accuracy in the Flanker task. This suggests that in the more difficult trials (i.e. incompatible trials), participants responded more slowly and less accurately and this effect was exaggerated in the more difficult block (100ms pre-cue block). However, no such effect was observed in the task switching paradigm indicating that task difficulty affected performance on switch and non-switch trials to a similar degree.

Additionally, in the Flanker task, we did not find effects of the opportunity cost of time on cognitive control. That is, there was no effect of average reward rate on RT nor on accuracy. Moreover, there was no interaction between task difficulty and average reward rate on RT or accuracy. These results replicate those of Experiment 1, in which no opportunity cost effects were observed in younger adults in this task.

In the task switching task, however, irrespective of task difficulty, young adults responded less accurately when opportunity costs were high. Thus, consistent with the results of Experiment 1, this finding suggests that on high reward rate trials younger adults reflexively withdrew cognitive effort, resulting in reduced accuracy.

Overall, the results from this follow-up experiment provide further evidence for the idea that young adults reflexively withhold resources when rewards are cheap (when the reward rate is high). Furthermore, they support the view that the age differences in sensitivity to opportunity costs observed in Experiment 1 are process-specific, such that young adults engaged in such effort withdrawal in task-switching, but not in attention control (the Flanker task). These results demonstrate that by increasing the task difficulty in an attempt to push young adults closer to their limits (as we presume old adults were in the first experiment), their sensitivity to the opportunity cost of time did not begin to resemble that of older adults. Thus, young and old adults may be implementing different strategies when faced with cognitive control tasks and differences in responses to the opportunity cost of time were not driven by perceived task difficulty.

General Discussion

The purpose of this study was to explore how age-related differences in cognitive control abilities affect effort cost-benefit trade-offs across the lifespan. We hypothesized that cognitive effort would be exerted in accordance with the opportunity cost of time and that the degree to which it would be exerted would depend on age-related cognitive limitations. In Experiment 1, we found that the opportunity cost of time differentially affected behaviour in children, adolescents, younger, and older adults. Namely, we found that while adolescents and young adults exhibited a reflexive, Pavlovian, withdrawal of effort when the opportunity cost of time was high (less accurate responding, but no change in RT), older adults expended effort to accumulate reward (faster RT and better or unchanging accuracy when average reward was high). Furthermore, we found that while older adults applied this strategy to cognitive control tasks more broadly, adolescents and younger adults seemed to selectively apply it to the task-switching paradigm.

We qualified this interpretation of age- and process-specific sensitivity to opportunity cost of time by addressing an alternative explanation of the data in Experiment 2; namely that differences in responses to the opportunity cost of time were driven by relative task difficulty. We predicted that increased task difficulty would shift younger adults' use of the opportunity cost of time to the more rational approach observed in older adults (contra Otto & Daw, 2019). Our findings did not support this alternative explanation, however. We found that young adults responded in the same way as Experiment 1, even when their cognitive resources were further taxed.

To summarize, in specific operationalizations of cognitive control, adolescents and young adults withhold cognitive resources when the opportunity cost of time is high. In contrast older adults and, to some degree children, expend cognitive effort to boost task performance. From this, we argue that there may exist age- and process-specific “sweet spots”, wherein individuals’ behaviours are differentially affected by the opportunity cost of time based on (a) their age and (b) what type of cognitive control process is needed to accomplish a task. Adolescents and younger adults reflexively withdraw effort when the opportunity cost of time is high, but only do so when the task engages specific cognitive control processes (e.g., during task-switching). In contrast, older adults seem to strategically allocate their (more limited) computational resources to accomplish challenging cognitive tasks (Simon, 1990; see also Griffith et al., 2015).

