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Qualitative change in executive control during childhood and adulthood

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Abstract

Executive control development typically has been conceptualized to result from quantitative changes in the efficiency of the underlying processes. In contrast, the present study addressed the possibility of qualitative change with age by examining how children and adults detect task switches. Participants in three age groups (5- and 10-year-old children, young adults) completed two conditions of a cued task-switching paradigm where task cues were presented either in isolation or in conjunction with transition cues. Five-year-olds performed better with transition cues, whereas the reverse effect was observed at age 10 and with adults. Unlike 5-year-olds who detect switches after semantically processing cues, older participants strategically detect switches based on perceptual processing only. Age-related qualitative changes promote increasingly optimal adjustment of executive resources with age.

Keywords

executive control; strategy; development; set-shifting; working memory

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1. Introduction

Over the last few decades, executive control, also referred to as cognitive control or executive function, has emerged as a major topic in cognitive science. Such interest arises largely from the necessity to control one's own thoughts and actions to carry out many everyday-life activities such as reading, driving, or even crossing the street. In this context, the development of executive control during childhood has attracted substantial scientific attention because the developmental dynamics of executive processes have the potential to shed new light on later regulatory processes as well as academic achievement, social competence and problem behaviors during childhood (Blair & Razza, 2007; Bull, Espy, Wiebe, Sheffield, & Nelson, 2011; Espy, Wiebe, Sheffield, Clark, & Moehr, 2011; Fuhs & Day, 2010). Implicit in most investigations heretofore is the assumption that executive control development reflects *quantitative* changes with advancing age; that is, at any age individuals exert control using the same processes and strategies that only improve in efficiency with age. In contrast, the present study investigates whether there are potential qualitative differences in executive control in childhood and early adulthood.

There are reasons to suspect that qualitative changes may play a role in executive control development. At the brain level, executive processes are supported by an extensive neural network that includes the prefrontal cortex (PFC) and basal ganglia (e.g., Aron, Robbins, & Poldrack, 2004; O'Reilly, 2006), and development is largely driven by PFC maturation (Munakata, Chatham, & Snyder, in press; Moriguchi & Hiraki, 2011). Given that PFC is the latest brain region to reach maturity, peaking in cortical thickness around 10.5 years of age (Shaw et al., 2008; Sowell et al., 2004), it is not surprising that executive control follows a protracted developmental trajectory through late adolescence or early adulthood (e.g., Best, Miller, & Jones, 2009; Garon, Bryson, & Smith, 2008). In addition to changing patterns of brain activation associated with executive control with age (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Durston et al., 2002; Durston et al., 2006; Morton, Bosma, & Ansari, 2009), gains in executive control have been hypothesized to result not only from PFC maturation, but from reorganization and specialization of brain regions with age, possibly through increasing connectivity between PFC and posterior regions (Crone & Ridderinkhof, 2010; Edin, Macoveanu, Olesen, Tegnér, & Klingberg, 2007; Johnson, 2011). These findings are compatible with qualitative cognitive changes occurring during childhood.

At the behavioral level, the factor structure of executive control likely changes with age, from a unitary structure at preschool age (Wiebe, Espy, & Charak, 2008; Wiebe et al., 2011; Willoughby et al., 2010) to multiple components observed at school age and in adulthood (e.g., Huizinga, Dolan, & van der Molen, 2006; Miyake et al., 2000; Shing, Lindenberger, Diamond, Li, & Davidson, 2010). Such structural changes may in turn result in qualitatively different control strategies with age. However, age-related, structural and brain-activation differences suggest but are not sufficient to indicate qualitative differences at the functional level insofar as (1) different patterns of brain activation with age may support the same cognitive processes and strategies, and (2) identical or partially differentiated processes across situations taxing executive control may still underlie implementation of the same underlying cognitive strategies. Stronger evidence for qualitatively different approaches would come from differential effects of experimentally manipulated variables with age.

To exert efficient control, one must first identify and activate the relevant goal to be reached because such goals guide cognitive activity towards appropriate behavior (e.g., Miller & Cohen, 2001). Goal activation is such a central aspect of executive control that it drives the relations among major forms of control (i.e. response inhibition, shifting, working memory maintenance) over the preschool years (Chevalier et al., 2012). Goals are identified through processing of available contextual cues. Contextual cue processing recently has been argued to constitute the principal prefrontally mediated ability underlying executive control (Chatham et al., 2012; Munakata et al., 2011). Therefore, children's processing of contextual cues to activate goals and potential qualitative changes regarding this ability with age are of prime interest for understanding control development.

The task-switching paradigm is particularly appropriate to further investigate this issue because it necessitates changing the relevant goal frequently. More precisely, this paradigm requires participants to switch back and forth between two tasks (e.g., indicating the color or shape of bidimensional cartoon characters) usually as a function of a task cue, that is, a visual cue signaling the relevant task (e.g., a hat on top of the stimulus if color is relevant, a cap if shape is relevant). The ability to switch back and forth on this type of paradigm emerges around 5 years of age and continues to improve through late adolescence, as shown by the reduction in switch cost (i.e., lower accuracy and longer response times on task switch than task repetition trials) with age (e.g., Cepeda, Kramer, & Gonzalez de Sather, 2001; Cragg & Nation, 2009; Espy, 1997).

Performance on the task-switching paradigm relies critically on task cue processing, as evidenced by better switching performance when task cues bear strong semantic associations with each task, relative to arbitrary cue-task associations (e.g. Miyake, Emerson, Padilla, & Ahn, 2004). Task cue processing is even more taxing for preschoolers (Blaye & Chevalier, 2011; Chevalier & Blaye, 2009), making it especially challenging for them to extract goal information, notably the necessity to switch task goals, on the basis of such cues. Indeed, preschoolers perform better on switch trials when they are given direct information on the necessity to switch or repeat the same task, through transition cues like "different" and "same", in addition to task cues (Chevalier, Wiebe, Huber, & Espy, 2011). This finding confirms that preschoolers struggle to detect task switches when only task cues (associated with task identity) are available, probably because preschoolers need to process task cues semantically, which they often fail to do, in order to infer the necessity to switch.

