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Underpinnings of the Costs of Flexibility in Preschool Children: The Roles of Inhibition and Working Memory

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Abstract

This study addressed the respective contributions of inhibition and working memory to two underlying components of flexibility, goal representation (as assessed by mixing costs) and switch implementation (as assessed by local costs), across the preschool period. By later preschool age (4 years 6 months and 5 years 3 months), both inhibition and working-memory performance were associated with mixing costs, but not with local costs, whereas no relation was observed earlier (3 years, 9 months). The relations of inhibition and working memory to flexibility appear to emerge late in the preschool period and are mainly driven by goal representation.

Keywords

flexibility; inhibition; working memory; executive control; preschool children

The preschool period is characterized by tremendous improvement in children's cognitive abilities, such as language (e.g., Deák, 2003), emotion understanding/regulation (e.g., Carlson & Wang, 2007), and theory of mind (e.g., Carlson & Moses, 2001), which are related to, or perhaps even driven by, the dramatic development of executive control. Executive control can be defined as the "top-down" or intentional control that one exerts over thoughts and actions to achieve a specified goal or outcome. Generally in adults and older children, executive control is considered to be composed of: (1) inhibition, which is defined as the ability to stop or suppress attending to task-irrelevant information and/or prepotent responding; (2) working memory, which is conceptualized in the developmental literature as the ability to actively maintain information in mind (rather than the broader construct that spans information maintenance and manipulation and is prevalent in cognitive

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psychology; e.g., Baddeley, 2003), and (3) flexibility, or the ability to switch between multiple representations, strategies, or responses when contingencies change (e.g., Best, Miller, & Jones, 2009; Garon, Bryson, & Smith, 2008; Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000).

The gains in executive control at preschool age, closely related to maturation of the prefrontal brain regions (e.g., Durston & Casey, 2006), are fundamental in that they support the transition from an “in the moment” toddler to an elementary aged child with sufficient regulatory capacity to attend to, and benefit from, structured instruction that accompanies traditional formal education (Espy, 2004). Given the central role that executive control plays in cognitive development (Deák, 2003), academic skills (Blair & Razza, 2007; Bull, Espy, Wiebe, Sheffield, & Nelson, in press), and problem behavior (Espy, Wiebe, Sheffield, Clark & Moehr, 2011), better characterization of the core executive processes at preschool age is of central importance for developmental science.

Of the three components of executive control, flexibility is probably the least well understood. Typically, flexibility has been viewed as a complex function that is somehow grounded in inhibition and working memory. For example, switching to a new task likely requires (1) inhibition to suppress attention to the task to be abandoned and (2) working memory to actively maintain the rules related to the upcoming task (e.g., Diamond, 2006). Indeed, flexibility development has been accounted for alternatively by increasing inhibition (Bialystok & Martin, 2004; Kirkham, Cruess, & Diamond, 2003) and memory resources (Chevalier & Blaye, 2008; Morton & Munakata, 2002; Marcovitch, Boseovski, Knapp, & Kane, in press). At the empirical level, performance on the Dimensional Change Card Sort (DCCS; Zelazo, 2006), where the child must execute a switch between sorting cards displaying bidimensional objects by color and shape, is correlated positively with performance on classical inhibition tasks (Carlson & Moses, 2001). In addition, preschoolers with higher memory spans—as assessed by the forward digit span task—outperform children with lower memory spans on the flexibility condition of the Shape School (Espy & Bull, 2005), a measure where children have to switch between naming bidimensional objects by shape and color when visually cued (Espy, 1997; Espy, Bull, Martin, & Stroup, 2006). Collectively, these findings suggest that perhaps both inhibition and working memory support flexibility in preschoolers, although the precise mechanisms and developmental time course by which they exert influence have not been delineated.

In the present study, we draw upon the switch cost literature (see Cragg & Chevalier, in press, and Meiran, 2010, for reviews in children and adults, respectively) to better explicate the relations of inhibition and working memory to flexibility. In adults, for example, whose executive control is mature, switching between tasks generates slower response latencies (sometimes with a concurrent reduction in accuracy) in comparison to performance on either task alone, a phenomenon that has been termed ‘switch cost’ (e.g., Monsell, 2003). Two types of switch costs are generally differentiated (see Figure 1). Local costs refer to the drop in performance related to the need to switch to a different task from the one performed on the previous trial in mixed blocks, that is, series of trials where participants have to repeatedly switch between multiple tasks. Unlike local costs that compare shift and no-shift trials within switch blocks, mixing costs compare only trials without any switching requirement. More specifically, they refer to the performance decrease on no-shift trials (in switch blocks) relative to baseline trials from blocks where the same dimension is relevant across all trials.

Mixing and local costs are of prime interest because they supposedly draw differentially on two components of flexibility: (1) *goal representation*, that is, monitoring for the necessity to switch and the selection of the relevant task goal, and (2) *switch implementation*, that is, the actual switch to the newly relevant task-set (i.e., the group of perceptual, mnemonic, attention, and motor processes that are relevant for a given goal and related to stimuli encoding, action rules, and response selection) if the goal has changed (Baddeley, Chincotta, & Adlam, 2001; Emerson & Miyake, 2003; Gruber & Goschke, 2004; Rubinstein, Meyer, & Evans, 2001; Schuch & Koch, 2003). Mixing costs are considered to reflect the goal representation component of flexibility. As none of the trial types contrasted in mixing costs have a switching requirement, mixing costs mainly reflect the additional necessity of generating/abstracting the relevant task goal. These mixing costs presumably arise due to the task uncertainty inherent to switch blocks of trials where multiple tasks are eligible to be relevant, as well as to the necessity of maintaining two task-sets active in working memory. In contrast, given that both shift and no-shift trials require maintaining multiple task-sets and determining task goals, but only shift trials necessitate switching, local costs are viewed as primarily sensitive to difficulties in switch implementation (Reimers & Maylor, 2005; Rubin & Meiran, 2005).