Our findings are not unlike past ones. The process-specificity of these sweet spots is also supported by recent findings regarding the adaptation of decision-making strategies: While older adults show reduced sensitivity to cost-benefit evaluations when adjusting their reliance on different strategies in a decision-making task, these same participants adapt their performance in cognitive control tasks to different reward magnitudes (Bolenz et al. 2019). Furthermore, our findings join work in demonstrating that older adults broadly allocate resources to even simple cognitive control tasks (Friedman et al., 2009). Generally speaking, this broad and unspecified allocation of resources is thought to result in poorer cognitive control among older adults (Friedman et al., 2009). In contrast to this work however, we contend that such allocation can *sometimes* be rational, strategic, and even result in increased performance, as seen in the Flanker task. Other times, however, such overgeneralization of effort exertion can be needless, as it does not meaningfully impact task performance (e.g., in the task-switching paradigm). Thus, while older adults may strategically allocate cognitive control resources in accordance with the opportunity cost of time, they seem to do so in an undifferentiated way, whether it confers benefits or not.

This view differs subtly from deficit-based accounts (e.g., Braver & Barch, 2002; West, 1996), which posit that older adults' limitations in cognitive control result *solely* from functional and structural decline in the prefrontal cortex. Rather, our view suggests that older adults can strategically balance their more limited cognitive resources to boost performance on some tasks that necessitate cognitive control. In this study, we argue that this balancing is reflected through their sensitivity to the opportunity cost of time, whereby older adults expended cognitive effort to maximize reward per unit time. From this perspective, poorer performance on cognitive tasks might occur when older adults misapply such strategies to tasks where they are not beneficial, effectively expending resources when they confer no benefit (e.g., in the task-switching paradigm in Experiment 1). Finally, we wish to emphasize that our view does not suggest that cognitive limitations do not play role in how individuals engage in these trade-offs. Rather, we assume that as these cognitive resources begin to develop or decline in childhood and old age respectively, humans seem to adaptively allocate them in accordance with the opportunity cost of time. Therefore, our view aims to supplement “deficit-based” interpretations (and indeed assumes their truth to some degree), rather than to supplant it.Thus, our work can be seen as a first step towards lifespan developmental theories that formalize the dependencies between process-specific cognitive limitations and effort allocation. There is an obvious need for more research in this area. In particular, futures studies should focus on more extreme age ranges while considering the process-specificity of these trade-offs and manipulating task demands.

To summarize, our findings join a spate of recent work that suggests that older adults *can* utilize such compensatory mechanisms to improve cognitive control, *despite* structural limitations and declines (Ruel et al., in prep; Ferdinand & Czernochowski, 2018; Yee et al., 2019; Patzelt et al., 2019; Harsay et al., 2010). Going beyond this work, we suggest that these compensatory mechanisms occur at developmental sweet spots at which the incentivisation structure and the task demands are tailored to the needs of the different age groups.

Deviations, Limitations, and Future Directions

It is important to note where the current results deviate from past work. One important difference between our results and the findings by Otto & Daw (2019) is that in current study, young adults were not sensitive to the opportunity cost of time in the Flanker task (neither in Experiment 1, nor in Experiment 2. In contrast, the study by Otto and Daw (2019) showed significant opportunity cost effects in a Simon task that is also supposed to assess conflict processing. One reason for this divergence in results between the two studies might be that the paradigms assess different types of conflict. The Flanker task applied in our study primarily assesses stimulus-driven conflict and it has been argued that conflict effects in the Flanker task may actually reflect stimulus-driven priming processes (Mayr, Awh, & Laurey., 2003). In contrast, the Simon task primarily taps into response conflict (for a discussion see Botvinnick, 2007). This interpretation is in line with the general conclusion of the current study regarding the process-specificity of the opportunity cost effects.

Moreover, this study has several important limitations that need to be considered. First, the total time on task in Experiment 1 differed between age groups. This was a necessary feature of our design to account for overall longer reaction times in children and older adults, which would have led to an overabundance of timeouts in these age groups (when using the same deadlines; see Salthouse, 2000; Kiselev et al., 2008; Fry & Hale, 2000). While important, this design feature also engenders confounds between the age groups which may have affected how they processed the opportunity cost of time (or perceived the task overall, see the point above; Dunn et al., 2019). This limitation is partially addressed in Experiment 2 however, as the young adults in this experiment experienced two difficulty conditions back-to-back (within-subjects design). In both cases, they showed a similar pattern of responding as they did in Experiment 1, despite a greater total time on task. Nonetheless, future designs should seek to rectify this issue from the outset, as it still represents a limitation in our original study's design.