The efficiency of switch detection likely increases during childhood because individuals semantically process task cues with increasing efficiency with age, granting them easier access to the relevant task goal and, as a consequence, easier inference of the necessity to switch. Therefore, like preschoolers, older children and adults may detect switches by semantically processing task cues on every trial, but they do so in a more efficiently way. Although transition cues used in isolation yield greater switch costs (Forstman, Brass, Koch, & Von Cramon, 2005), they have never been tested in combination with task cues in adults. This "quantitative-change" hypothesis predicts that the beneficial effect of transition cues should progressively diminish with age because semantic processing of task cues becomes so efficient that direct information on the necessity to switch is no longer necessary.

Alternatively, older children and adults may take a qualitatively different approach to switch detection consisting in strategically processing task cue dissimilarity across trials, because such dissimilarity is predictive of a task switch (as opposed to stimulus dissimilarity that varies randomly across trial types). They may assume by default that the previously performed task will repeat, unless there is a visual mismatch between the current task cue and the previous one maintained in working memory. If so, task switches would be detected *before* semantic processing of task cues for these individuals. Such a “perceptual cue mismatch” strategy allows the participant to allocate extra control resources to semantic processing of task cues only when a perceptual mismatch is detected, thus functioning more economically on the other trials (see Monsell & Mizon, 2006). This strategy seems common in adulthood given that performance costs are observed on trials where cues change despite task repetition, suggesting that perceptual cue change misleads adults into false switch detection (Monsell & Mizon, 2006; Logan & Schneider, 2006). Although the perceptual cue mismatch strategy seems efficient and economical, it places high demands on working memory (to maintain task cue information from the previous trials) and requires strategic processing of task cues, hence likely becoming more advantageous as working memory resources increase with age (Gathercole, Pickering, Ambridge, & Wearing, 2004).

The perceptual cue mismatch strategy is optimal when one task cue is associated with each task because any perceptual change in task cue necessarily signals a task change too. Transition cues, however, may interfere with this strategy because they reduce the overall perceptual dissimilarity of switch trials relative to prior trials, hence potentially influencing the outcome of the perceptual cue mismatch strategy. More precisely, when task switches and repetitions are signaled by transition cues, four types of transition can be distinguished (Figure 1): (1) *complete change* where both the transition cue and the relevant task change (from a “same” no-switch trial to a “different” switch trial), (2) *complete repetition* where both the transition cue and the relevant task repeat (from a “same” no-switch trial to another “same” no-switch trial), (3) *task change only* where the relevant task changes but the transition cue repeats (from a “different” switch trial to another “different” switch trial), and (4) *transition change only* where the relevant task repeats but the transition cue changes (from a “different” switch trial to a “same” no-switch trial) (Van Loy, Liefooghe, & Vandierendonck, 2010). On *task change only* trials, transition cues reduce the perceptual dissimilarity of the cues on the current switch trial relative to the cues on the previous trials (i.e. the task cue changes but the transition cue repeats). On such trials, applying the perceptual cue mismatch strategy to task cues is more challenging because the overall perceptual dissimilarity of such switch trials is dampened by the repetition of the transition cue. Therefore, if one does not actively ignore the transition cue, one may fail to detect the necessity to switch tasks.

To investigate potential changes in switch detection strategy during childhood and adulthood, 5- and 10-year-old children and young adults completed two conditions of a task-switching paradigm, where visual task cues (a cap for the color-matching task and a hat for the shape-matching task, or vice-versa) were presented either with or without auditory transition cues (the words “different” on switch trials, “same” on no-switch trials). Based on previous findings and the hypothesis that preschoolers base switch detection on semantic processing of task cues (Chevalier et al., 2011), we expected 5-year-old children to benefit from the introduction of transition cues that allow switch detection independently of task cue processing. If, like preschoolers, older children and adults detect switches after semantically processing task cues but do so more efficiently (quantitative change with age), the beneficial effect of transition cues should progressively diminish across age groups. In contrast, if older individuals use the perceptual cue mismatch strategy (qualitative change with age), transition cues should have a detrimental effect on older children and adults’ performance. Further, for these participants, the detrimental effect of transition cues should be more marked in low span participants who have less working memory resources to keep track of previous task cues in the face of interfering transition cue information, whereas working memory resources should not relate to the magnitude of the beneficial effect of transition cues in preschoolers.

2. Method

2.1. Participants

Study participants included 31 5-year-old children (*M* = 67.7 month, *SD* = 2.9 months, range = 61-72 months, 16 females) and 31 10-year-old children (*M* = 125.6 month, *SD* = 3.5 months, range = 120-131 months, 15 females) from a small Midwestern city, and 31 undergraduate students (*M* = 20.5 years, *SD* = 1.6 years, range = 18-24 years, 16 females) from the major university in the same area. In each age group, participants were predominantly White (30 5-year-olds, 27 10-year-olds, and 27 adults). Before children were enrolled in the study, their parents completed a telephone screening using an IRB-approved, customized interview about the languages spoken at home and past/current medical conditions, to ensure children were English monolingual and had not been diagnosed with developmental or language delays or behavioral disorders known to impact task performance. Parental informed consent was obtained for all children prior to participation, and child assent also was obtained from 10-year-olds. Undergraduate students completed informed consent before beginning the session.