Mixing and local costs represent a promising method to better delineate the processes underpinning flexibility in preschool children as they better parse the potential cognitive processes underlying goal representation and switch implementation components of flexibility. These processes may differentially rely on working memory and inhibition and thus offer a new window on the relations of flexibility to these executive sub-skills. Different hypotheses can be derived regarding the influence of working memory and inhibition on goal representation and switch implementation at preschool age. If flexibility relies mainly on inhibition (e.g., Kirkham et al., 2003), then both goal representation and switch implementation should relate more strongly to inhibition than working memory. In contrast, if flexibility depends primarily on memory resources (e.g., Morton & Munakata, 2002), then both of its components should draw upon working memory to a greater extent than inhibition. Flexibility is also sometimes considered an epiphenomenon, or inherent "by-product" of the ongoing interplay between inhibition and working memory, reflecting suppression of the task from which to switch away and maintenance of the rules associated with the newly relevant task (Diamond, 2006; Roberts & Pennnington, 1996). According to this view, one may hypothesize that working memory is required for goal representation, and thus modulates the magnitude of mixing costs, whereas inhibition is more directly involved in switch implementation and as such influences local costs.

However, flexibility may be more than a mere combination of inhibition and working memory. Confirmatory factor analyses, which extract the common variance shared among different executive measures and compare the relative fit of different theoretical structures, have shown that, from school age onward, flexibility is separable from inhibition and working memory (Miyake et al., 2000; Huizinga, Dolan, & van der Molen, 2006; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; St Clair-Thompson & Gathercole, 2006; van der Sluis et al., 2007). As separable as the executive functions may be, they do share considerable overlapping variance that, according to some authors (Friedman, Miyake, Young, DeFries, Corley, & Hewitt, 2008), may be due to a common goal representation component. If goal representation drives most of the common variance among executive functions, then performance on inhibition and working memory tasks should mainly relate to mixing costs and not as strongly to local costs.

Finally, the relation of working memory and flexibility may change over development. Flexibility has been conceptualized as a complex, late developing executive skill, which is built on, and acts upon, rudimentary working memory and inhibition skills (Garon et al., 2008, Best et al., 2009). In preschoolers, the structure of executive control appears to be much more unitary (Wiebe, Espy, & Charak, 2008; Wiebe, Sheffield, Nelson, Clark, Chevalier, & Espy, 2010) than in adults, without strong evidence for separable executive functions. If executive control is unitary at preschool age, then one would expect working memory and inhibition to be similarly related to goal representation and switch implementation and for performance on tasks assessing these constructs to influence mixing and local costs in a similar fashion. In addition, if executive functions progressively separate and specialize with advancing age—as one may assume to reconcile the unitary with the 3 factor structure predominantly observed at later ages—then the modulation that working memory and inhibition exert on goal representation and switch implementation may decrease over the preschool period.

The purpose of the present study was to investigate how flexibility relates to inhibition and working memory and how this relation changes over the preschool period. To this end, mixing costs and local costs were computed to examine in more detail how the two different components of flexible behavior—in particular, goal representation and switch implementation—are supported by inhibition and working memory task performance. We used the Shape School to address this question because it contains both baseline and mixed-task blocks, and has demonstrated psychometric reliability and validity (Espy et al., 2006). We examined performance on the Shape School, in relation with a working memory task and an inhibition task, at three ages spanning the preschool period.

A specific challenge to keep in mind regarding the computation of mixing and local costs in young children, whose flexibility skills are emerging, is that children with inadequate flexibility skills often perseverate with a single task on all trials—a response pattern that is more prevalent in younger preschoolers (e.g., Zelazo et al., 2003). This perseverative response pattern is distinct in nature from shifting failures that occur occasionally. It probably reflects specific conceptual misunderstanding of the task instructions and requirements (Deák, 2003; Kloo & Perner, 2005), including the understanding that tasks must be switched at times, and/or selective attention limitations (Hanania, 2010; Hanania & Smith, 2010) that do not apply to individuals who switch correctly (hence demonstrating correct understanding of task instructions) but fail to do so on specific trials. Consistent with the distinction between the perseverative response pattern and occasional shifting errors, dissociating color and shape on task stimuli has been shown to reduce the prevalence of perseveration at age 3 (Diamond, Carlson, & Beck, 2005; Kloo & Perner, 2005), but to have no effect on occasional shifting errors at later ages (Chevalier, Blaye, Dufau, & Lucenet, 2010; Cragg & Nation, 2009). With the traditionally calculated difference score, the perseverative profile is associated with artificially inflated mixing costs, because children automatically lose credit on half of the trials in the switch block, and artificially reduced local costs, because children show equivalent performance on shift and no-shift trials of the switch block. Therefore, we elected to specifically model and account for the influence of perseveration while empirically examining whether working memory and inhibition would differentially relate to goal representation and switch implementation in these children across age.

