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Adaptiveness in proactive control engagement in children and adults

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ABSTRACT

Age-related progress in cognitive control reflects more frequent engagement of proactive control during childhood. As proactive preparation for an upcoming task is adaptive only when the task can be reliably predicted, progress in proactive control engagement may rely on more efficient use of contextual cue reliability. Developmental progress may also reflect increasing efficiency in how proactive control is engaged, making this control mode more advantageous with age. To address these possibilities, 6-year-olds, 9-year-olds, and adults completed three versions of a cued task-switching paradigm in which contextual cue reliability was manipulated. When contextual cues were reliable (but not unreliable or uninformative), all age groups showed greater pupil dilation and a more pronounced (pre)cue-locked posterior positivity associated with faster response times, suggesting adaptive engagement of proactive task selection. However, adults additionally showed a larger contingent negative variation (CNV) predicting a further reduction in response times with reliable cues, suggesting motor preparation in adults but not children. Thus, early developing use of contextual cue reliability promotes adaptiveness in proactive control engagement from early childhood; yet, less efficient motor preparation in children makes this control mode overall less advantageous in childhood than adulthood.

1. Introduction

Behaving with increasing autonomy and flexibility is a hallmark of growing up and is supported by protracted gains in cognitive control, the goal-directed regulation of attention and actions, intrinsically related to the development of frontoparietal networks with age (e.g., Baum et al., 2017; Crone and Steinbeis, 2017). Efficient engagement of cognitive control requires dynamic adjustments to meet moment-to-moment variations in task demands. In particular, control can be engaged either *proactively*, that is, in anticipation of upcoming task demands to minimize subsequent interference, or *reactively,* that is, in the moment to resolve current interference (Braver, 2012). For instance, as children cycle to school, they may need to proactively monitor for traffic lights in a busy city section and then release control on a quiet bike path while still being able to reactively mobilise it if a dog unexpectedly runs across the path. Proactive control is behaviourally advantageous when task demands can be predicted, whereas reactive control is more adaptive for unforeseen task demands.

As they grow up, children increasingly engage proactive control (e.g., Chatham et al., 2009). However, unlike older children and adults, who adaptively engage either control mode as a function of task demands (Braver, 2012; Lewis-Peacock et al., 2016; Mäki-Marttunen et al., 2019), children around 5 and 6 years of age tend to rely mostly on reactive control, even though they are already capable of proactive control (e.g., Chevalier and Blaye, 2016; Chevalier et al., 2015; Hadley et al., 2020; Troller-Renfree et al., 2020). For example, when switching between colour- and shape-matching rules as a function of task cues, one can proactively prepare to process either the colour or shape of the upcoming target when the task cue is presented early. In adults, such proactive preparation yields faster responses (e.g., Kiesel et al., 2010; Vandierendonck et al., 2010), is supported by frontoparietal activity (e.g., Cooper et al., 2017), and is associated with a cue-locked posterior positivity in electroencephalogram (EEG) data reflecting proactive task selection (e.g., Karayanidis et al., 2009; Nicholson et al., 2005). Simply presenting the cue ahead of the target is sufficient to observe proactive preparation in 10-year-olds but not in 5-year-olds, who tend to process the cue reactively after target onset. However, even 5-year-olds proactively process task cues when reactive control is made more difficult by removing the cue after target onset, as shown by faster response times, greater cue-locked pupil dilation (which suggests earlier cognitive

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effort, Beatty, 1982; Eckstein et al., 2017), as well as a more pronounced cue-locked posterior positivity (Chevalier et al., 2015).

As proactive control is adaptive only if upcoming task demands can be reliably predicted based on contextual cues (e.g., task cues), adaptiveness of proactive engagement likely relies on contextual cue reliability. However, children may not use contextual cue reliability effectively yet, as they tend to overlook and struggle to process contextual cues. They show less prefrontal activation than adults while processing task cues (Church et al., 2017), and perform better after practicing contextual cue monitoring or when cue processing is facilitated (e.g., Barker and Munakata, 2015; Chevalier and Blaye, 2009; Chevalier et al., 2014; Towse et al., 2007). Further, unlike adults (e.g., Kool et al., 2010), younger children do not use contextual information, such as variations in cognitive control demands, to avoid unnecessary cognitive effort and optimise their performance (Niebaum et al., 2019; Niebaum and Munakata, 2020; O'Leary and Sloutsky, 2017, 2019).

Alternatively, children may use contextual cue reliability as well as adults, but be biased to reactive control because they implement proactive control less efficiently and thus are less likely to benefit from it. Indeed, proactive control engagement does not always yield a behavioural benefit in 5- and 6-year- olds (Hadley et al., 2020; Jin et al., 2020), perhaps because children do not efficiently engage the same cognitive processes as adults while proactively preparing for an upcoming task. In particular, proactive preparation for an upcoming task entails cue- based task selection and proactive motor preparation. Task-selection is indexed by a cue-locked posterior positivity that is larger (i.e., more positive) when the cue predicts the upcoming task than when it is uninformative (e.g., Karayanidis et al., 2009). Proactive motor preparation is indexed by a frontocentral contingent negative variation (CNV) observed just before target onset that is larger (i.e., more negative) when task-relevant stimulus-response mappings can be activated ahead of target onset (e.g., Kray et al., 2005). Unlike the posterior positivity, which shows a similar pattern in middle childhood and adulthood (e.g., Chevalier et al., 2015), the CNV becomes larger from adolescence to adulthood (Killikelly and Szűcs, 2013), suggesting more efficient motor preparation with age.

We investigated adaptiveness of proactive control engagement based on contextual cue reliability and efficiency of proactive control engagement in children and adults. Behavioural, pupillometry, and EEG data were collected while 6-year-olds, who are relatively new to proactive control, 9-year- olds, who more ably use either control mode, and young adults performed a cued task-switching paradigm. The task cues presented ahead of the target either (a) reliably predicted the upcoming task on all trials, hence making proactive control adaptive, (b) unreliably predicted the upcoming task (i.e., correct information on half of the trials only), making proactive control possible but maladaptive, or (c) did not provide any information about the upcoming task, hence making reactive control adaptive. Proactive preparation was probed through cue-locked pupil dilation (as greater pupil dilation is a proxy for greater general cognitive effort), posterior positivity (reflecting proactive task selection), and CNV (reflecting motor preparation). Finally, reactive control was indexed by the frontal pre-response negativity (PRN) observed shortly before the response when adults engage control reactively (Czernochowski, 2014).

Efficient use of cue reliability should result in selective engagement of proactive control with reliable but not unreliable cues, as proactive control would be maladaptive with unreliable cues. This should be evidenced by faster responses, greater cue-locked pupil dilation (indicating greater cognitive effort), a more positive posterior positivity (reflecting proactive task selection) and a more negative CNV (reflecting proactive motor preparation) with reliable than unreliable or uninformative cues. Further, efficient proactive preparation should decrease the need to engage reactive control after target onset as shown by a reduced (less negative) PRN. Importantly, we expected proactive control markers to be more pronounced and vary more as a function of cue reliability in older age groups.

2. Methods

2.1. Participants

Participants included 35 six-year-old children ($M = 6.5$ years, $SD = 0.3$, age range = 6;0–6;11, 17 females, 18 males), 32 nine-year-old children ($M = 9.5$ years, $SD = 0.3$; age range = 9;0–9;11, 15 females, 17 males), and 33 adults ($M = 24.6$ years, $SD = 6.8$; age range = 18;3–34;5, 19 females, 14 males). An additional four 6-year-olds, four 9-year-olds, and one adult were recruited but excluded because they failed to complete the session. Most children's ethnicity was Caucasian ($n = 56$), nine children were of mixed ethnicities, and one was Asian (ethnicity information was missing for one child). Fifty children had at least one parent with a university degree and nine had parents with high-school or vocational training (this information was missing for eight children). Adults' ethnicity was either Caucasian ($n = 21$) or Asian ($n = 12$). Adults either were undergraduate students ($n = 22$) or held a university degree ($n = 11$). As EEG data could not be correctly recorded for some participants due to technical issues, participant recruitment stopped after EEG data were collected for 30 participants in each age group. Prior to participation, written informed consent was obtained from all adults (participant or parent). In addition, 9-year-olds also gave written informed assent. Adult participants and parents were compensated £30, while children received small, age-appropriate prizes.

2.2. Materials and procedure

Two trained experimenters tested each participant individually in a 90-min long session. Behavioural, EEG, and pupil dilation data were recorded while participants completed all three conditions of the cued task-switching paradigm. One experimenter conveyed task instructions while the other monitored EEG and eye-tracking data acquisition. After applying the EEG cap on the participant's head, the participant sat 60 cm away from the computer screen, using a chin rest to minimize movement artefacts and optimize pupil data quality, and completed the eye-tracking calibration procedure. Parents completed a short demographic questionnaire while children completed the tasks, whereas adult participants completed the questionnaire during net application.