Second, our sample's developmental age range was constraint with lower bound at age 8 years. As discussed earlier (and in the Supplement), there is reason to believe that the sensitivity to the opportunity cost of time follows a developmental pattern, such that younger children expend effort when average reward is high (like older adults), but learn over time to withdraw it (like the adolescents and young adults). This interpretation remains speculative however. Future research should try to provide a more fine-grained analysis of the developmental trajectories in younger children.

Finally, our sample did not include any middle-aged participants (36-56 years old). This would have been necessary to explore lifespan developmental trajectories while treating age as a continuous variable. Furthermore, it would have qualified the findings we observed in the older adults, such that we could have explored changes in the sensitivity to the opportunity cost of time as a function of changes in cognitive abilities from young adulthood to older age.

Conclusion

Overall, our results point to age- and process-specific sensitivities to the opportunity cost of time. That is, we find that older adults (and to a lesser degree children) expend cognitive effort to accumulate reward when the opportunity cost of time is high, whereas adolescents and younger adults withdraw effort. While our interpretation remains tentative and more work is needed to understand the developmental trajectory of these strategies, the current study suggests a potential computational mechanism that older adults (and possibly children) use to strategically adapt to heightened cognitive control demands in their environment: the opportunity cost of time.

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Supplemental

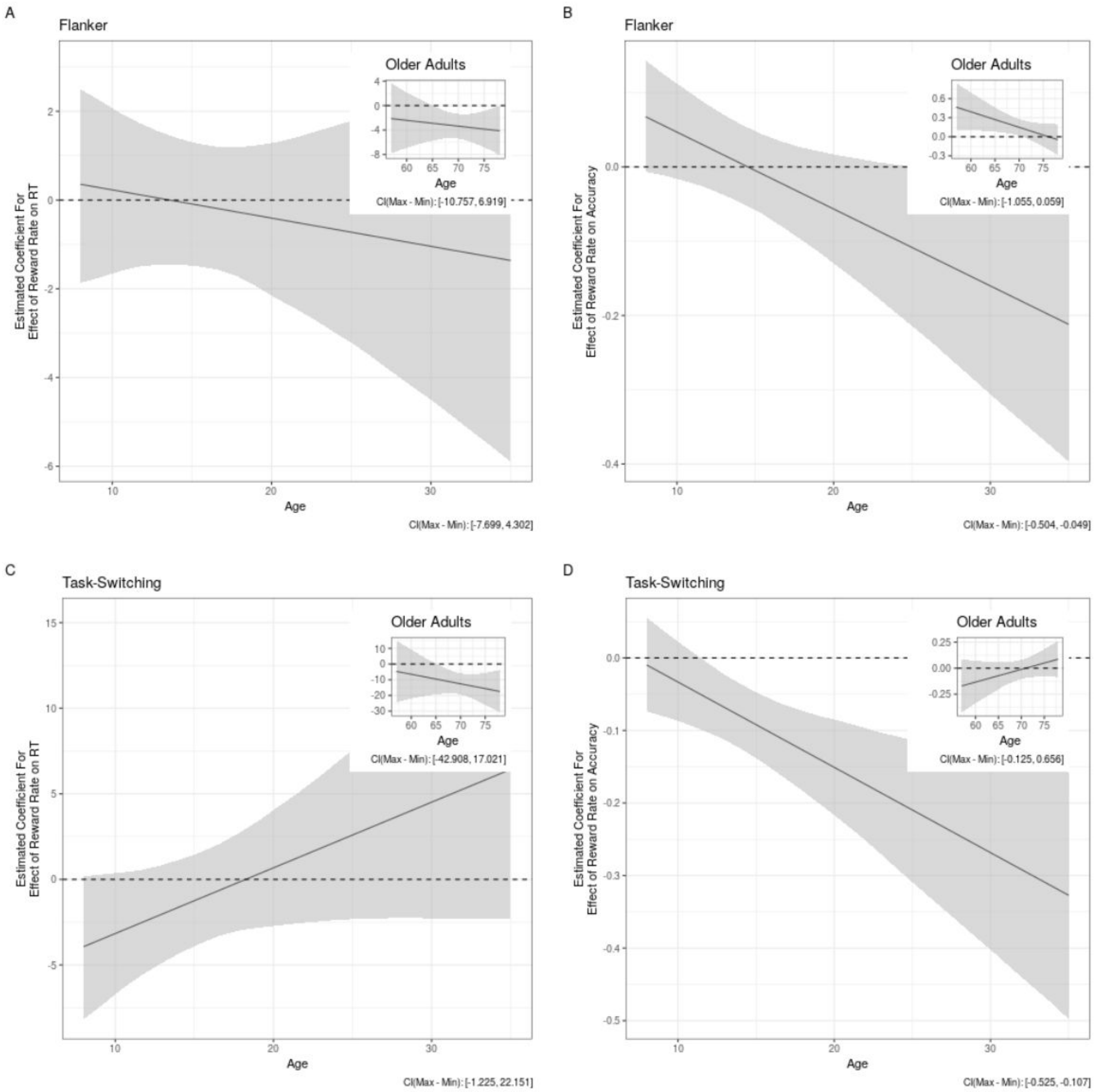
Chronological Age and Opportunity Cost Effects