2.2. Materials and Procedure

Each participant was tested by a trained examiner at the laboratory, in a single session lasting approximately 1 hour. The session started with one condition of the Shape School, followed by the Counting Span, and finally a second condition of the Shape School. Each child participant’s parent filled out a background questionnaire on family demographics during the session, and each undergraduate participant filled out a background questionnaire before testing began. The children received a developmentally appropriate toy and a snack after the session was completed, and the undergraduates received credit for class. All tasks were run on IBM-compatible computers using E-Prime 1.2 or 2.0 (Psychology Software Tools, Pittsburgh, PA, USA).

Shape School—In the Shape School (adapted from Espy, 1997; Espy, Bull, Martin, & Stroup, 2006), participants were shown bidimensional stimuli (e.g., a red square), presented one at a time, and had to switch between indicating the stimulus color and shape as a function of visual task cues and/or auditory transition cues. Stimuli were 12 × 9-cm cartoon characters who were shaped as either circles or squares, and were colored either red or blue. Participants responded by pressing one of four buttons on a response pad. Response pictures (a patch of red, a patch of blue, a circle, and a square) were displayed on the screen below the stimulus characters and attached to the corresponding buttons so participants did not have to remember each button's meaning. Two response configurations with interleaved color and shape buttons were created, and response configuration was counterbalanced across participants. Participants were asked to keep their first and middle fingers from each hand on the four buttons, and push the correct button as quickly and as accurately as possible without moving the position of their fingers. The instructions were conveyed in a story about school activities, following the exact same procedure as in Chevalier et al. (2011).

The Shape School task started with two simple blocks in which participants had to perform the same task (responding to color or shape) across all trials. Each simple block included 4 practice trials and 15 test trials. Next, participants completed a mixed block in which they switched between tasks. The mixed block began with 6 practice trials followed by 66 test trials, including 16 switch trials, where the relevant task differed from the previous trial, 48 no-switch trials, where the relevant task repeated, and 2 start trials, discarded from analysis. Further, switch trials fell into 10 *complete change* trials (switch trial preceded by a no-switch trial) and 6 *task change only* trials (switch trial preceded by another switch trial). No-switch trials fell into 38 *complete repetition* trials (no-switch trial preceded by another no-switch trial) and 10 *transition change only* trials (no-switch trial preceded by a switch trial) (Figure 1). The unbalanced numbers of trials across transition types resulted from the high proportion of no-switch trials combined with the following set of necessary constraints for trial list construction: both tasks had to be equally frequent, equally associated with each trial type, each transition type and each correct response. No-switch trials outnumbered switch trials in order to maximize the magnitude of switch costs as well as the default assumption that the same task would repeat; hence inciting participants to use the perceptual cue mismatch strategy. The mixed block was split into two parts by a short break. Guidance and feedback was provided in practice trials, but participants did not receive any feedback on test trials.

Each participant completed two Shape School conditions, the Transition Cue and No Transition Cue conditions, where order was counterbalanced across participants. Both conditions contained visual task cues, that is, cues associated with the relevant task (color or shape). Task cues were a top hat or a baseball cap on top of the stimulus character. The association between each task cue and its corresponding task was counterbalanced across participants, but remained the same across conditions for each participant. In the Transition Cue condition, auditory transition cues associated with trial type (switch or no-switch), were used in conjunction with task cues. Participants heard the word "same" on single-block and no-switch trials, and the word "different" on switch trials. Transition cues were auditory in order to limit the complexity of the visual information that participants were required to process and to minimize encoding competition with task cues. In the No Transition Cue condition, participants heard the pseudoword “diyo” on every trial, in order to equalize the amount of auditory information to encode. As this auditory message was the same on all trials, it was uninformative regarding trial type. All auditory cues had the same duration (600ms) and were recorded by the same female voice. Task and transition cues had the same onset as the stimuli, and the stimulus and task cue remained on the computer screen until the response was entered, which triggered the next fixation cross for 500ms. At the end of each condition, participants were asked to tell the examiner the meaning of each task and transition cue (except for the No Transition Cue condition where participants were asked about task cue meanings only) to check their knowledge of the cue meanings.

Counting Span—The Counting Span (adapted from Case, Kurland, & Goldberg, 1982; Handley, Capon, Beveridge, Dennis, & Evans, 2004) was used to assess working memory capacity. Participants were presented with an array of blue and yellow dots on a black background, presented on a computer screen, and asked to count only the blue dots out loud. After counting the first array, the process was repeated for a second array. Participants were then asked to recall how many blue dots were in the first array, and how many blue dots were on the second array. After two practice trials, two test trials each containing two arrays were presented. If the participant failed to recall correctly on at least one of these trials, a third two-array trial was presented, otherwise the third trial was skipped. If the response was correct on at least one trial at a given array length, the number of arrays was increased by one and two/three new trials were presented. This pattern continued until none of the three trials at a given length was recalled correctly. Participants responded verbally while a researcher recorded their response on paper and entered response accuracy on each trial using the keyboard. Following Handley et al. (2004), scores were calculated as the maximum sequence length with at least two correct responses, plus .5 point for each subsequent correct response.

2.3. Exclusion criteria and data analysis

One adult participant was excluded from statistical analyses because of an accuracy rate lower than 25% on Shape School. Seven 5-year-olds and three 10-year-olds failed to recall the task (color- or shape-matching) associated with each task cues, and were therefore dropped from subsequent analyses to ensure that task cue confusion did not interfere with the effect of transition cues. By contrast, as transition cue have been shown to benefit children’s performance independent of children’s recall of their meaning (Chevalier et al., 2011), failure to recall transition cue meanings was not an exclusion criterion. All analyses were run after discarding start trials because they were neither switch nor no-switch trial and did not indicate any transition. In addition, response time (RT) analyses included only correct trials immediately preceded by another correct trial and excluded RT outliers, that is, response times greater than 10,000ms, lower than 200ms, or greater than $3SD+M$ response time of each age group (2.4% of trials). RT analyses were conducted on log-transformed RTs to control for baseline differences dependent on age group (Meiran, 1996). For the sake of clarity, reported values were back-transformed. Participants with missing RT data from some cells of the experimental design were excluded from RT analysis. Data were analyzed using mixed analyses of variance (ANOVA), LSD post-hoc tests, and linear regressions. When appropriate (as evidenced by Mauchly (1940) tests), the Greenhouse-Geisser correction (Greenhouse & Geisser, 1959) was applied for violation of the sphericity assumption.