Each participant completed three conditions of the cued task-switching paradigm, which was run using E-Prime 2 (Psychology Software Tools, Pittsburgh, PA) and introduced as the 'Santa Claus Game' (adapted from Chevalier et al., 2015). To help Santa and his elves prepare for Christmas, participants sorted toys (i.e., targets) by their shape or colour (Fig. 1). Specifically, they had to switch between matching the target with the response option of the same colour or shape as a function of the visual task cue presented alongside the target. Importantly, an initial cue presented ahead of target onset predicted the upcoming relevant task (colour- or shape-matching) with varying reliability across conditions, influencing to what extent proactive control was adaptive.

Each trial started with a fixation cross within a black circle (7 cm diameter) at the centre of the screen for a duration jittered between 1000 and 1200 ms. It was followed by an elf holding an initial cue (referred to as 'precue' thereafter) potentially signalling the upcoming task for a duration jittered between 1500 and 1700 ms. The target was then displayed within the black circle surrounded by the actual task cue overlaid on the black circle: either grey geometrical shapes for shape-sorting or patches of colours for colour- sorting. Participants had to sort the target as a function of the actual cue (rather than the precue) and enter their responses by pressing one of four horizontally aligned buttons on a response box. They had to keep their index and middle fingers on top of the response buttons throughout the game. Although there was no response time limit, participants were instructed to respond as fast and accurately as they could. Upon entering the response, feedback was displayed for 1000 ms in the form of a thumb-up for correct responses or thumb-down for errors.

Critically, the precues differed across conditions. In the reliable-

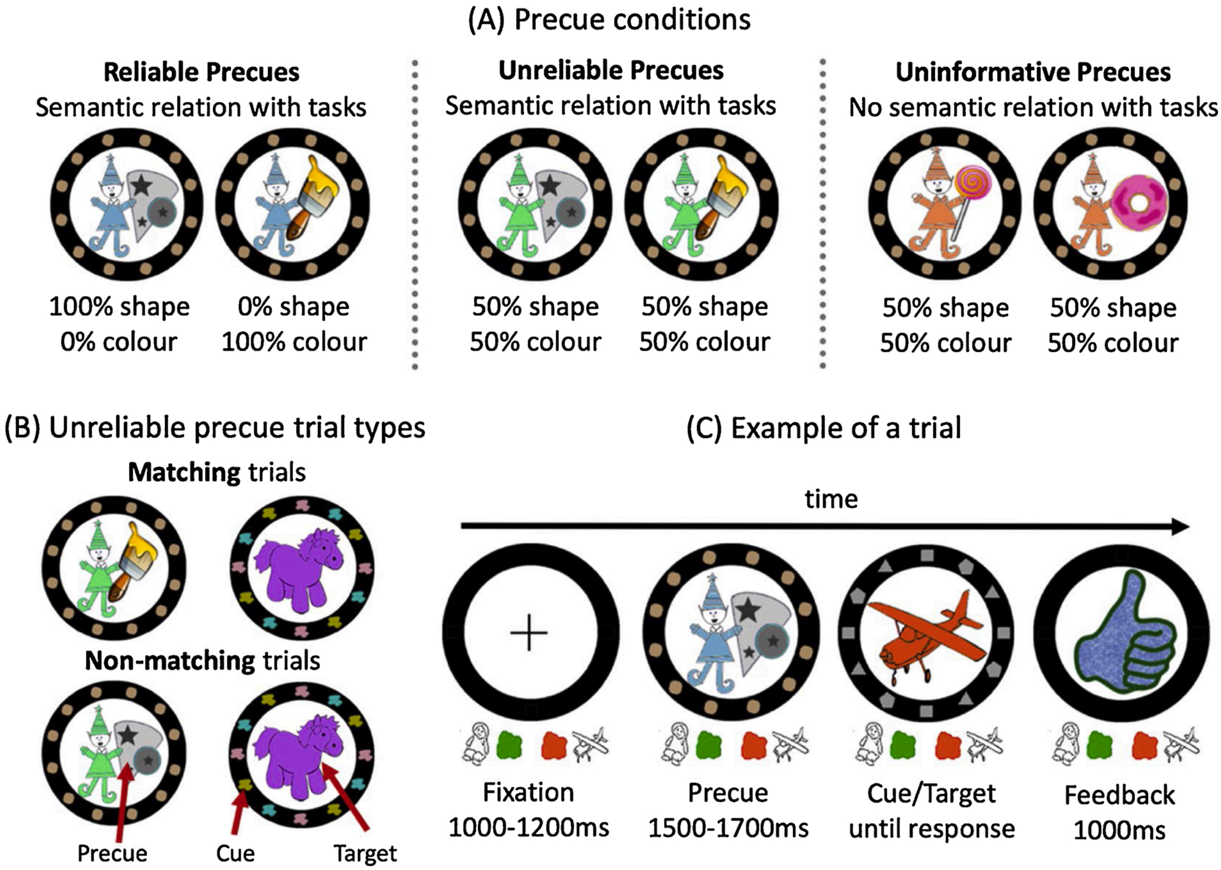

Fig. 1. Cued task-switching paradigm. Participants had to match the target (toy within the black circle) with the response option (below the black circle) of the same colour or shape depending on the task cue (patches of colour or geometric shapes on the black circle). A precue (held by an elf and displayed ahead of cue and target onset) predicted the upcoming task (colour- or shape-matching) with varying reliability. (A) Precues in the reliable-, unreliable-, and uninformative-precue conditions varied as a function of whether or not they bore a semantic relation with one of the sorting tasks and whether or not they systematically occurred before the same task cue. (B) The precue could either match or mismatch the following task cue (patches of colours or geometrical shapes on the black circle) in the unreliable-precue condition. (C) Example of a shape trial in the reliable-precue condition. The response pictures were constantly displayed under the black circle.

precue condition, the precues were held by a blue elf and corresponded to grey shapes (triangles, stars, circles) for shape-sorting and a yellow paint brush for colour-sorting. Each precue always matched the task cue it was semantically associated with (e.g., the shape precue always preceded the shape cue), making precue-based proactive preparation both possible and adaptive. In the unreliable-precue condition, the exact same precues were used but this time they were held by a green elf and, importantly, they matched the upcoming task cue (e.g., shape precue preceding a shape cue) on only half of the trials (matching trials) and mismatched the upcoming task cue (e.g., shape precue preceding a colour cue) on the remaining half (non-matching trials). Thus, precue-based proactive preparation was possible but maladaptive in that condition (as it would lead the participant to prepare for the wrong task on mismatching trials). Finally, the precues used in the uninformative-precue condition (lollipop or donut held by an orange elf) bore no semantic associations with colour- or shape-matching, and equally preceded a shape or colour cue (Fig. 1), rendering precue-based proactive preparation impossible. Participants were informed at the start of each condition that the elf would help them by showing the upcoming task (reliable-precue condition), the elf would try to help but it was a bit absent-minded (unreliable-precue condition), it would not be able to help as it did not know which task would come next (uninformative-precue condition). We elected to explicitly communicate this information to participants as (1) we were interested in whether they would use precue reliability to adaptively adjust cognitive control engagement (rather than whether they would notice precue reliability), and (2) it avoided having to disclose this information only to the participants who would inquire about it as they noticed precue unreliability during the game. Condition order was counterbalanced across participants.

For the sake of pupil data, all precues, cues and targets were matched in luminance (similar colour brightness calculated based on the RGB colour model). Similarly, precues were accompanied by uninformative brown dots over the black circle so they matched cue + target compounds in visual complexity. Targets corresponded to three combinations of colours and shapes (green/orange doll/airplane, pink/blue bear/car, red/purple horse/train) and changed as participants moved from one condition to the next, to keep participants engaged and highlight condition changes. Small (2 × 2 cm), unidimensional response pictures (e.g., outline of a doll, patch of green, patch of orange, and outline of an airplane) were constantly displayed right underneath the black circle to minimize working memory demands.

Each condition started with two demonstration trials during which the experimenter provided guidance on how to sort based on the cued dimension (e.g., colour), followed by four practice trials in which the same dimension was always relevant. Demonstration and practice trials were then repeated for the other sorting task (e.g., colour). Participants then completed four demonstration and eight practice trials in which both tasks were mixed. Finally, participants completed three blocks of 21 test trials for each condition (63 test trials/condition), including 30 no-switch trials in which the relevant task repeated and 30 switch trials in which the relevant task differed from the previous trial (plus 3 start trials). Switch and no-switch trials alternated unpredictably. In total, participants completed 189 test trials. At the very end of the session, participants were shown all three elves (corresponding to the three conditions) and asked the following questions: *Did you like playing with any of these elves best? Did you dislike playing with any of these elves? Do you think it was easier to play with one of these elves?* These questions assessed metacognitive reflection on task demand variation across conditions, as such reflection increases during childhood (e.g., Niebaum et al., 2019; O'Leary and Sloutsky, 2017, 2019).

2.3. Data recording and processing

Behavioural data. Response times (RTs) were examined for correct responses only after removing outliers corresponding to values greater than either $M+3SD$ or 10000 ms and values lower than $M\text{-}3SD$ or 200 ms (2.9 % of trials). RTs were log-transformed prior to statistical analyses to control for skew.