Method

Participants

Study participants included 250 preschool children (130 girls and 120 boys; 192 White non-Hispanic, 12 African American, 17 Hispanic, and 29 multiple race-ethnicity) who were recruited through birth announcements, local preschools, the local health department, and by word of mouth from two Midwestern study sites, a small city and a rural, multi-county area. Before enrollment in the study, parents completed a telephone screening; children with diagnosed developmental or language delays or behavioral disorders or whose families planned to move out of the area within the study timeline were deemed ineligible at screening and were not recruited. Children were enrolled in a longitudinal project for which they were administered a battery of executive tasks every 9 months between the ages of 3 years 0 months and 5 years 3 months in a lagged cohort sequential design. Data from three time points were included in the present study: 3 years 9 months, 4 years 6 months, and 5 years 3 months. Children were tested within two weeks of the exact targeted age (mean age 3.71: *SD* = .04 and age range = 3.67–3.83; mean age 4.45: *SD* = .04 and age range = 4.42–4.5; mean age 5.19: *SD* = .04 and age range = 5.08–5.25). The data at age 3;0 were not used because 3-year-olds usually obtain floor performance on flexibility tasks (e.g., Jacques & Zelazo, 2001; Zelazo, Müller, Frye, & Marcovitch, 2003), and only 42% of the children completed the switch condition of the Shape School at age 3;0. Stratified sampling on social risk was used to ensure a balanced sample (40.8% met federal poverty guidelines). On average, participants' mothers had completed 14.8 years of education (*SD* = 1.8 years, range 11 – 18 years). Parental informed consent was obtained for all children prior to participation.

Materials and Procedure

At each time point, preschoolers were administered individually the battery of executive tasks designed to measure flexibility, inhibition, and working memory, by a trained examiner in a quiet room with a parent or guardian present (in the back of the room completing study forms). The battery of tasks was administered in one single videorecorded session in the laboratory and lasted about 120 minutes (including other tasks not included in the present report). Short breaks were used when necessary to maintain cooperation and interest. The tasks were administered on a PC desktop computer and presented via a 19-inch (48cm) monitor, and were run with E-Prime 1.1 (Psychology Software Tools, Pittsburgh, PA; Shape School and Go/No-Go) or using Perl v5.8.8 (ActiveState Software, Vancouver, BC; Nebraska Barnyard). Parents were compensated for study participation, and the children received developmentally appropriate toys, stickers, and other small items.

Flexibility—In the Shape School (Espy, 1997; see Espy et al., 2006 for more details), children named stimuli by either shape or color as quickly and accurately as possible, with the demands for each task condition conveyed in a story about school activities (e.g., calling children's names for lunch). In the present computerized version, stimuli were cartoon characters whose main body part was a square or a circle colored in blue or red. Some of the stimuli wore a hat (the dimension cue) whereas others were hatless. Stimuli were presented one at a time at the center of the screen on a white background. On each trial, the stimulus was visually displayed until the participant verbally responded (by naming the stimulus color or shape, depending on the relevant dimension). After the child responded, the examiner triggered procession to the next trial.

At the beginning of the Shape School, children were presented with two introductory trials with two stimuli present to ensure that they could name the colors used in this task. Child participants then completed a color baseline condition, consisting of a block of 12 test trials naming stimulus color. Thereafter, during a shape baseline condition, participants completed another series of 6 practice and 12 test trials during which they were required to name the stimuli by shape. Finally, participants moved on to the switch condition, where the hatted and hatless stimuli were mixed, and the child had to switch unpredictably between naming the hatless stimuli by color and the hatted stimuli by shape for a series of 6 practice trials and 15 test trials. Within the switch condition, after the first starting trial, there were 10 shift trials, where the relevant dimension for the current stimulus differed from that in the previous trial, and 4 no-shift trials, where the relevant dimension was the same as in the previous trial. The Shape School also includes two other conditions where different faces with different emotional expressions cue response suppression. However, these conditions were not used in the present paper and thus are not discussed further.

Trained undergraduate students coded response accuracy for each test trial from videorecorded task sessions, using Noldus Observer 5.12 (inter-rater agreement was 93.83%). Accuracy was computed for baseline, shift and no-shift trials separately including only test trials and excluding start trials because these trials could not be classified as either shift or no-shift trials since no trial preceded them. Although switching from the first to the second baseline block already is challenging for 3-year-olds (e.g., Kirkham et al., 2003; Zelazo et al., 2003), we elected to collapse the color and shape baseline conditions, as is traditionally done with older children and adults in the task-switching paradigm, to make our findings more comparable with this literature. More importantly, as the switch condition contained both color and shape trials, collapsing color and shape conditions allowed us to avoid the confounding of the number of dimensions involved when comparing across trial types, which is an important issue given that color matching and shape matching differ in task difficulty (e.g., Davidson, Amso, Cruess Anderson, & Diamond, 2006; Ellefson, Shapiro, & Chater, 2006). There were not sufficient trials to adequately measure the dimension effect within each cost comparison, and increasing the number of trials was not possible due to potential fatigue and noncompliance in the young preschoolers.