4. Results

4.1. Effect of transition cues on single-block, no-switch, and switch trials

We first examined the effect of transition cues on single-block, no-switch, and switch trials in order to determine the effect of transition cues on traditional trial types in the task-switching paradigm, and whether this effect varied across age groups. Two 3 (age: 5 years, 10 years, adults) × 2 (transition cues: yes, no) × 3 (trial type: single-block, no-switch, switch) ANOVAs were performed on accuracy rates and RTs, with age as a between-subjects variable, and transition cues and trial type as within-subjects variables.

On accuracy rates, there were significant main effects of age, $F(2, 79) = 11.89$, $p < .001$, $^2{}_p = .23$, and trial type, $F(2, 158) = 43.20$, $p < .001$, $^2{}_p = .35$. Overall, 5-year-olds were less accurate (84%) than 10-year-olds (91%) and adults (93%), all *p*s < .001, whereas the latter two groups did not differ from each other. Accuracy decreased across single-block (94%), no-switch (90%), and switch trials (84%), all *p*s < .013, indicating that both task mixing and task switching incurred significant costs. Most importantly, there was a significant three-way interaction between transition cues, trial type and age group, $F(4, 158) = 5.03$, $p = .001$, $^2{}_p = .11$, indicating that transition cues differentially affected trial types across age groups (Figure 2). At age 5, the presence of transition cues lead to higher accuracy on switch trials relative to the condition without such cues (82% vs. 75%, respectively), $p = .005$. In contrast, at age 10, transition cues significantly impaired performance on both no-switch trials (90% vs. 95%), $p = .03$, and switch trials (80% vs. 90%), $p < .001$. Similarly, transition cues had a detrimental effect on switch performance in adults (84% vs. 93%), $p < .001$. Transition cues did not affect single-block trials at any age or no-switch trials at age 5 and in adulthood, *p*s < .49. All other effects were not significant.

On RTs, the analysis showed significant main effects of age, $F(2, 78) = 120.45$, $p < .001$, $^2{}_p = .75$, and trial type, $F(2, 156) = 878.76$, $p < .001$, $^2{}_p = .92$. Response times decreased across all 3 age groups (2207ms at age 5, 1265ms at age 10, 957ms in adults), all *p*s < .001, and increased across single-block (913ms), no-switch (1534ms), and switch trials (1982ms), all *p*s < .001. Finally, there was a significant interaction between transition cues and trial type, $F(2, 156) = 8.51$, $p < .001$, $^2{}_p = .10$. Across age groups, transition cues had no effect on single-block trials (926ms vs. 900ms), $p = .48$, whereas they decreased response times on no-switch trials (1487ms vs. 1580ms), $p < .001$, and marginally increased them on switch trials (2027ms vs. 1938ms), $p = .09$. Although the three-way interaction between age, trial type and transition cues was not significant ($p = .635$), Figure 3 shows that only at age 5 did transition cues slow down responses on switch trials (3091ms vs. 2831ms). A post-hoc t-test confirmed that this difference was significant, $t(23) = -2.29$, $p = .031$.

In brief, consistent with a qualitative change in switch detection with age, transition cues had a beneficial effect on 5-year-olds' accuracy on switch trials, but at the cost of slower responses. In contrast, their effect was detrimental on 10-year-olds' and adults' accuracy performance.

4.2. Effect of transition cues as a function of transition types

To further analyze the effect of transition cues on mixed-block trials and evaluate the hypothesis that transition cues interferes with the perceptual cue mismatch strategy by decreasing perceptual dissimilarity on some switch trials and perceptual similarity on some no-switch trials, we examined the effect of transition cues as a function of all four possible trial transitions. Two 3 (age: 5 years, 10 years, adults) × 2 (transition cues: yes, no) × 4 (transition type: complete change, transition change only, task change only, complete repetition) ANOVAs were performed on accuracy rates and RTs, with age as a between-subjects variable, and transition cues and transition type as within-subjects variables.

On accuracy, the ANOVA revealed significant main effects of age, $F(2, 79) = 5.47$, $p = .006$, $^{2}_{p} = .12$, transition cues, $F(1, 79) = 7.43$, $p = .008$, $^{2}_{p} = .09$, transition type, $F(3, 237) = 29.18$, $p < .001$, $^{2}_{p} = .27$, as well as significant two-way interactions between transition cues and age, $F(2, 79) = 3.80$, $p = .026$, $^{2}_{p} = .09$, transition type and age, $F(6, 237) = 6.04$, $p < .001$, $^{2}_{p} = .13$, and transition cues and transition type, $F(3, 237) = 18.23$, $p < .001$, $^{2}_{p} = .19$. Most importantly, all of these effects were qualified by a significant three-way interaction between transition cues, transition type and age, $F(6, 237) = 3.62$, $p = .002$, $^{2}_{p} = .08$ (Figure 4). At age 5, transition cues had a beneficial effect on *complete change* trials (i.e., “same” no-switch to “different” switch transitions) (83% vs. 70%), $p < .001$. In contrast, transition cues impaired 10-year-olds’ performance on both *transition change only* trials (i.e., “different” switch to “same” no-switch transitions) (88% vs. 97%), $p = .001$, and *task change only* trials (i.e., “different” switch to “different” switch trials) (67% vs. 90%), $p < .001$. Finally, transition cues had a detrimental effect on *task change only* trials (i.e., “different” switch to “different” switch transitions) in adults (73% vs. 93%), $p < .001$. All other pairwise comparisons were not significant, all *p*s > .15.