Pupil dilation. Pupil dilation was recorded at a 1000 Hz sampling rate using an EyeLink 1000 eye-tracker (SR Research, Ottawa, ON, Canada), tracking either the right or left eye. A 5-point calibration procedure was performed prior to starting the game. Analysis of pupil dilation was limited to a window from 300 ms before precue onset to 3200 ms after. The 300 ms before precue onset were used as baseline for each trial. Pupil dilation was calculated as percent change from this baseline to control for age-related difference in baseline pupil diameter (Chatham et al., 2009). Measurements for correct trials were averaged into consecutive 10 ms bins and smoothed over a 100 ms moving window. Trials with valid values for less than half of the segment length were discarded. The data from participants with at least 10 good segments per condition were included in the analyses. As precue-based proactive preparation has been previously shown to peak between 1000 and 2000 ms after precue onset (Chevalier et al., 2015), mean change in pupil dilation was calculated over this window. Outliers over 40 or $M+3SD$ or below -40 or $M\text{-}3SD$ were removed (<.01 % of values removed). On average, there were 45 good segments/condition at age 6 ($n = 31$), 53 at age 9 ($n = 32$), and 58 in adults ($n = 32$).

EEG data. EEG data were recorded at a 512 Hz sampling rate using a BioSemi ActiveTwo system with 64 channels (BioSemi BV, Amsterdam, Netherlands). Impedances were kept below 50 kΩ. The data were processed offline using EEGLAB (Delorme and Makeig, 2004) and ERPLAB (Lopez-Calderon and Luck, 2014). The continuous data were re-referenced to the average of the two mastoids and band-pass filtered (0.1−30 Hz). Bad channels were visually identified and removed ($M = 1.4$ channels, $SD = 1.9$). The data were first segmented around precue onset (from −1 s to 4 s) and response (from −3 s to 2 s), and trials with an incorrect response were removed. An independent component analysis (ICA) was run to correct for eye- blinks and other eye-movement artefacts, using ADJUST (Mognon et al., 2011). Missing channels were then replaced through spline interpolation. The initial epochs were converted back to continuous data and segmented again in ERPLAB. Segmentation was done twice, once around precue onset (−200 ms to 1500 ms) with the initial 200 ms as baseline, and once around the response (−1000 ms to 500 ms) with the 200 ms before target onset as baseline. After baseline correction, remaining artefacts were rejected using a 200 ms peak-to-peak moving window, 200 Hz maximum amplitude threshold, and 100 ms window step, and again using a simple threshold of 200 Hz. The data from participants with at least 10 good segments/condition were included in the analyses.

As the posterior positivity (PP) occurred later in younger than older participants, time windows with different latency boundaries were used to extract mean amplitudes in each age group. Latency boundaries were selected based on visual inspection to capture peak amplitude in each age group. As in previous work (Chevalier et al., 2015), the precue-locked PP was right-lateralised and maximal over P2, P4, P6, PO4 and PO8. Amplitude was averaged across these channels for the following windows: 600−1000 ms at age 6, 500−900 ms at age 9, and 300−700 ms in adults. A lateralised CNV was observed in adults, which is consistent with prior work (Mueller et al., 2007) but not in children. In adults, it was left-lateralised and maximal over frontocentral channels Fz, F1, F3, F5, FCz, FC1, and FC3. CNV amplitude was averaged across these channels from 1200 to 1500 ms post precue onset. Finally, the pre-response negativity (PRN) was maximal over the midline and examined by averaging frontal channels F1, Fz, and F2 using the last 200 ms before the response in adults, as in prior work (Czernochowski, 2014). As the PRN component was slower in children, the last 400 ms before the response were used for 6- and 9-year-olds. For each component, outliers over 100 Hz or $M+3SD$ or below -100 Hz or $M\text{-}3SD$ were removed (<0.02 % of values removed). On average, there were 43 good segments/condition at age 6 ($n = 26$), 54 at age 9 ($n = 26$), and 58 in adults ($n = 30$) for the PP and CNV, and 34 at age 6 ($n = 24$), 53 at age 9 ($n = 26$), and 57 in adults ($n = 30$) for the PRN.

2.4. Data analysis

We ran ANOVAs including age group (6-year-olds, 9-year-olds, adults), condition (reliable-precue, unreliable-precue, uninformative-precue), and trial type (switch, no-switch) as predictors on response times and accuracy. Trial type was not entered in models on precue-locked pupil dilation and ERPs because (a) trial type was not psychologically meaningful before target/cue onset in the unreliable and uninformative precue conditions, (b) proactive preparation did not interact with trial type in prior research with children (Chevalier et al., 2015; Jin et al., 2020), and (c) this allowed optimisation of signal-to-noise ratios. As the numbers of good segments differed significantly across age groups ($ps<.001$), this factor was entered as a covariate (except for accuracy). Greenhouse-Geisser correction was applied when necessary, as evidenced by Mauchly's sphericity test. Generalised eta squared values are reported as estimates of effect sizes (Olejnik and Algina, 2003). Post-hoc tests were run using Bonferroni correction. Relations among variables were examined with Pearson's correlations. To investigate to what extent the PP and CNV independently predicted performance, a mixed model was run on RTs with condition and age group as categorical predictors, and PP and CNV amplitudes as continuous predictors. Amplitudes for each ERP were centred for each age group separately and, for ease of interpretation, CNV values were flipped so that greater values indicated more pronounced amplitudes for both ERPs. All fixed effects and interactions were tested with random intercepts for subjects. Effects were examined by comparing models with likelihood ratio tests (LRT).

3. Results

3.1. Behaviour

As all three age groups performed the task well above chance (indicating that RT effects are interpretable), we first report RT effects, for which we had the strongest predictions, and then move on to accuracy effects.

Response Times (RTs). RTs for correct responses varied as a function of age group, $F(2, 97) = 44.33$, $p < .001$, $\eta^2_G = .424$, precue condition, $F(2, 194) = 69.28$, $p < .001$, $\eta^2_G = .101$, and trial type, $F(1, 97) = 23.32$, $p < .001$, $\eta^2_G = .003$ (Fig. 2). They decreased across all three age groups (7.92 log ms at age 6, 7.47 log ms at age 9, 6.90 log ms in adults, respectively, $ps<.001$), and were faster with reliable precues (7.28 log ms) than either unreliable (7.51 log ms) or uninformative precues (7.53 log ms), $ps<.001$, whereas the latter two precue conditions did not differ ($p = 1$). Importantly, precue condition interacted with age group, $F(4, 194) = 4.10$, $p = .004$, $\eta^2_G = .013$. Although all age groups responded faster with reliable than other precues ($ps<.038$), this difference was greater in adults than 6-year-olds ($p = .001$), with 9-year-olds differing marginally from 6-year-olds ($p = .061$) but not from adults ($p = .258$). Responses were overall faster in no-switch (7.42 log ms) than switch trials (7.46 log ms). However, trial type interacted with age group, $F(2, 97) = 3.97$, $p = .021$, $\eta^2_G = .001$. Adults and 6-year-olds showed significant switch costs (.03 and .07 log ms, respectively, $ps<.002$), but not

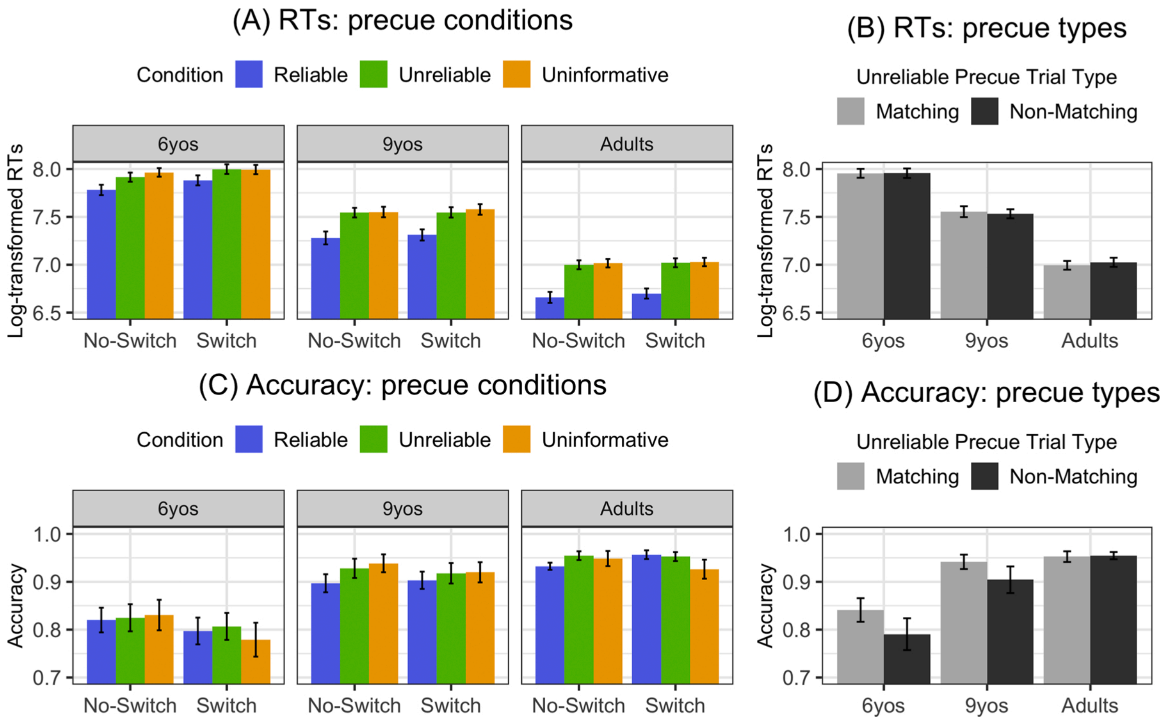

Fig. 2. Log-transformed response times (RTs) and accuracy. (A) RTs in the three precue conditions: all age groups responded faster with the reliable than the other precues, and the benefits from reliable precues increased with age. (B) RTs as a function of matching vs. non-matching unreliable precue trials. (C) Accuracy in the three precue conditions: switch costs decreased with age and informative precues. (D) Accuracy as a function of matching vs. non-matching unreliable precue trials: Only children showed signs of preparing based on unreliable precues (difference in accuracy on matching and non- matching trials). Error bars show standard errors.