In Experiment 1, we explored how the opportunity cost of time affected effort exertion (reflected in RT and accuracy) in children, adolescents, young adults, and older adults. We did so by using age as a grouping factor. This analysis failed to capture the continuous relationship that might exist between these participants' age and their sensitivity to the opportunity cost of time. In this section, we turn to explore these relationships in more detail.

Specifically, we ran the same mixed-effects regressions described in the Method section for Experiment 1, substituting age group for chronological age. We did so for all participants aged 8 to 35 years old (for which we had chronologically continuous data). In particular, we were interested in exploring whether children in our sample were differentially affected by the opportunity cost of time based on their age, given that we observed a trend for such behaviour in the task-switching paradigm in Experiment 1. We also conducted the same analyses in older adults as a point of comparison for the children.

In the Flanker task, we found a significant interaction between average reward and age predicting accuracy (β = - 0.0103, SE = 0.0044, p = .01865), but not predicting RT (β = - 0.0641, SE = 0.1138, p = .5743). Similarly, in the task-switching paradigm, we found a significant interaction between age and average reward on accuracy (β = -0.0115, SE = 0.0040, p = .0035), but not RT (β = - 0.3814, SE = 0.2196, p = .0895).

As shown in Supplemental Figure 1, the expected coefficients for average reward on RT and accuracy demonstrate that the younger children are, the more effort they exert when the opportunity cost of time is high (improved accuracy or faster RT without loss of accuracy). That is, there seems to be a trend such that younger children expend effort when the opportunity cost of time is high, whereas older children and younger adults withdraw effort. Taken together, the current findings may suggest that there are significant developmental changes in the way opportunity costs are processed. Younger children may resemble older adults in their sensitivity to the opportunity cost of time. The older the children get, the more they may withdraw effort when the opportunity cost of time is high. It has to be noted, however, that this trend for children in our sample *never* reaches statistical significance (the confidence intervals always include zero at young ages). Future research should tackle this question either by using a broader developmental sample or by applying a longitudinal design.



Supplemental Figure 1. Interaction plots for chronological age ✕ average reward effects on RT and accuracy in both tasks. The x-axis represents chronological age, from 8 to 35 years old. The y-axis represents the expected effect (regression coefficient) of average reward on the variable of interest. In the corner of each plot, we've included a similar figure for data in the older adult group. In these cases, the interaction between age and average reward on the outcome was never statistically significant. These plots are included mainly as a point of comparison to demonstrate the younger children trend toward experiencing similar opportunity cost effects as the older adults.