Inhibition—In the Go/No-Go task (adapted from Simpson & Riggs, 2006), children were presented with pictures of colored fish and sharks. On Go trials (75% of trials), a fish appeared at the center of the screen on a white background, and children were asked to “catch” the fish by pressing the button on the button box. On less frequent No-Go trials (25% of trials), a shark appeared and children were instructed to avoid “catching” the shark by withholding their response. After correct responses on Go trials, positive feedback was provided for 1000 ms in the form of a net containing the fish and a bubbling sound. When children made an error of commission (i.e., pressing the button on no-go trials) resulting in “catching” the shark, negative feedback was provided for 1000 ms in the form of a picture of a broken fishing net accompanied by a buzzer. The Go and No-Go stimuli were presented for 1,500 ms, with an inter-stimulus interval of 1000 ms. Children completed 6 practice trials (3 Go and 3 No-Go trials) and 40 test trials (30 Go trials and 10 No-Go trials interspersed across the Go trials). Instructive guidance was provided on practice trials, but not on test trials. The percentage of correct responses on No-Go trials was used as the dependent variable, reflecting the child’s inhibition of the prepotent, more frequent button press response.

Working Memory—The *Nebraska Barnyard* (adapted from the *Noisy Book* task; Hughes, Dunn, & White, 1998) is a computerized complex span task requiring children to remember a sequence of animal names and press corresponding buttons on a touch screen in the correct order. In an initial training phase, children were introduced to a set of 9 colored pictures of animals arranged in a 3 × 3 grid of colored “boxes” on the computer screen. Box color was associated with animal identity (i.e., the “frog” button was green, the “cow” button was brown, etc.). In the initial training phase, children pressed each animal box and the computer produced the corresponding animal sound. Thereafter, the animal pictures were removed (but box colors remained the same) and children completed a set of 9 practice trials during which the examiner named each animal individually, and the child was required to press the box corresponding to that animal. Finally, trials with sequences of animals were administered, beginning with sequences of 2 animals and increasing progressively until the child’s performance met the discontinuation criterion. Up to 3 trials were administered at each span length: if the first 2 trials for a span were correct, the third trial was omitted, and if all 3 trials for a span were incorrect, the task was discontinued. The maximum span length (highest span where the subject was correct on two trials) obtained by the participant was scored, reflecting the child’s maintenance of the sequence in mind.

Statistical Analysis

Analyses were run separately at each time point. We purposefully chose this cross-sectional analysis strategy of our longitudinal data because we were *not* interested in specifically modeling the developmental change in mixing and local costs. Rather, the focus was on developmental differences in the pattern of relations among flexibility, working memory, and inhibition at each age. Furthermore, because perseverative profile was not a fixed grouping variable or static across age, a cross sectional approach was most appropriate.

Unlike many papers that use simple subtraction to calculate costs via a difference score, we elected to use multilevel modeling to test the stated hypotheses regarding how working memory and inhibition relate to mixing and local costs. Methodologists have highlighted in recent years the benefits of utilizing multilevel modeling to analyze data from experimental designs with repeated measures (see Hoffman & Rovine, 2007; Quené & van den Bergh, 2004). In contrast to traditional ANOVA methods, multilevel modeling does not require the assumptions of homoscedasticity (homogeneity of variances), compound symmetry, and sphericity, although, as a class of the linear model, it is not without some distributional assumptions (see Singer & Willett, 2003). Multilevel models also permit testing of interactions between discrete and continuous predictors (e.g., discrete switch costs contrasts and continuous inhibition task scores in the present study) and parse the relative contribution of within- and between-subjects sources of variance in performance.

Separate models were used for mixing and local costs, where a priori condition contrasts were used to evaluate the within-subjects predictor (i.e., “trial type”) for the main effect of the respective switch cost on performance. The mixing costs contrast compared the average performance collapsed across the color and shape trials in baseline conditions of the Shape School to the performance on the no-shift trials of the Shape School switch condition. The local costs contrast compared each child’s performance on the shift trials with that on the no-shift trials within the switch condition of the Shape School. These models also included the perseverator grouping variable (perseverators vs. non-perseverators dummy coded, with non-perseverators coded as the reference group) in order to statistically model and control for perseveration. Perseverators were identified on the basis of the binomial distribution. Children who responded on the same dimension differently from chance (i.e, on only three or fewer trials or on 11 or more trials) were categorized as perseverators.

To address the questions of interest, the following main effect and interaction terms were added to the multilevel models in addition to main effect contrasts representing mixing and local costs and the perseverator group variables described above. To evaluate the relative contributions of inhibition and working memory on mixing and local costs, cross-level interaction terms between inhibition or working memory (between-subjects) and the respective trial type contrasts representing either mixing or local costs (within-subjects) were modeled. For example, the working memory × mixing cost interaction term tested whether individual variation in children’s working memory predicted the difference in accuracy on baseline trials compared to no-shift trials of the Shape School. Note that inhibition and working memory can influence performance in the Shape School in an overall fashion for all trials (independent of type), which was tested by incorporating main effects for inhibition and working memory into all models. The models also included perseverator group × working memory and perseverator group × inhibition interaction terms in order to determine whether perseveration was specifically associated with poor inhibition or working memory performance. Three-way interaction terms between trial type, perseverator group and either inhibition or working memory were also tested but, if they were not significant, we trimmed them in order to better estimate the main effects and two-way interactions (Singer & Willett, 2003). Scores on Go/No-Go (inhibition) and Nebraska Barnyard (working memory) were standardized in scale prior to their incorporation into the models, so that the magnitude of their effects on costs was directly comparable.