On RTs, there were significant main effects of age, $F(2, 72) = 138.02$, $p < .001$, $^{2}_{p} = .79$, and transition type, $F(3, 216) = 229.92$, $p < .001$, $^{2}_{p} = .76$. These effects were qualified by a transition type by age interaction, $F(6, 216) = 2.37$, $p = .031$, $^{2}_{p} = .06$, and a transition cues by transition type interaction, $F(3, 216) = 27.22$, $p < .001$, $^{2}_{p} = .27$ (Figure 5). Within each age group, all pairwise comparisons were significant (all ps < .001), except the differences between *complete change* and *task change only* trials at age 5 ($p = .08$) and between *complete change* and *transition change only* trials in adults ($p = .09$). Overall, the presence of transition cues slowed down responses on *transition change only* trials (1928ms vs. 1702ms) and *task change only trials* (2328ms vs. 2042ms), whereas it decreased response times on *complete repetition* trials (1360ms vs. 1550ms), all *p*s < .001. Transition cues had no influence on *complete change* trials (1915ms vs. 1910ms), $p = .19$. All other effects were not significant.

In brief, transition cues facilitated the detection of switches that followed no-switch trials in 5-year-olds, hence requiring them to break out of an established task set. In contrast, accuracy results showed that in older age groups, transition cues were detrimental on *task change only* trials and, to a lesser extent and only at age 10, on *transition change only* trials, that is, when transition cues decrease the dissimilarity of switch trials and the similarity of no-switch trials. Further, the analysis on RTs showed that transition cues slowed down responding when they decreased perceptual dissimilarity on switch trials and perceptual similarity on no-switch trials, whereas it decreased response times when they increased perceptual similarity on no-switch trials. These findings are consistent with the claim that older participants used the perceptual cue mismatch strategy to detect switches.

4.3. Relations between performance on Shape School and Counting Span

To examine whether working-memory capacity modulated the effect of transition cues on accuracy performance, we computed transition cue costs/benefits (accuracy performance with transition cues minus accuracy performance without transition cues) on no-switch and switch trials (Table 1). We used transition cue costs/benefits as the dependent variable in two linear regression analyses (one for switch trials and the other for no-switch trials). These regression analyses allowed us to take advantage of the fact that the same working-memory task was administered to all age groups and they increased statistical power relative to separate correlations for each age group. As we hypothesized a change in switch-detection strategy between preschoolers and older participants, we entered the following age contrast as a predictor in the regression analyses: 5-year-olds vs. older participants (10-year-olds and adults). To explore any potential difference between the two older groups, we also entered a second age contrast as a predictor: 10-year-olds vs. adults. Finally, Counting Span scores and interaction terms between age contrasts and Counting Span scores were also entered as predictors to determine whether working memory was related to transition benefits/costs and whether this relation differed with age. On switch trials, the 10-year-olds vs. adult contrast ($\beta = .28$, $p = .041$) and the interaction between Counting Score scores and the 5-year-olds vs. older participants contrast ($\beta = -.34$, $p = .030$) were significant predictors (overall model fit $R^2 = .248$). This interaction shows that Counting Span scores were differentially related to transition costs/benefits at age 5 and later in development. More specifically and as shown in Figure 6, transition benefits on switch trials were not related to working memory capacity at age 5, whereas transition costs were greater for 10-year-old and adult participants with lower working memory capacity. On no-switch trials, only the interaction between Counting Span scores and the 10-year-olds vs. adult contrast approached significance ($\beta = .29$, $p = .054$, over all model fit $R^2 = .085$), suggesting that the relation between Counting Span scores and transition costs tended to differ for 10-year-olds and adults on no-switch trials. Figure 6 shows that the performance decrement due to transition cues at age 10 was smaller on no-switch trials when working memory capacity was high, but no such relation was observed in adults (or at age 5).

5. Discussion

The present study examined potential qualitative changes in switch detection by investigating the effect of transition cues, combined with task cues, on switching performance in 5- and 10-year-old children, and adults. The results showed that transition cues had a beneficial effect at age 5, replicating previous findings (Chevalier et al., 2011). This improvement on accuracy came at the cost of slower responding, likely reflecting further attention processing on switch trials with transition cues. Further, transition cues mainly improved performance on switch trials that followed a no-switch trial (*complete change* trials), suggesting that without such transition cues preschoolers fail to detect task switches after settling into a task set, which results from and may even further contribute to children's inadequate semantic processing of task cues.

In contrast, when combined with task cues, transition cues had a detrimental effect on switch trials at age 10 and in adults. Transition cues proved especially detrimental to older children and adult participants' accuracy and response times when they decreased the perceptual dissimilarity of a switch trial relative to the previous trial (*task change only* trials). These findings are consistent with qualitative changes in switch detection strategy: Unlike 5-year-olds who detect switches after semantically processing task cues, older participants rely on the perceptual dissimilarity characteristic of task cues on switch trials relative to prior trials. The efficacy of this strategy is reduced by the introduction of "interfering" transition cues that decrease overall perceptual dissimilarity on *task change only* trials; which is consistent with the general principle that switching is easier when everything changes rather than only part of the available information (Diamond, 2009). Further, consistent with the perceptual cue mismatch strategy, transition cues had the strongest interference effect in participants with lower working memory capacity, probably because those participants had less resources to inhibit this distracting information and maintain the previous task cue in working memory. Interestingly, transition cues also impaired 10-year-olds' performance on no-switch trials, in particular on *transition change only* trials. This result may actually reflect an increase with age in the sensitivity and strategic use of cognitive demand variations across trials. Specifically, 10-year-olds may not use the probabilistic information about trial type frequency as efficiently as do adults. As they may not assume as strongly that by default the relevant task will repeat, they may show more effortful decision-making on no-switch trials (based on perceptual similarity of the task cue). On *transition change only* trials, transition cues reduce the overall perceptual similarity to prior trials and misleading 10-year-olds into detecting false switches.