9-year-olds (.02 log ms, $p = .111$). No other effects were significant, *ps*>.135.

Accuracy. Response accuracy increased across age group, $F(2, 97) = 15.74$, $p < .001$, $\eta^2_G = .179$, although the increase was significant from 6- to 9-year-olds (.81 vs. .92, $p < .001$) but not between 9-year-olds and adults (.95, $p = .098$). Collapsing across all age groups, accuracy was slightly higher in no-switch (.90) than switch trials (.88), $F(1, 97) = 12.95$, $p < .001$, $\eta^2_G = .002$. Trial type interacted with both age group, $F(2, 97) = 6.51$, $p = .002$, $\eta^2_G = .003$, and precue condition, $F(2, 194) = 6.35$, $p = .002$, $\eta^2_G = .003$. Six-year-olds showed significant switch costs (.03, $p < .001$) but not 9-year-olds or adults (.01 and <.01, respectively, *ps* >.178). In addition, switch costs were significant with uninformative precues (.03, $p < .001$), marginally significant with unreliable precues (.01, $p = .061$), but not with reliable precues (<.01, $p = 1$; Fig. 2). No other effects were significant, *ps*>.533.

Matching vs. non-matching unreliable precue trials. In the unreliable-precue condition, proactive preparation may be helpful on trials where the precue matched the actual cue but detrimental on trials where the precue and actual cue mismatched. Thus, proactive preparation in that condition would lead to a performance difference between matching and non-matching precue trials. Although no such difference was found for RTs (*ps*>.139), accuracy was higher when the precue and cue matched (.91) than when they mismatched (.88), $F(1, 97) = 9.29$, $p = .002$, $\eta^2_G = .181$, consistent with proactive preparation in the unreliable-precue condition. The interaction with age group was marginal, $F(2, 97) = 2.77$, $p = .067$, $\eta^2_G = .008$. The difference between precue trial types was significant in 6-year-olds (.05, $p = .011$), marginally significant in 9-year-olds (.04, $p = .053$) but not in adults (<.01, $p = .845$), potentially due to their relatively high levels of accuracy.

3.2. Pupil dilation as an index of cognitive effort

Change in pupil dilation varied as a function of precue condition, $F(2, 184) = 9.22$, $p < .001$, $\eta^2_G = .027$, due to greater change with reliable precues (1.04 %) than either unreliable or uninformative precues (0.42 % and 0.28 %, respectively), *ps*<.002, with no difference between the latter, $p = .970$ (Fig. 3). No other effects were significant, *ps*>.140.

3.3. ERPs

Posterior Positivity (PP) as an index of proactive task selection. The precue-locked PP amplitude varied across precue conditions, $F(2, 158) = 22.59$, $p < .001$, $\eta^2_G = .110$ (Fig. 4). It was greater with reliable precues (7.00 μV) than either unreliable or uninformative precues (4.34 μV and 3.40 μV, respectively), *ps*<.001, with no difference between the latter two, $p = .270$. No other effects were significant, *ps*>.946.

Contingent Negative Variation (CNV) as an index of motor preparation. There was a significant interaction between precue condition and age group, $F(4, 158) = 3.13$, $p = .016$, $\eta^2_G = .037$ (Fig. 5). In adults, precue-locked CNV amplitude was lower with reliable precues (-2.49 μV) than either unreliable or uninformative precues (-1.19 μV and -0.91 μV, respectively), *ps*<.033, with no difference between the latter two, $p = 1$, whereas no differences were observed in children, all *ps*>.140. No other effects were significant, *ps*>.284.

Pre-Response Negativity (PRN) as an index of reactive control. Precue condition and age group significantly interacted, $F(4, 154) = 3.08$, $p = .017$, $\eta^2_G = .030$ (Fig. 6). In adults, PRN amplitude was lower with uninformative (-3.57 μV) than reliable precues (-1.22 μV), $p = .018$, while unreliable precues (-3.04 μV) did not differ from the other precues, *ps*>.134. No differences reached significance in children, *ps*>.130. No other effects were significant, *ps*>.282.

3.4. Relations between response times, PP and CNV

Correlations among behavioural, pupil, and ERP indices broken down by age group and precue condition are provided in Appendix A. Only the correlation between PRN amplitudes and RTs with reliable precues in adults held after false discovery rate (FDR) correction, $r=-.68$,

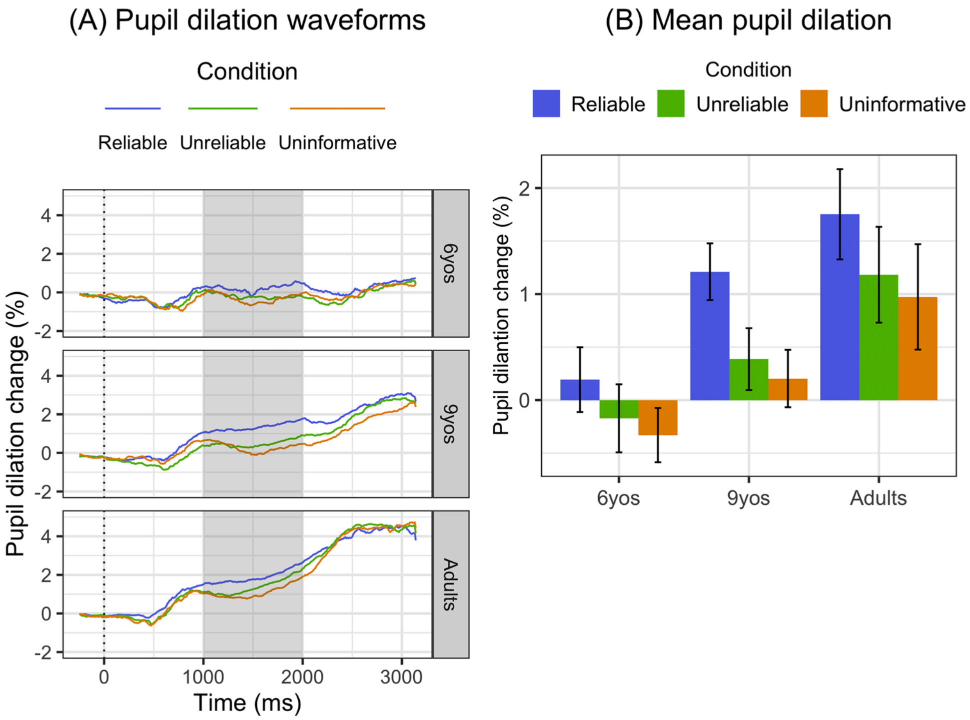

Fig. 3. Precue-locked pupil dilation change (%) as an index of cognitive effort. (A) Pupil dilation waveforms. The vertical dotted line indicates precue onset. The grey area indicates the time window for analysis. (B) Mean pupil dilation between 1000 and 2000 ms post precue onset. Error bars indicate standard errors. Pupil dilation was greater with the reliable than the other precues.