All study analyses were run using the PROC MIXED component of the SAS statistical package (SAS Institute, Cary, NC, USA), with a critical α of .05 for all tests. Effect sizes are reported as two pseudo-R^2 values for each model, one representing the proportional reduction of within-subject variance and the other of between-subject variance. Each respective indicator of reduction in variance is due to predictors added to the model, in comparison to the unconditional (no predictors) model (Singer & Willett, 2003). Therefore, pseudo-R^2 values indicate the proportion of the within-subject variance and between-subject variance in the unconditional model is explained by the independent variables included in the model.

Results

Descriptive statistics for children's performance on Shape School, Go/No-Go and Nebraska Barnyard are provided in Table 1. Consistent with previous studies (e.g., Zelazo et al., 2003), the proportion of perseverators differed between age 3;9 (38%) and age 4;6 (18%), McNemar's $\chi^2(1) = 49.84$, $p < .001$, and between age 4;6 and age 5;3 (8%), McNemar's $\chi^2(1) = 115.56$, $p < .001$.

Mixing costs

Before examining how inhibition and working memory task performance predicted mixing costs, multilevel models were computed predicting accuracy on the Shape School at each time point with only Trial Type (Baseline trials vs. No-shift trials) and Perseverator Group (Perseverators vs. Non-Perseverators) included as independent variables to test whether preschoolers showed the expected mixing costs. In all mixing cost analyses, the reference group for trial type was baseline trials and the reference group for perseverator group was non-perseverators. As anticipated, the fixed effect of trial type was significant at each time point, indicating there were significant mixing costs, $\gamma = -.184$, $SE = .02$, $F(1, 399) = 65.89$, $p < .001$ at age 3;9, $\gamma = -.108$, $SE = .02$, $F(1, 469) = 35.60$, $p < .001$ at age 4;6 and $\gamma = -.074$, $SE = .01$, $F(1, 467) = 30.75$, $p < .001$ at age 5;3. In addition, the effect of the perseverator group was also significant at each time point: $\gamma = -.287$, $SE = .02$, $F(1, 399) = 151.17$, $p < .0001$ at age 3;9, $\gamma = -.292$, $SE = .02$, $F(1, 469) = 155.26$, $p < .001$ at age 4;6 and $\gamma = -.293$, $SE = .02$, $F(1, 467) = 141.69$, $p < .001$ at age 5;3. Perseverators had significantly lower overall performance than non-perseverators at each age, where accuracy on no-shift trials was 18%, 11% and 7% less accurate than baseline trials at ages 3;9, 4;6 and 5;3, respectively. The pseudo-R^2 values for within-subject and between-subject variance at each age are .32 and 1.00 at age 3;9, .18 and 1.00 at age 4;6 and .21 and 1.00 at age 5;3. The observation of significant mixing costs indicates that repeating a dimension for naming is more difficult when the stimuli are mixed than in the blocked baseline condition, and this difficulty seems to decrease with age reflected by better performance with age, which merited proceeding with the evaluation of the impact of the inhibition and working memory predictors.

Table 2 and Figure 2 present the effects from the models that additionally contained main effects of performance on Go/No-Go (GNG) and Nebraska Barnyard (NB), as well as interaction terms between these predictors and trial type. At age 3;9, neither GNG nor NB performance interacted with trial type ($p = .069$ and $p = .118$, respectively), suggesting that mixing costs do not depend on inhibition and working memory at this age. GNG performance had a small but significant main effect ($\gamma = .004$, $p = .023$), suggesting that children who scored one *SD* higher than average were about 0.4% more accurate on both baseline and no-shift trials.

In contrast to the earlier time point, at ages 4;6 and 5;3, GNG performance significantly interacted with trial type ($\gamma = .069$, $p = .002$ at age 4;6; $\gamma = .054$, $p = .011$ at age 5;3). Higher GNG performance resulted in smaller mixing costs. At age 4;6, children who scored one *SD* higher than average on GNG were about 6.9% ($\gamma_{GNG} + \gamma_{GNG \times \text{trial type}} = -.00015 + .069 = .069$) more accurate on no-shift trials than children who scored at the GNG mean, whereas no difference was observed for baseline trials. At age 5;3, the GNG score × Trial Type interaction was accompanied by a small, yet significant main effect of GNG performance ($\gamma = -.011$, $p = .006$), suggesting that GNG performance affected both baseline and no-shift trials though the effect was stronger for the latter. Children who scored one *SD* higher than average on GNG were 4.3% ($\gamma_{GNG} + \gamma_{GNG \times \text{trial type}} = -.011 + .054 = .043$) more accurate on shift trials and only 0.1% less accurate on baseline trials.

Similarly at ages 4;6 and 5;3, trial type also significantly interacted with NB performance ($\gamma = .058$, $p = .003$ at age 4;6; $\gamma = .034$, $p = .022$ at age 5;3). In addition, NB performance had a small but significant main effect at age 4;6 ($\gamma = -.008$, $p = .019$). Higher NB performance was associated with smaller mixing costs. At age 4;6, children who scored one *SD* higher than average on NB were 0.8% less accurate on baseline trials and 5.0% ($\gamma_{NB} + \gamma_{NB \times \text{trial type}} = -.008 + .058 = .050$) more accurate on no-shift trials than children who scored at the NB mean. At age 5;3, children who scored one *SD* higher than average on NB were 2.3% ($\gamma_{NB} + \gamma_{NB \times \text{trial type}} = -.011 + .034 = .023$) more accurate on no-shift trials than children who scored at the NB mean whereas no such difference was observed for baseline trials.