Although the present findings speak to the use of the perceptual cue mismatch strategy by older children and adults, they may also be construed in terms of inner speech, which is used to translate task cues into task goal representations (Baddeley, Chincotta, & Adlam, 2001; Emerson & Miyake, 2003; Miyake, Emerson, Padilla, & Ahn, 2004; Logan & Schneider, 2006; Saeki & Saito, 2004). The verbal format of transition cues may have interfered with the use of inner speech to verbally process task cues in 10-year-olds and adults, whereas transition would not have affected 5-year-olds because children under age 8 are not considered to use inner speech for task cue processing (Chevalier & Blaye, 2009; Cragg & Nation, 2010). This hypothesis, however, does not account for the present findings as straightforwardly as the cue mismatch hypothesis. If preschoolers do not use inner speech, transition cues should not have created interference at that age (no effect), but they should not have had a beneficial effect either. Further, as inner speech is required to translate task cues into verbal task goals on all trials, transition cues should have had a similarly detrimental effect on switch and no-switch trials in older participants irrespective of the transition type. However, these two hypotheses could be distinguished further by using visual transition cues as such cues would affect overall perceptual similarity/dissimilarity but their non-verbal nature should not affect inner speech.

The present study focused on the role of perceptual similarity and dissimilarity at the level of the cues because switch detection relies on cue processing. However, perceptual mismatch at the level of the stimulus may also influence children's strategies. Preschool children may pay more attention to the stimuli than to the cues because the stimuli convey the information that they ultimately need to respond to and because salient stimuli features change very frequently. Such frequent changes in stimulus features and potentially higher priority granted to this information over cues potentially contribute to preschoolers not adopting the perceptual cue mismatch strategy. Further, as stimulus information affects overall perceptual mismatch across trials, perceptual changes at the level of the stimuli may increase the likelihood to detect task switches successfully, whereas stimulus repetitions may reduce it later in development when children use the perceptual cue mismatch strategy. Thus, the influence of stimulus changes should be examined in future research.

The observation of strategy change with age has important methodological and theoretical implications. At the methodological level, it shows that one cannot assume that variables that affect school-age children and adults in executive control tasks will necessarily have the same effect in younger children earlier in development. At the theoretical level, our findings suggest that executive control development does not result exclusively from quantitative increases in the efficiency of executive processes, but it is also driven by qualitative changes in strategies with age. Because of the 5-year gap between the two groups of children, our findings do not inform on whether the qualitative change reflects a clear-cut, "off-on" type change or, alternatively, occurs continuously between 5 and 10 years of age. Importantly, though, this qualitative change need not be discrete "off-on" strategy deployment because children could infer the need to switch by semantically processing task cue on some trials and using the perceptual cue mismatch on the remaining trials. With age, the use of the latter strategy may become increasingly prevalent across trials, or tasks, yielding continuous performance changes, despite a qualitative change in strategy deployment. Indeed, coexistence of strategies and continuous change in strategy use lie at the core of the "overlapping waves theory" of cognitive development (Chen & Siegler, 2000).

The perceptual cue mismatch strategy allows participants to function economically on most trials, expecting task repetitions by default, and only engaging in semantic cue processing and recruiting more executive processes on the few trials where a switch is highly probable. In contrast, by processing cues more independently on each trial, preschoolers likely allocate executive resources more evenly across switch and no-switch trials, hence maintaining a highly resource-demanding level of functioning throughout the task (or disengaging executive resources unstrategically on all trials to a similar extent). Therefore, executive control development seems to result, at least partly, from increasingly optimal adjustment of executive resources to variations of contextual demands with age. Adjustment of executive resource may continue to refine later in development as suggested by fMRI data showing that, whereas adults recruit supplementary motor areas (SMA) and pre-SMA to a greater extent on switch trials than no-switch trials, 8- to 12-year-olds strongly recruit this area on both switch and no-switch trials (Crone, Donohue, Honomichl; Wendelken, & Bunge, 2006).

In addition, optimal adjustment probably operates in most executively demanding situations. Evidence consistent with this claim comes from event-related potentials. Adult-like performance generally is characterized on the most demanding trials by more pronounced magnitude of the components associated with control. In the Go/No-Go task, the magnitude of the P3, a frontocentral positive component (see Polich et al., 2007), is equally high on Go and No-Go trials at preschool, whereas it is less marked on Go than No-Go trials in adults (Davis, Bruce, Snyder, & Nelson, 2003; see also Maguire et al., 2009). In the Flanker task, preschoolers show similarly pronounced frontal negativity (N2) on congruent and incongruent trials, but do show the adult-like dissociation between trial types after a short executive-control training program (Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005). Finally, consistent with increasingly optimal adjustment of executive resource with age, Luna, Padmanabhan and O'Hearn (2010) reviewed fMRI studies of executive control development and concluded that with age individuals "transition to utilizing multiple posterior regions specialized for specific aspects of a task that together provide a rapid response tailored to the task, freeing up executive regions for more complex duties" (p. 112).