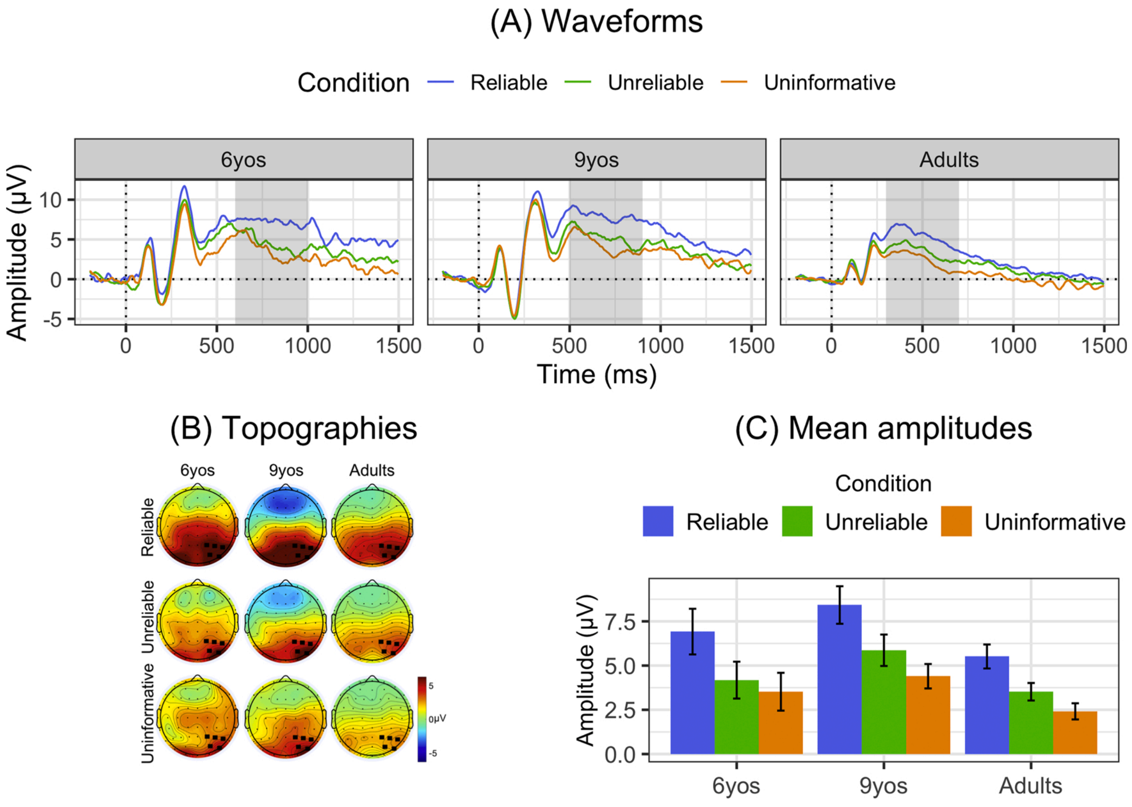

Fig. 4. Precue-locked posterior positivity as an index of proactive task selection. (A) Waveforms averaged across channels. The dotted vertical line indicates precue onset. The window used for statistical analysis is shown in grey. (B) Topographies. Mean amplitude over the window of interest for each age group. Black squares indicate the channels used to compute the posterior positivity (P2, P4, P6, PO4, PO8). (C) Mean amplitudes. Error bars indicate standard errors. Reliable precues yielded a more pronounced posterior positivity than the other precues.

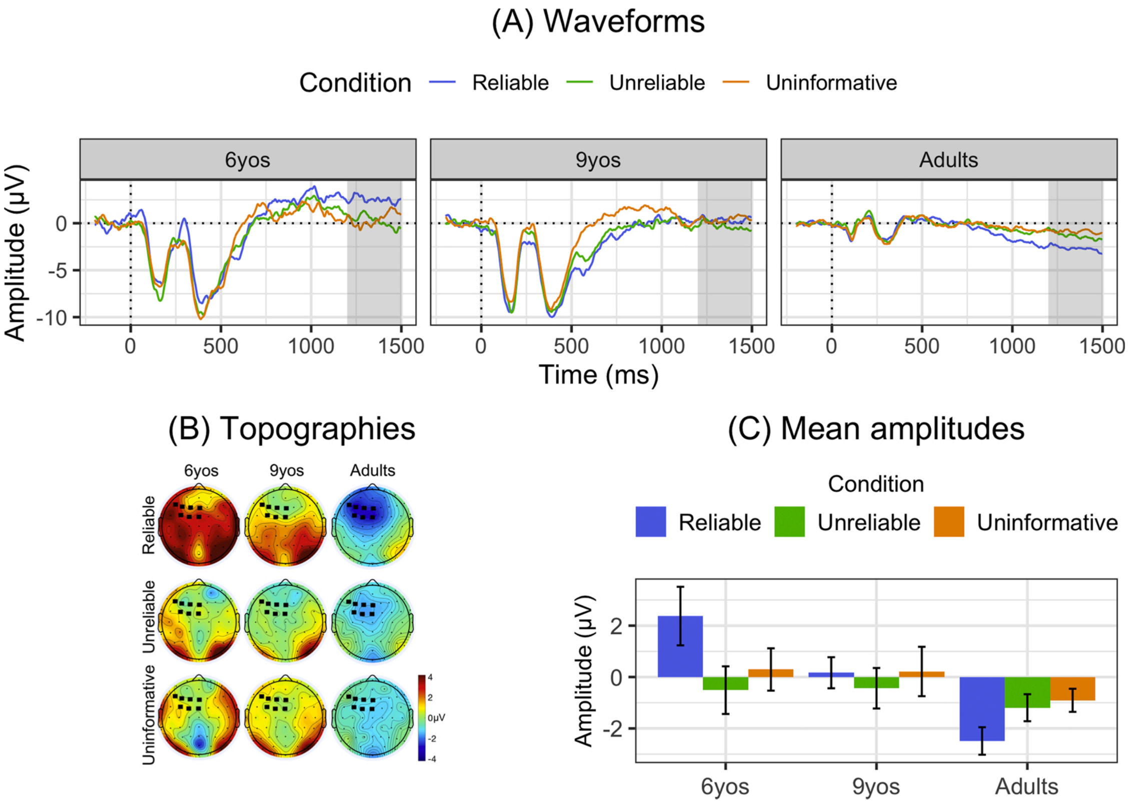

Fig. 5. Precue-locked contingent negative variation (CNV) as an index of motor preparation. (A) Waveforms averaged across channels. The dotted vertical line indicates precue onset. The window used for statistical analysis is shown in grey. (B) Topographies. Mean amplitude over the window of interest for each age group. Black squares indicate the channels used to compute the CNV (F5, F3, F1, Fz, FC3, FC1, FCz). (C) Mean amplitudes. Error bars indicate standard errors. Reliable precues yielded a more pronounced CNV than the other precues in adults only.

$p < .001$, suggesting that when adults proactively prepared with reliable precues, less reactive control engagement was associated with faster responses. A mixed model was run to examine whether PP and CNV amplitudes predicted RTs. Besides the effects of condition, age group, and condition × age group, *ps*<.012, PP interacted with condition, LRT $\chi^2(2) = 6.87$, $p = .032$, and CNV with age group, LRT $\chi^2(2) = 10.78$, $p = .004$, More pronounced PP amplitudes predicted faster RTs with reliable precues (β=-.086, $p = .023$) but not other precues (*ps*>.777). More pronounced CNV amplitudes predicted faster RTs in adults (β=-.105, $p = .011$), but not in children (*ps*>.091). Finally, RTs tended to be fastest when both PP and CNV were pronounced, LRT $\chi^2(1) = 3.49$, $p = .062$ (Fig. 7). No other effects were significant, *ps*>.284.

3.5. Metacognitive questions

Answers to the three metacognitive questions are provided in Table 1. Overall, participants preferred playing with the reliable elf (43 %), $\chi^2(1) = 4.08$, $p = .043$, with no differences across age groups, $\chi^2(4) = 4.22$, $p = .377$. Regarding the elf they disliked playing with, although differences across age groups did not reach significance, $\chi^2(4) = 8.36$, $p = .079$, 6-year-olds disliked the uninformative elf significantly more than chance (63 %), $\chi^2(1) = 12.79$, $p < .001$, whereas older age groups' choices did not differ from chance, *ps*>.138. Finally, participants identified the reliable elf as the easiest to play with significantly more than chance (70 %), $\chi^2(1) = 60.26$, $p < .001$, with no differences across age groups, $\chi^2(4) = 1.98$, $p = .738$.

4. Discussion

The present study examined age-related changes in adaptiveness of proactive control engagement as a function of precue reliability in 6- and 9-year-olds and adults, and yielded two main findings. First, all age groups showed adaptiveness in proactive control engagement as function of precue reliability. Specifically, they adaptively engaged proactive control with reliable but not unreliable precues, as evidenced by more pronounced precue-locked pupil dilation and posterior positivity with reliable than unreliable and uninformative precues. Consistently, the vast majority of participants in all age groups correctly identified the reliable-precue (and not the unreliable-precue) condition as the easiest. Second, when participants did engage proactive control, children, especially 6-year-olds, did so less efficiently than adults. They showed no evidence of CNV while preparing for the upcoming target (unlike adults), less subsequent variation in reactive control engagement after target onset, and a smaller reduction of response times with reliable precues than in adults.

Thus, even 6-year-olds, who have just transitioned to engaging proactive control (e.g., Lucenet and Blaye, 2014), could use precue reliability to tailor cognitive control engagement. This is especially remarkable given children's difficulty processing and monitoring for contextual cues (Chevalier and Blaye, 2009; Chevalier et al., 2014; Church et al., 2017). These findings show that children can already use *contingencies* between contextual cues and tasks. They may build on early developing use of contextual cue reliability to subsequently process and monitor for contextual cues with growing efficiency. Indeed, infants show efficient implicit learning of statistical regularities in the environment (Aslin and Newport, 2012; Saffran et al., 1996) and are not only sensitive to contingencies between events but can also use this information to derive expectations about people's actions (e.g., Johnson et al., 2010). As proactive control is advantageous only if one can reliably anticipate upcoming events, some form of sensitivity and use of contextual cue reliability may be needed for spontaneous engagement of proactive control to emerge during childhood.