Interestingly, the perseverator group interacted with neither GNG nor working memory performance at any age (all *p*s > .058). The pseudo-R^2 values for within-subject and between-subject variance at each age are .34 and 1.00 at age 3;9, .23 and 1.00 at age 4;6 and .24 and 1.00 at age 5;3.

Local costs

In a parallel manner, multilevel models were computed predicting accuracy on the Shape School at each time point with only Trial Type (Baseline trials vs. No-shift trials) and Perseverator Group (Non-Perseverators vs. Perseverators) included as independent variables to evaluate whether preschoolers showed the expected local costs before the respective roles of inhibition and working memory task performance were examined. The fixed effect of trial type was significant at each time point, $\gamma = -.065$, $SE = .02$, $F(1, 200) = 13.06$, $p < .001$ at age 3;9, $\gamma = -.045$, $SE = .01$, $F(1, 235) = 11.06$, $p = .001$ at age 4;6 and $\gamma = -.030$, $SE = .01$, $F(1, 234) = 6.00$, $p = .015$ at age 5;3. The effect of perseverator group was also significant at each time point: $\gamma = -.419$, $SE = .03$, $F(1, 199) = 239.85$, $p < .001$ at age 3;9, $\gamma = -.450$, $SE = .03$, $F(1, 234) = 244.89$, $p < .001$ at age 4;6 and $\gamma = -.432$, $SE = .03$, $F(1, 233) = 193.58$, $p < .001$ at age 5;3. By definition, perseverators performed more poorly than non-perseverators (they were between 41.9% and 45.0% less accurate). Children encountered more difficulty switching between dimensions than repeating the same dimension within the Switch Condition. They were 6.5%; 4.5%, and 3% less accurate on shift trials than no-shift trials at ages 3;9, 4;6 and 5;3, respectively. The pseudo-R^2 values for within-subject and between-subject variance at each age are .06 and .68 at age 3;9, .04 and .62 at age 4;6 and .02 and .63 at age 5;3. These findings warranted proceeding with testing the impact of inhibition and working memory.

Results from the models that additionally contained main effects of performance on Go/No-Go (GNG) and Nebraska Barnyard (NB), as well as interaction terms between these predictors and trial type, are shown in Table 3 and illustrated in Figure 2. At all ages, neither GNG performance nor NB interacted with trial type ($p = .566$ and $p = .449$, respectively), suggesting that local costs did not depend on inhibition and working memory in this preschool age range. GNG performance had a significant main effect at ages 3;9 ($\gamma = .038$, $p = .008$) and 4;6 ($\gamma = .059$, $p = .043$). Children who scored one *SD* higher than average were 3.8% more accurate overall than children who scored at the GNG mean at age 3;9, and 5.9% more accurate at age 4;6. Similarly, NB performance had a significant main effect at ages 3;9 ($\gamma = .056$, $p = .036$), 4;6 ($\gamma = .040$, $p = .001$) and 5;3 ($\gamma = .016$, $p = .36$). Children who scored one *SD* higher than average were 5.6% more accurate overall than children who scored at the NB mean at age 3;9, and 4.0% more accurate at age 4;6 and 1.6% more accurate at age 5;3. The Perseverator Group variable did not significantly interact with GNG and NB performance at any time point (all *p*s > .084). The pseudo-R^2 values for within-subject and between-subject variance at each age are .05 and .73 at age 3;9, .04 and .68 at age 4;6 and .03 and .66 at age 5;3.

Discussion

The study purpose was to investigate how cognitive flexibility relates to inhibition and working memory and how these relations differ over the preschool period. Specifically, we examined the effect of performance on the Go/No-Go and Nebraska Barnyard tasks on mixing and local switch costs computed by a priori contrasts of children’s performance on the Shape School at three time points: ages 3;9, 4;6 and 5;3. As mixing and local costs are meaningless in cases of perseveration and because persistent perseveration likely reflects an ability pattern that is distinct from those who have reliable switch costs, all analyses were run explicitly modeling and accounting for the effect of the perseverator group. These analyses revealed that individual differences in the ability to maintain information ‘online’ and to inhibit prepotent responses were associated with mixing costs at ages 4;6 and 5;3, whereas there was no such relation at age 3;9. Unlike mixing costs, local costs were mostly unrelated to inhibition and working memory. Finally, Go/No-Go and Nebraska Barnyard performance of perseverators did not significantly differ from non-perseverators at any time point.

The observed relation of working memory and inhibition to mixing costs at 4 and 5 years of age suggests that older preschoolers draw upon these executive skills to behave flexibly and, in particular, to identify and maintain task goals. The role of working memory in goal representation is in line with theoretical accounts suggesting that working memory, especially the phonological loop, is involved in building and maintaining verbal representations of task goals (Gruber & Goschke, 2004) and findings that disruption of the phonological loop impairs mixing costs in adults (Baddeley et al., 2001; Bryck & Mayr, 2005). In addition, children likely rely on working memory to maintain two task-sets active in the mixed block (Reimers & Maylor, 2005), hence further accounting for the relation between mixing costs and working memory task performance in the present study.