Recently, Chatham, Frank, and Munakata (2009) proposed another qualitative transition during childhood, from reactive control, that is, "a tendency to react to events only as they occur, retrieving information from memory as needed in the moment" (p. 5529), to proactive control, that is, advance active preparation for events that are likely to occur through sustained maintenance of information in working memory (see Andrews-Hanna et al., 2011, for consistent findings in adolescence). Using the CPT-AX task, where children are asked to press a button only after a specific prime-probe combination, and pupillometry to assess mental effort, they observed that 8-year-olds engage executive resources (as evidenced by larger pupil dilation) right after the prime, hence anticipating probe events, whereas 3-year-olds engage executive resources only after the probe, suggesting a reactive mode of control. Although those patterns of pupillometric dilation are highly indicative of a qualitative transition with age, our findings are the first, to our knowledge, to show such a qualitative change through the effect of an experimentally manipulated variable on executive control during childhood and adulthood. In our study, cues and stimuli were presented simultaneously, leaving no time for active preparation, so it is unclear whether or not the change in switch detection strategies is an instance of the reactive to proactive transition. It can be viewed as such because older participants are strategically maintaining previous trial information in working memory rather than processing task cues independently on each trial. If so, our findings suggest that the transition to proactive control corresponds not only to more anticipation and preparation for likely future events, but also encompasses increasingly optimal adjustment of executive resource to the particularly context demands.

The present study is limited by the use of a relatively small number of trials in each condition, a necessary limitation with preschoolers in order to limit potential fatigue and the risk of non-compliance. Small numbers of trials may decrease findings reliability. We used a majority of no-switch trials (a) to ensure comparability with previous studies, (b) to maximize the likelihood of the perceptual cue mismatch strategy as the default assumption that the task will repeat is valid on most trials, and (c) because small proportions of switch trials yield large switch costs (see Monsell & Mizon, 2006). As a consequence, *task change* *only* trials were especially infrequent, making this trial type particularly vulnerable to the influence of potential outliers. However, the fact that we replicated prior findings at age 5 and observed the same pattern of results across the two older groups in the present study speaks to the robustness of the reported effects. Participant screening was achieved via parent-reported questionnaire, which is not as reliable as a standardized tests or diagnostic instruments. In particular, although individuals were asked for any potential hearing or visual problems and no participants commented on difficulty comprehending the cues, the basic hearing level of each participant was not directly tested, hence subtle differences in primary sensory abilities between age groups cannot be completed ruled out.

To conclude, the present study showed that an experimental manipulation had opposite effects across childhood, revealing a qualitative change in control strategies with age. In other words, young children are not merely less efficient at regulating their thoughts and actions, they also do so in a different way than older children. Age-related qualitative differences complement a recent report of strategy variability within a group of 5-to-6-year-old children in a task-switching paradigm (Dauvier, Chevalier, & Blaye, 2012). Such variability in control strategies may be indicative of developmental trajectories that vary across individuals, potentially under the influence of environmental factors such as socioeconomic background (Clark, Sheffield, Chevalier, Nelson, Wiebe, & Espy, in press). Such developmental trajectories will be important to clarify in future studies.

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Highlights

- This study examines qualitative change in executive control with age.
- Transition cues had opposite effects in preschoolers and older participants.
- Executive control strategies shift qualitatively with age.
- Older children and adults more flexibly adjust executive resources to situational demands.

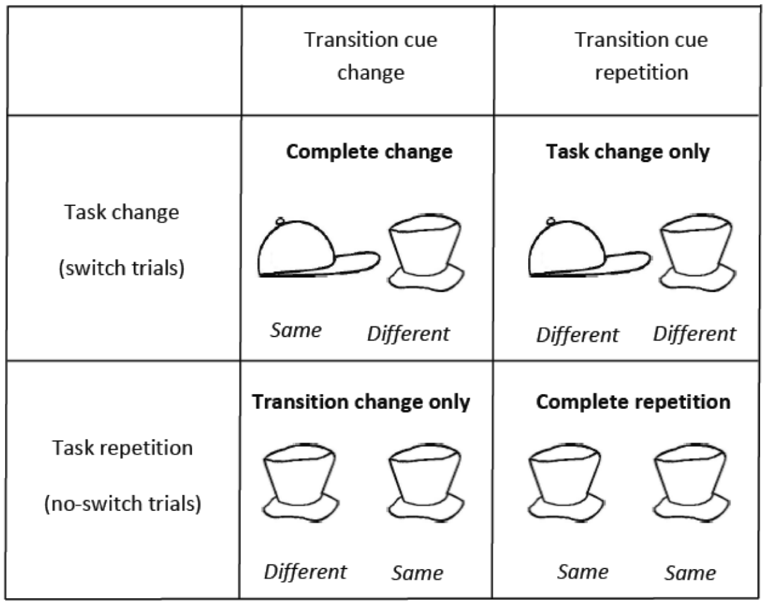

Figure 1.
Illustrations of the cues used four possible transition types. The transition type label (in bold) applies to the second trial in each example. The hat and cap signal the relevant task (task cues), whereas the transition cues are the words shown below. When no transition cues were used, these words did not apply.

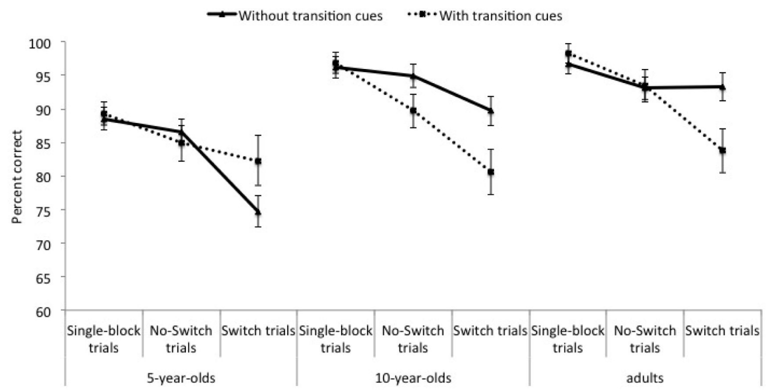

Figure 2.
Accuracy rates on the Shape School as a function of transition cues, trial type, and age. Error bars denote standard errors.