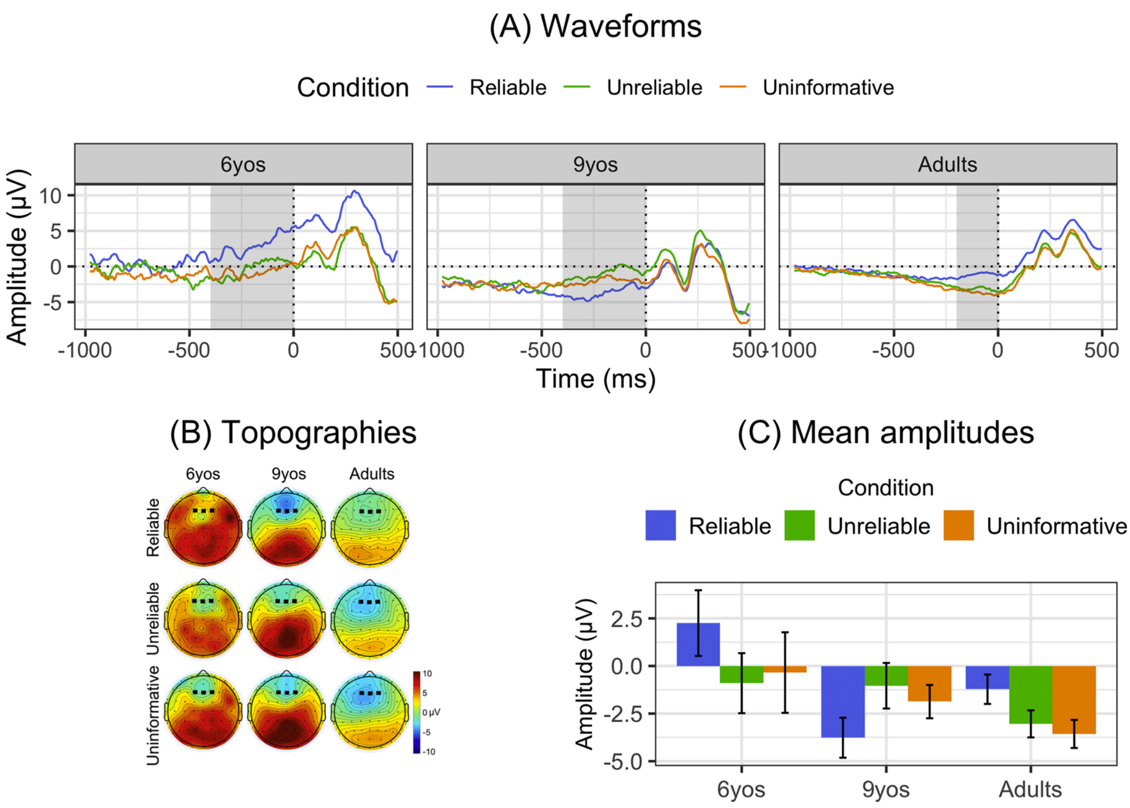

Fig. 6. Response-locked pre-response negativity (PRN) as an index of reactive control. (A) Waveforms averaged across channels. The dotted vertical line indicates the response. The window used for statistical analysis is shown in grey. (B) Topographies. Mean amplitude over the window of interest for each age group. Black squares indicate the channels used to compute the PRN (F1, Fz, F2). (C) Mean amplitudes. Error bars indicate standard errors. The PRN was significantly less marked with reliable precues in adults only.

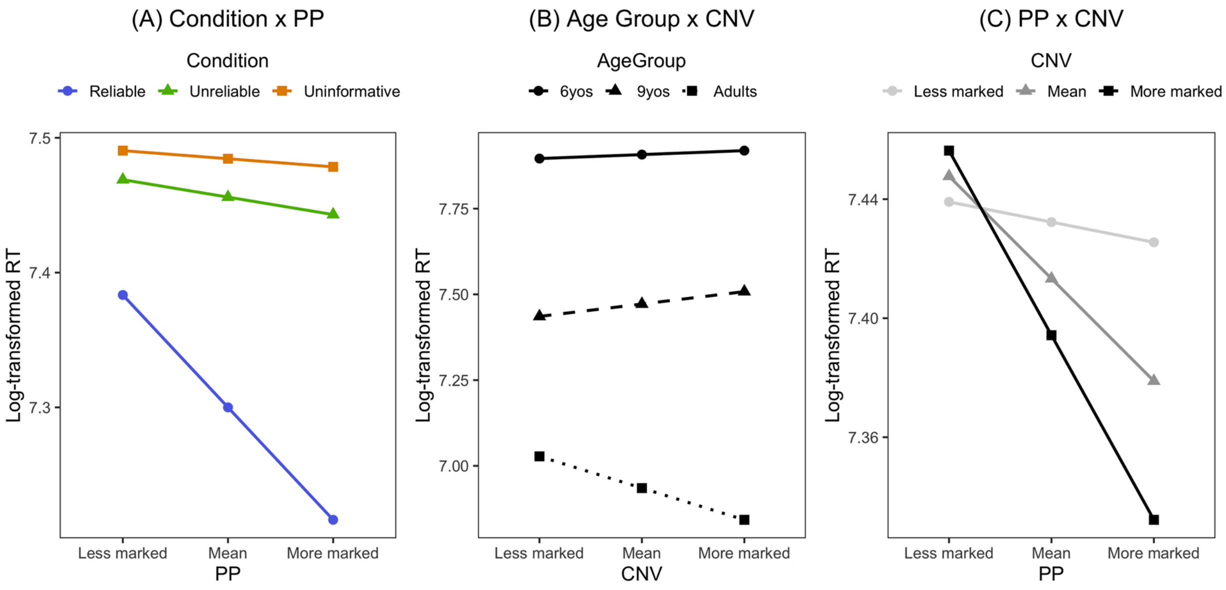

Fig. 7. Predicted log-transformed response times (RT) as a function of posterior positivity (PP) and contingent negative variation (CNV) amplitudes. (A) A more pronounced posterior positivity predicted faster RTs with reliable precues. (B) A more pronounced CNV predicted faster RTs in adults. (C) RTs tended to be fastest when both the PP and CNV were pronounced. Less marked = 1 *SD* below the mean. More marked = 1 *SD* above the mean.

However, although even 6-year-olds showed evidence of adaptive proactive control engagement, this adaptiveness may refine with age, as 6-year-olds and to a lesser extent 9-year-olds (but not adults) responded more accurately when the unreliable precue and the actual cue matched than when they mismatched. As proactive preparation would be advantageous in the former and disadvantageous in the latter, the performance difference between the two types of trial may hint at some proactive processing of the unreliable precues in childhood, even though a reactive approach is more adaptive with such cues. Moreover, unlike older children and adults, a majority of 6-year-olds disliked the uninformative precues the most, perhaps reflecting limited metacognitive awareness of the misleading nature of the unreliable precues. However,

Table 1
Percentages of participants selecting reliable, unreliable or uninformative precues for each metacognitive question (numbers of participants are shown in parenthesis).

Question	Age Group	Precue Condition		
		Reliable	Unreliable	Uninformative
Did you like playing with any of these elves best?	6-year-olds	51 % (18)	29 % (10)	20 % (7)
	9-year-olds	41 % (13)	18 % (6)	41 % (13)
	Adults	36 % (12)	28 % (9)	36 % (12)
Did you dislike playing with any of these elves?	6-year-olds	20 % (7)	17 % (6)	63 % (22)
	9-year-olds	22 % (7)	31 % (10)	47 % (15)
	Adults	24 % (8)	46 % (15)	30 % (10)
Do you think it was easier to play with one of these elves?	6-year-olds	78 % (27)	11 % (4)	11 % (4)
	9-year-olds	62 % (20)	19 % (6)	19 % (6)
	Adults	70 % (23)	12 % (4)	18 % (6)

as the interactions with age were only marginal and there was no similar trend for RTs, these findings should be interpreted with caution at this stage.

Furthermore, explicitly informing participants about precue reliability in the present study may have favoured adaptiveness in proactive control engagement, especially in children. Preschoolers do not seem to be aware of and use variations in task demands to optimize their performance (Niebaum et al., 2019; O'Leary and Sloutsky, 2017, 2019). Yet, they can use this information when it is explicitly communicated to them (Niebaum and Munakata, 2020; O'Leary and Sloutsky, 2017). Although there are reasons to expect lower adaptiveness in proactive control engagement when children need to infer contextual cue reliability from experience, this issue will need to be directly examined in the future. In addition, how children (and adults) use contextual cue reliability to adjust proactive control engagement may depend on the order in which they experience cues of varying reliability. For instance, people may (maladaptively) try to engage proactive control with unreliable precues if they experience these precues first, before situations where proactive control is clearly adaptive (reliable precues) or maladaptive (uninformative precues), whereas greater adaptiveness may be observed when unreliable precues are experienced last. As our sample size was not large enough to examine potential effects of precue condition order, this possibility will need to be addressed in a future study.