Unlike working memory, the relation between mixing costs and inhibition was less expected. Children with higher inhibition skills showed more accurate performance on no-shift trials, which is surprising given the prevailing conceptualization of no-shift trials as not involving any inhibitory demands. This result contradicts the claim that inhibition would be involved in flexibility only to suppress irrelevant task-sets (while working memory would be required to maintain newly relevant task rules; Diamond, 2006). Instead, the unexpected influence of inhibition on accuracy mixing cost can be interpreted in two ways that are not mutually exclusive. First, maintenance of two task-sets in an active state in working memory and/or task-goal representation may tax both working memory and inhibition, at least in preschoolers. Although no previous results have related goal representation to inhibition, it is possible that representing the newly relevant goal in working memory requires inhibiting the formerly relevant one. Second, because both tasks are possible in the Switch Condition, resistance to distracter interference may be necessary for preschoolers to ignore the stimulus feature related to the irrelevant dimension in the no-shift trials even though no switch is required per se. Consistent with this idea, 5- and 6-year-old children, unlike adults, have been found to gaze at the irrelevant dimension of stimuli significantly longer in no-shift trials relative to baseline trials, suggesting this dimension creates more interference in the former trial type for preschool children (Chevalier et al., 2010). However, resistance to distracter interference is conceptually distinct from inhibition of motor responses, as assessed with the Go/No-Go task, although these two forms of inhibition are closely related (Friedman & Miyake, 2004).

Mixing costs may relate to both working memory and inhibition not only because the processes underlying mixing costs rely on these executive skills. It is equally possible that this relation is driven by a factor common to flexibility, working memory and inhibition. Goal representation or activation could be this common factor, as suggested by Friedman et al. (2008) and Miyake et al. (2000), which would account for the variance shared by the commonly observed three latent factors in adults and older children. Consistent with this account, recent findings point out the key role of goal representation, selection and maintenance in children's inhibition (Blaye & Chevalier, 2011; Bub, Masson, & Lalonde, 2006; Lorsbach & Reimers, 2010) and flexibility (Chevalier & Blaye, 2009; Chevalier, Dauvier, & Blaye, 2009; Marcovitch, Boseovski, & Knapp, 2007; Marcovitch, Boseovski, Knapp, & Kane, 2010; Snyder & Munakata, 2010; Towse, Lewis & Knowles, 2007). Whether goal representation plays a role in traditional working memory tasks at preschool age and actually draws upon the same processes in situations tapping inhibition, flexibility and, possibly, working memory remains to be documented. Nevertheless, it is plausible that goal representation is a common component of all executive functions, hence accounting for the relation observed between mixing costs and inhibition and working memory performance in the present study.

Contrary to mixing costs, no association was found between local costs and Go/No-Go and Nebraska Barnyard performance, suggesting that the processes underpinning switch implementation do not depend on inhibition and working memory. Our findings suggest that switch implementation does not relate to inhibition and working memory task performance, at least in preschoolers, which fails to support theoretical proposals that switching is mainly driven by either inhibition (e.g., Kirkham et al., 2003) or memory resources (e.g., Morton & Munkata, 2002). They also rule out the postulation that flexibility is a byproduct of working memory and inhibition as switch implementation is clearly independent of such an interplay. However, inhibition is not a monolithic entity but includes some types of inhibition devoted to suppressing incorrect responses and others devoted to filtering out irrelevant information (e.g., Nigg, 2000). Our findings suggest that switch implementation does not relate to response inhibition, but its functional dependence on resistance to distractor interference (i.e., inhibition of irrelevant information) remains plausible and should be tested in future studies. Alternatively, switch implementation may be modular and thus task-content specific. Yehene and Meiran (2007) observed that, unlike mixing costs, local costs shared little variance across isomorphic task-switching paradigms that involved different task contents, when adult participants had little time to prepare for the next trial (i.e., small cue-stimulus interval). If local costs are primarily content specific, then it is no surprise that we did not observe any relation with inhibition and working memory performance in the present study, especially given that cues and stimuli were simultaneously displayed in the Shape School, preventing advance preparation. However, Yehene and Meiran's study also pointed to substantial common variance across contents for "residual switch costs", that is, the local costs observed when participants are given ample time for advance preparation (typically, over 600 ms for adults). Their results suggest that switch implementation is not fully content-specific, but rather partially relies on a domain-general skill if there is sufficient time for controlled processing.

Unlike local costs, there were important differences across ages in the pattern of relations of working memory and inhibition task performance and mixing costs. Although there was no relation at age 3;9, inhibition and working memory performance were associated with mixing costs at ages 4;6 and 5;3, suggesting that the relation of working memory and inhibition to flexibility is more prominent later in the preschool period. This pattern is in blatant opposition to what would be expected if flexibility progressively developed on the basis of the other executive skills (Garon et al., 2008) or if the main executive functions progressively separated throughout the preschool period, as suggested by evidence for unitary executive function in preschoolers (Wiebe et al., 2008, 2011) and separate functions later in development (e.g., Lehto et al., 2003). The relatively late emerging relation of the other executive skills to flexibility during the preschool years suggests age-related changes in the processes recruited to complete the flexibility task, with a shift from bottom-up or task-related processes to increasingly efficient top-down executive skills that are common to flexibility, inhibition and working memory. More precisely, as they grow older, children may increasingly draw upon developing goal representation skills to complete flexibility tasks as well as working memory and inhibition tasks. With this formulation then one would expect increasing relations among executive skills observed across different executive function tasks. Along with our finding that mixing costs are more developmentally sensitive than local costs in this age range, this hypothesis suggests that goal representation may have an essential role in executive control development.