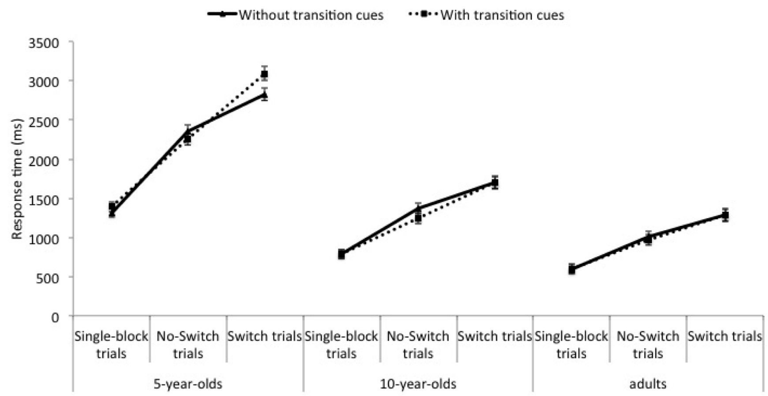

Figure 3.

Response times (ms) on the Shape School as a function of transition cues and trial type. Response times are collapsed across age groups. Error bars denote standard errors.

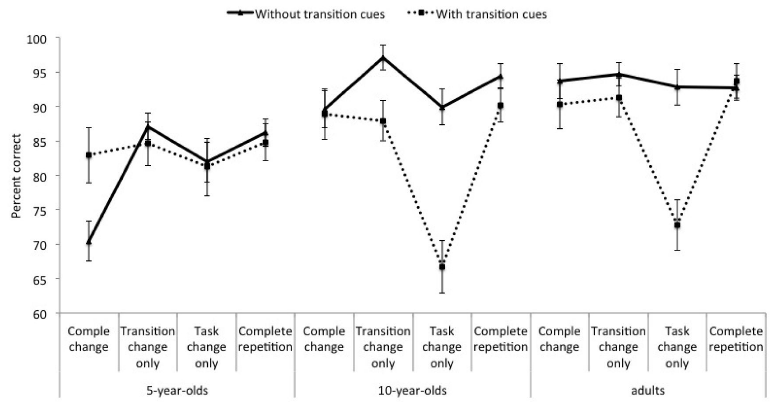

Figure 4.

Accuracy rates on the Shape School as a function of transition cues, trial transition type, and age. Error bars denote standard errors.

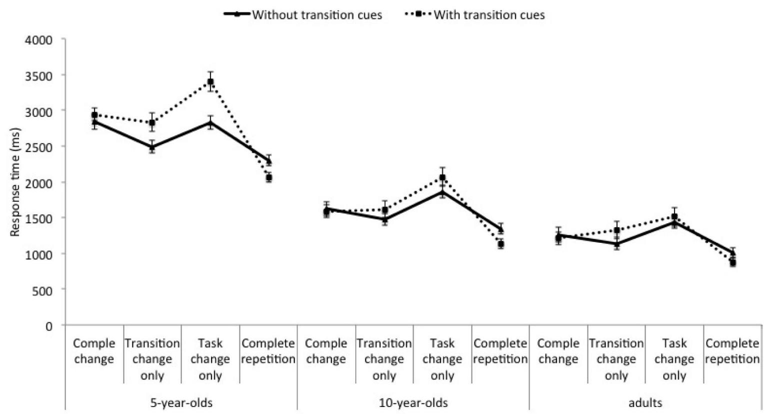

Figure 5.

Response times (ms) on the Shape School as a function of transition cues trial transition type, and age. Error bars denote standard errors.

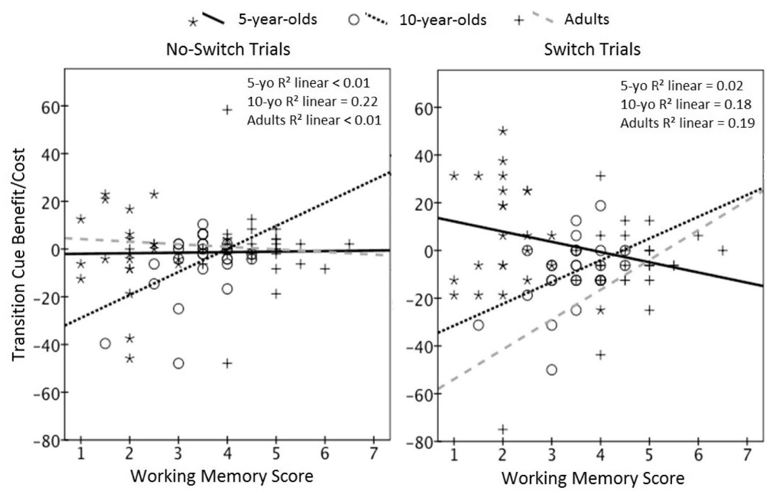

Figure 6.

Working-memory score, transition cue benefit/cost and fit lines on no-switch trials (left panel) and switch trials (right panel) for each age group.

Table 1

Descriptive statistics for Working-Memory scores and transition cue benefit or cost on no-switch and switch trials of the Shape School.

	5-year-olds	10-year-olds	Adults
Counting Span score (CS)	*M* = 2.08 (*SD* = .14)	*M* = 3.45 (*SD* = .12	*M* = 4.55 (*SD* = .15)
Condition difference on No-switch trials (Diff-No-switch)	*M* = −1.74 (*SD* = 3.36)	*M* = −5.28 (*SD* = 2.49)	*M* = −.35 (*SD* = 2.78)
Condition difference on Switch trials (Diff-Switch)	*M* = 7.55 (*SD* = 4.32)	*M* = −9.15 (*SD* = 2.60)	*M* = −9.58 (*SD* = 4.40)

Note. Transition cue benefits/costs correspond to accuracy on Transition Cue condition minus accuracy on No Transition Cue condition. Positive differences denote a beneficial effect of transition cues, whereas negative differences denote a detrimental effect of transition cues.