Although children engaged proactive control when this control mode was adaptive, their proactive preparation was less efficient than in adults, as the RT advantage of proactive preparation increased across age groups. Critically, the partially different patterns of ERPs across age groups shed new light on why proactive preparation is less efficient in children. The posterior positivity was enhanced with reliable cues and predicted faster responses in all three age groups, but only adults subsequently showed a marked CNV before target onset. These two components reflect different cognitive processes and indeed each uniquely predicted response times in adults. The posterior positivity is robustly observed during the cue-target interval in the cued task switching paradigm in both children and adults and likely reflects proactive task selection (Chevalier et al., 2015; Elke and Wiebe, 2017; Karayanidis et al., 2013; Manzi et al., 2011). In contrast, the CNV is observed in various paradigms (e.g., Hämmerer et al., 2010; Kray et al., 2005; Pauletti et al., 2014) but not as systematically as the posterior positivity in the cued task-switching paradigm (Kang et al., 2014). It has been associated with activity in the supplementary motor area and is thought to reflect motor preparation such as task-relevant stimulus-response mapping activation (Forstmann et al., 2007; Nagai et al., 2004; Rektor et al., 2004). Motor preparation seems to develop late in this paradigm as the CNV is still less pronounced in adolescents than adults (Killikelly and Szűcs, 2013).

Thus, children seem to have engaged only partial proactive preparation, selecting the relevant task but not preparing the motor responses (i.e., getting ready to press one of the two task-relevant buttons) accordingly ahead of target onset. Consistently, they showed less variation in PRN amplitude across conditions, suggesting that proactive preparation with reliable precues alleviated less the need for control after target onset in children than adults. The PRN in children should be interpreted with caution, though, as children have a greater tendency than adults to look at their hands while responding, creating more artefacts around the response, hence reducing signal-to-noise ratios and potentially the chance to detect PRN variations across conditions. In adults, a more pronounced CNV (i.e., greater motor preparation before target onset) was indeed associated with a less pronounced PRN (i.e., less reactive control after target onset) and in turn both were associated with faster RTs, further suggesting proactive motor preparation contributed to proactive control efficiency. These findings show that proactive control is less efficient in childhood because children do not proactively prepare in all the ways that adults do (and not just because they are less consistent in proactive task selection across trials). Growing efficiency of proactive control likely contributes to more frequent use of this control mode with age.

Why did children not engage in proactive motor preparation? One possibility is that they simply did not have enough time. Although this cannot be ruled out, it seems unlikely given that children often do not fully prepare even when they are given as long as they want before triggering the target (Chevalier and Blaye, 2016). Alternatively, anticipating the benefit of early motor preparation may require more metacognitive reflection than selection of the relevant task, as the (pre)cue directly relates to the relevant task but only indirectly to responses. As metacognition develops (e.g., Roebers, 2017), children may better recognize the additional benefit of proactive motor preparation. Finally, children may not yet have enough working memory resources for full proactive preparation, making proactive control more cognitively demanding, less efficient to implement and less behaviourally advantageous than in adults. Therefore, children may have a higher threshold to engage this control mode. Consistently, when given the choice between versions of the task-switching paradigm in which the cue was presented either ahead of or on target onset, hence encouraging proactive or reactive control, respectively, children either showed no preference or preferred the version allowing reactive control, whereas adults favoured proactive control (Niebaum et al., 2020). Indeed, proactive control development closely relates to working memory development during childhood (Gonthier et al., 2019; Kubota et al., 2020; Troller-Renfree et al., 2020), and age-related gains in both proactive control and working memory performance relate to increasing frontostriatal connectivity with age (Rubia et al., 2006; Vink et al., 2014).

In conclusion, the present study reported evidence for early adaptiveness in proactive control engagement as a function of contextual cue reliability and potential refinement with age, and showed that less efficient proactive control in children relates to a lack of motor preparation in the cued task- switching paradigm. The early emerging ability to tailor cognitive control engagement as a function of contextual cue reliability may play an important role in the spontaneous use of proactive control that children start to demonstrate from 6 years of age. Growing efficiency of proactive preparation likely contributes to increasing engagement of proactive control with age.

Note

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.dcn.2020.100870.

References

Aslin, R.N., Newport, E.L., 2012. Statistical learning: from acquiring specific items to forming general rules. Curr. Dir. Psychol. Sci. 21 (3), 170–176. https://doi.org/10.1177/0963721412436806.

Barker, J.E., Munakata, Y., 2015. Time isn't of the essence: activating goals rather than imposing delays improves inhibitory control in children. Psychol. Sci. 26 (12), 1898–1908. https://doi.org/10.1177/0956797615604625.

Baum, G.L., Ciric, R., Roalf, D.R., Gur, R.C., Bassett, D.S., Satterthwaite, T.D., et al., 2017. Modular segregation of structural brain networks supports the development of executive function in youth. Curr. Biol. 27, 1–12. https://doi.org/10.1016/j.cub.2017.04.051.

Beatty, J., 1982. Task-evoked pupillary responses, processing load, and the structure of processing resources. Psychol. Bull. 91 (2), 276–292. https://doi.org/10.1037/0033-2909.91.2.276.

Braver, T.S., 2012. The variable nature of cognitive control: a dual mechanisms framework. Trends Cogn. Sci. (Regul. Ed.) 16 (2), 106–113. https://doi.org/10.1016/j.tics.2011.12.010.

Chatham, C.H., Frank, M.J., Munakata, Y., 2009. Pupillometric and behavioral markers of a developmental shift in the temporal dynamics of cognitive control. Proc. Natl. Acad. Sci. U. S. A. 106 (14), 5529–5533. https://doi.org/10.1073/pnas.0810002106.

Chevalier, N., Blaye, A., 2009. Setting goals to switch between tasks: effect of cue transparency on children's cognitive flexibility. Dev. Psychol. 45 (3), 782–797. https://doi.org/10.1037/a0015409.

Chevalier, N., Blaye, A., 2016. Metacognitive monitoring of executive control engagement during childhood. Child Dev. 87 (4), 1264–1276. https://doi.org/10.1111/cdev.12537.

Chevalier, N., Chatham, C.H., Munakata, Y., 2014. The practice of going helps children to stop: the importance of context monitoring in inhibitory control. J. Exp. Psychol. Gen. 143 (3), 959–965. https://doi.org/10.1037/a0035868.

Chevalier, N., Martis, S.B., Curran, T., Munakata, Y., 2015. Metacognitive processes in executive control development: the case of reactive and proactive control. J. Cogn. Neurosci. 27 (6), 1125–1136. https://doi.org/10.1162/jocn.

Church, J.A., Bunge, S.A., Petersen, S.E., Schlaggar, B.L., 2017. Preparatory engagement of cognitive control networks increases late in childhood. Cereb. Cortex 27 (3), 2139–2153. https://doi.org/10.1093/cercor/bhw046.

Cooper, P.S., Wong, A.S.W., McKewen, M., Michie, P.T., Karayanidis, F., 2017. Frontoparietal theta oscillations during proactive control are associated with goal-updating and reduced behavioral variability. Biol. Psychol. 129 (September), 253–264. https://doi.org/10.1016/j.biopsycho.2017.09.008.

Crone, E.A., Steinbeis, N., 2017. Neural perspectives on cognitive control development during childhood and adolescence. Trends Cogn. Sci. (Regul. Ed.) xx, 1–11. https://doi.org/10.1016/j.tics.2017.01.003.

Czernochowski, D., 2014. ERPs dissociate proactive and reactive control: evidence from a task-switching paradigm with informative and uninformative cues. Cogn. Affect. Behav. Neurosci. 15 (1), 117–131. https://doi.org/10.3758/s13415-014 -0302-y.

Delorme, A., Makeig, S., 2004. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. J. Neurosci. Methods 134 (1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009.

Eckstein, M.K., Guerra-carrillo, B., Miller, A.T., Bunge, S.A., 2017. Beyond eye gaze: what else can eyetracking reveal about cognition and cognitive development? Dev. Cogn. Neurosci. 25, 69–91. https://doi.org/10.1016/j.dcn.2016.11.001.

Elke, S., Wiebe, S.A., 2017. Proactive control in early and middle childhood: an ERP study. Dev. Cogn. Neurosci. 26 (April), 28–38. https://doi.org/10.1016/j.dcn.2017.04.005.

Forstmann, U.B., Ridderinkhof, K.R., Kaiser, J., Bledowski, C., 2007. At your own peril: an ERP study of voluntary task set selection processes. Cogn. Affect. Behav. Neurosci. 7 (4), 286–296.

Gonthier, C., Zira, M., Colé, P., Blaye, A., 2019. Evidencing the developmental shift from reactive to proactive control in early childhood and its relationship to working memory. J. Exp. Child Psychol. 177, 1–16. https://doi.org/10.1016/j.jecp.2018.07.001.

Hadley, L.V., Acluche, F., Chevalier, N., 2020. Encouraging performance monitoring promotes proactive control in children. Dev. Sci. (May), e12861 https://doi.org/10.1111/desc.12861.

Hämmerer, D., Li, S.C., Müller, V., Lindenberger, U., 2010. An electrophysiological study of response conflict processing across the lifespan: assessing the roles of conflict monitoring, cue utilization, response anticipation, and response suppression. Neuropsychologia 48 (11), 3305–3316. https://doi.org/10.1016/j.neuropsychologia.2010.07.014.

Jin, X., Auyeung, B., Chevalier, N., 2020. Positive emotion and reward motivation promote different cognitive control engagement strategies in children. Dev. Cogn. Neurosci. 44, 100806 https://doi.org/10.1016/j.dcn.2020.100806.

Johnson, S.C., Dweck, C.S., Chen, F.S., Stern, H.L., Ok, S.J., Barth, M., 2010. At the intersection of social and cognitive development: internal working models of attachment in infancy. Cogn. Sci. 34 (5), 807–825. https://doi.org/10.1111/j.1551-6709.2010.01112.x.

Kang, M.S., DiRaddo, A., Logan, G.D., Woodman, G.F., 2014. Electrophysiological evidence for preparatory reconfiguration before voluntary task switches but not cued task switches. Psychon. Bull. Rev. 21 (2), 454–461. https://doi.org/10.3758/s13423-013 -0499-8.

Karayanidis, F., Mansfield, E.L., Galloway, K.L., Smith, J.L., Provost, A., Heathcote, A., 2009. Anticipatory reconfiguration elicited by fully and partially informative cues that validly predict a switch in task. Cogn. Affect. Behav. Neurosci. 9 (2), 202–215. https://doi.org/10.3758/CABN.9.2.202.

Karayanidis, F., Jamadar, S., Sanday, D., 2013. Stimulus-level interference disrupts repetition benefit during task switching in middle childhood. Front. Hum. Neurosci. 7 (December), 841. https://doi.org/10.3389/fnhum.2013.00841.

Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A.M., Koch, I., 2010. Control and interference in task switching—A review. Psychol. Bull. 136 (5), 849–874. https://doi.org/10.1037/a0019842.

Killikelly, C., Szűcs, D., 2013. Delayed development of proactive response preparation in adolescents: ERP and EMG evidence. Dev. Cogn. Neurosci. 3, 33–43. https://doi.org/10.1016/j.dcn.2012.08.002.

Kool, W., McGuire, J.T., Rosen, Z.B., Botvinick, M.M., 2010. Decision making and the avoidance of cognitive demand. J. Exp. Psychol. Gen. 139 (4), 665–682. https://doi.org/10.1037/a0020198.

Kray, J., Eppinger, B., Mecklinger, A., 2005. Age differences in attentional control: an event-related potential approach. Psychophysiology 42 (4), 407–416. https://doi.org/10.1111/j.1469-8986.2005.00298.x.

Kubota, M., Hadley, L.V., Schaeffner, S., Könen, T., Meaney, J.A., Auyeung, B., et al., 2020. Consistent use of proactive control and relation with academic achievement in childhood. Cognition 203 (May). https://doi.org/10.1016/j.cognition.2020.104329.

Lewis-Peacock, J.A., Cohen, J.D., Norman, K.A., 2016. Neural evidence of the strategic choice between working memory and episodic memory in prospective remembering. Neuropsychologia 93 (November), 280–288. https://doi.org/10.1016/j.neuropsychologia.2016.11.006.

Lopez-Calderon, J., Luck, S.J., 2014. ERPLAB: an open- source toolbox for the analysis of event-related potentials. Front. Hum. Neurosci. 8 (1 APR), 1–14. https://doi.org/10.3389/fnhum.2014.00213.

Lucenet, J., Blaye, A., 2014. Age-related changes in the temporal dynamics of executive control: a study in 5- and 6-year-old children. Front. Psychol. 5 (July), 1–11. https://doi.org/10.3389/fpsyg.2014.00831.

Mäki-Marttunen, V., Hagen, T., Espeseth, T., 2019. Task context load induces reactive cognitive control: an fMRI study on cortical and brain stem activity. Cogn. Affect. Behav. Neurosci. 19 (4), 1094. https://doi.org/10.3758/s13415-019-00701-7.

Manzi, A., Nessler, D., Czernochowski, D., Friedman, D., 2011. The development of anticipatory cognitive control processes in task-switching: an ERP study in children, adolescents, and young adults. Psychophysiology 48 (9), 1258–1275. https://doi.org/10.1111/j.1469-8986.2011.01192.x.

Mognon, A., Jovicich, J., Bruzzone, L., Buiatti, M., 2011. ADJUST: an automatic EEG artifact detector based on the joint use of spatial and temporal features. Psychophysiology 48 (2), 229–240. https://doi.org/10.1111/j.1469-8986.2010.01061.x.

Mueller, S.C., Swainson, R., Jackson, G.M., 2007. Behavioural and neurophysiological correlates of bivalent and univalent responses during task switching. Brain Res. 1157, 56–65. https://doi.org/10.1016/j.brainres.2007.04.046.

Nagai, Y., Critchley, H.D., Featherstone, E., Fenwick, P.B.C., Trimble, M.R., Dolan, R.J., 2004. Brain activity relating to the contingent negative variation: an fMRI investigation. NeuroImage 21 (4), 1232–1241. https://doi.org/10.1016/j.neuroimage.2003.10.036.

Nicholson, R., Karayanidis, F., Poboka, D., Heathcote, A., Michie, P.T., 2005. Electrophysiological correlates of anticipatory task-switching processes. Psychophysiology 42 (5), 540–554. https://doi.org/10.1111/j.1469-8986.2005.00350.x.

Niebaum, J.C., Munakata, Y., 2020. Deciding what to do: developments in children's spontaneous monitoring of cognitive demands. Child Dev. Perspect.

Niebaum, J.C., Chevalier, N., Guild, R.M., Munakata, Y., 2019. Adaptive control and the avoidance of cognitive control demands across development. Neuropsychologia 123 (April 2018), 152–158. https://doi.org/10.1016/j.neuropsychologia.2018.04.029.

Niebaum, J.C., Chevalier, N., Guild, R., Munakata, Y., 2020. Developing adaptive control: age-related differences in task choices and awareness of proactive and reactive control demands. Cogn. Affect. Behav. Neurosci. https://doi.org/10.3758/s13415-020-00832-2 in press.

O'Leary, A.P., Sloutsky, V.M., 2017. Carving metacognition at its joints: protracted development of component processes. Child Dev. 88 (3), 1015–1032. https://doi.org/10.1111/cdev.12644.

O'Leary, A.P., Sloutsky, V.M., 2019. Components of metacognition can function independently across development. Dev. Psychol. 55 (2), 315–328. https://doi.org/10.1037/dev0000645.

Olejnik, S., Algina, J., 2003. Generalized eta and omega squared statistics: measures of effect size for some common research designs. Psychol. Methods 8 (4), 434–447. https://doi.org/10.1037/1082-989X.8.4.434.

Pauletti, C., Mannarelli, D., Grippo, A., Currà, A., Locuratolo, N., De Lucia, M.C., Fattapposta, F., 2014. Phasic alertness in a cued double-choice reaction time task: a Contingent Negative Variation (CNV) study. Neurosci. Lett. 581, 7–13. https://doi.org/10.1016/j.neulet.2014.07.059.

Rektor, I., Bareš, M., Kaňovský, P., Brázdil, M., Klajblová, I., Streitová, H., et al., 2004. Cognitive potentials in the basal ganglia - frontocortical circuits. An intracerebral recording study. Exp. Brain Res. 158 (3), 289–301. https://doi.org/10.1007/s00221-004-1901-6.

Roebers, C.M., 2017. Executive function and metacognition: towards a unifying framework of cognitive self-regulation. Dev. Rev. 45, 31–51. https://doi.org/10.1016/j.dr.2017.04.001.

Rubia, K., Smith, A.B., Woolley, J., Nosarti, C., Heyman, I., Taylor, E., Brammer, M., 2006. Progressive increase of frontostriatal brain activation from childhood to adulthood during event-related tasks of cognitive control. Hum. Brain Mapp. 27 (12), 973–993. https://doi.org/10.1002/hbm.20237.

Saffran, J.R., Aslin, R.N., Newport, E.L., 1996. Statistical learning by 8-months-old infants. Science 274 (5294), 1926–1928. https://doi.org/10.1126/science.274.5294.1926.

Towse, J.N., Lewis, C., Knowles, M., 2007. When knowledge is not enough: the phenomenon of goal neglect in preschool children. J. Exp. Child Psychol. 96, 320–332. https://doi.org/10.1016/j.jecp.2006.12.007.

Troller-Renfree, S.V., Buzzell, G.A., Fox, N.A., 2020. Changes in working memory influence the transition from reactive to proactive cognitive control during childhood. Dev. Sci. (February), 1–9. https://doi.org/10.1111/desc.12959.

Vandierendonck, A., Liefooghe, B., Verbruggen, F., 2010. Task switching: interplay of reconfiguration and interference control. Psychol. Bull. 136 (4), 601–626. https://doi.org/10.1037/a0019791.

Vink, M., Zandbelt, B.B., Gladwin, T., Hillegers, M., Hoogendam, J.M., van den Wildenberg, W.P.M., et al., 2014. Frontostriatal activity and connectivity increase during proactive inhibition across adolescence and early adulthood. Hum. Brain Mapp. 35 (9), 4415–4427. https://doi.org/10.1002/hbm.22483.