The possibility cannot be excluded that mixing and local costs are more reliable measures of flexibility components as children grow older, which provides an alternative explanation of the emergence of a relation between mixing costs and inhibition and working memory performance at age 4;6. Although the computation of switch costs has the potential to further the understanding of flexibility development at preschool age by more precisely targeting specific flexibility components, it can only provide meaningful information—with lower costs signaling higher switching ability—as long as participants do possess rudimentary switching abilities, as is the case from late preschool age onward. When these rudimentary abilities have not yet emerged, minimal switch costs (especially local costs) may also be indicative of overall poor performance due to perseveration on a single task, as it is the case in a substantial proportion of 3-year-olds. Given this issue, we explicitly modeled and accounted for perseverator group to prevent artificial distortion of the switch cost magnitudes. Importantly, perseverators did not differ from non-perseverators in inhibition and working memory performance, which suggests that the absence of relation of inhibition and working memory to flexibility at age 3;9 was not due to the prevalence of perseveration at that age and implies that inhibition and working memory do not account for the difference between perseverators and non-perseverators.

However, young children’s poorer flexibility does not always result in systematic, perseverative responses. Non-perseverative errors are frequent, too (Chevalier & Blaye, 2008; Deák, 2000, 2003). For instance, young children may be more likely to respond randomly (i.e., switch independently of task cues) because they have more acute difficulty exerting and removing inhibition multiple times (Diamond, 2009), and/or have difficulty understanding the necessity to switch from task instructions (Deák, 2003; Kloo & Perner, 2005). Such random switching/responding strategies also might affect switch cost magnitudes, but such idiosyncratic response patterns are difficult to detect, and thus cannot be modeled. Random switching/responding strategies would lead to relatively low accuracy and would not yield local costs because switches would occur roughly equally often on shift and no-shift trials. In this study at age 3;9, accuracy rates in shift and no-shift trials were relatively high and local costs were significant in non-perseverators, hence failing to support this interpretation.

One limitation of the present study is the impossibility of investigating the potential effect of dimension (color or shape) on the relation among inhibition, working memory, and flexibility. An asymmetry in switch costs has been observed between color and shape in school aged children (e.g., Davidson et al., 2006; Ellefson et al., 2006). Dimension might have independent or interactive effects in this age range that could not be modeled adequately because of the number of trials and fixed order of the conditions in the Shape School. Future investigations are needed to determine whether dimension asymmetry modulates the relation of inhibition and working-memory performance to switch costs in children.

In conclusion, the present study clarified the relation of inhibition and working memory to flexibility by showing that the components underlying flexible behaviors differentially draw upon these executive skills at preschool age. This relation seems exclusively driven by goal representation whereas switch implementation appears independent of these other executive skills, suggesting that goal representation might be a fundamental component of executive skills. If this interpretation is correct, as preschoolers grow older, they are increasingly able to draw upon maturing goal representation skills to exert control over their thoughts and actions.

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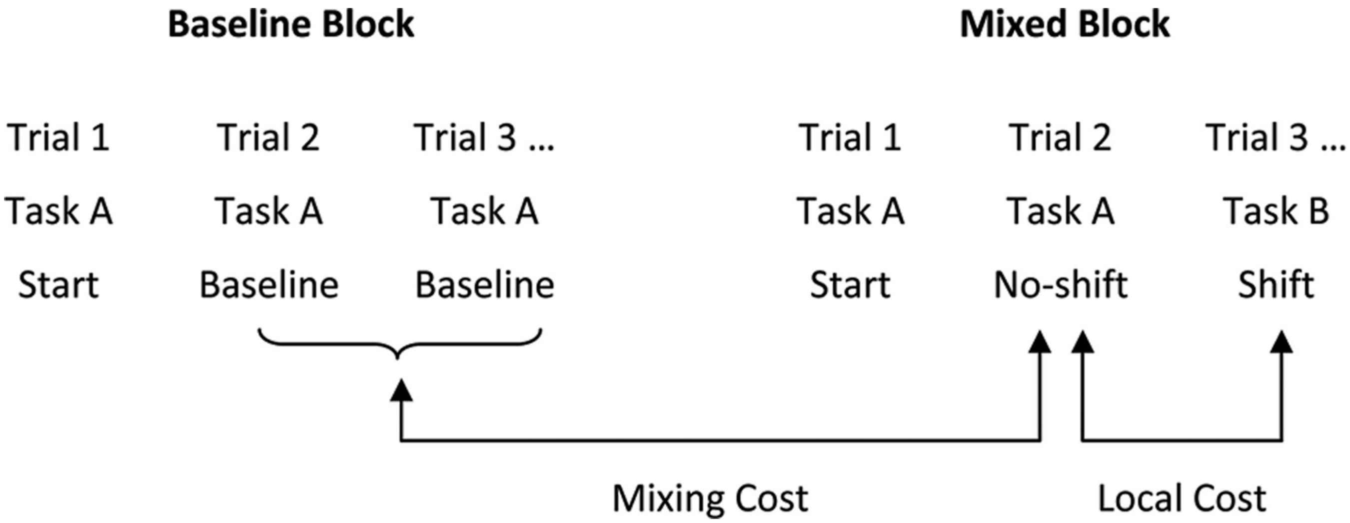

Figure 1.

Schematic illustration of the task-switching paradigm and the mixing and local costs. The figure only presents a few trials of each block. There are baseline blocks for each task. Mixing costs are usually computed by collapsing all baseline trials and contrasting their mean with mean performance on all no-shift trials. Local costs are computed by contrasting mean performance on all no-shift trials and mean performance on all shift trials.

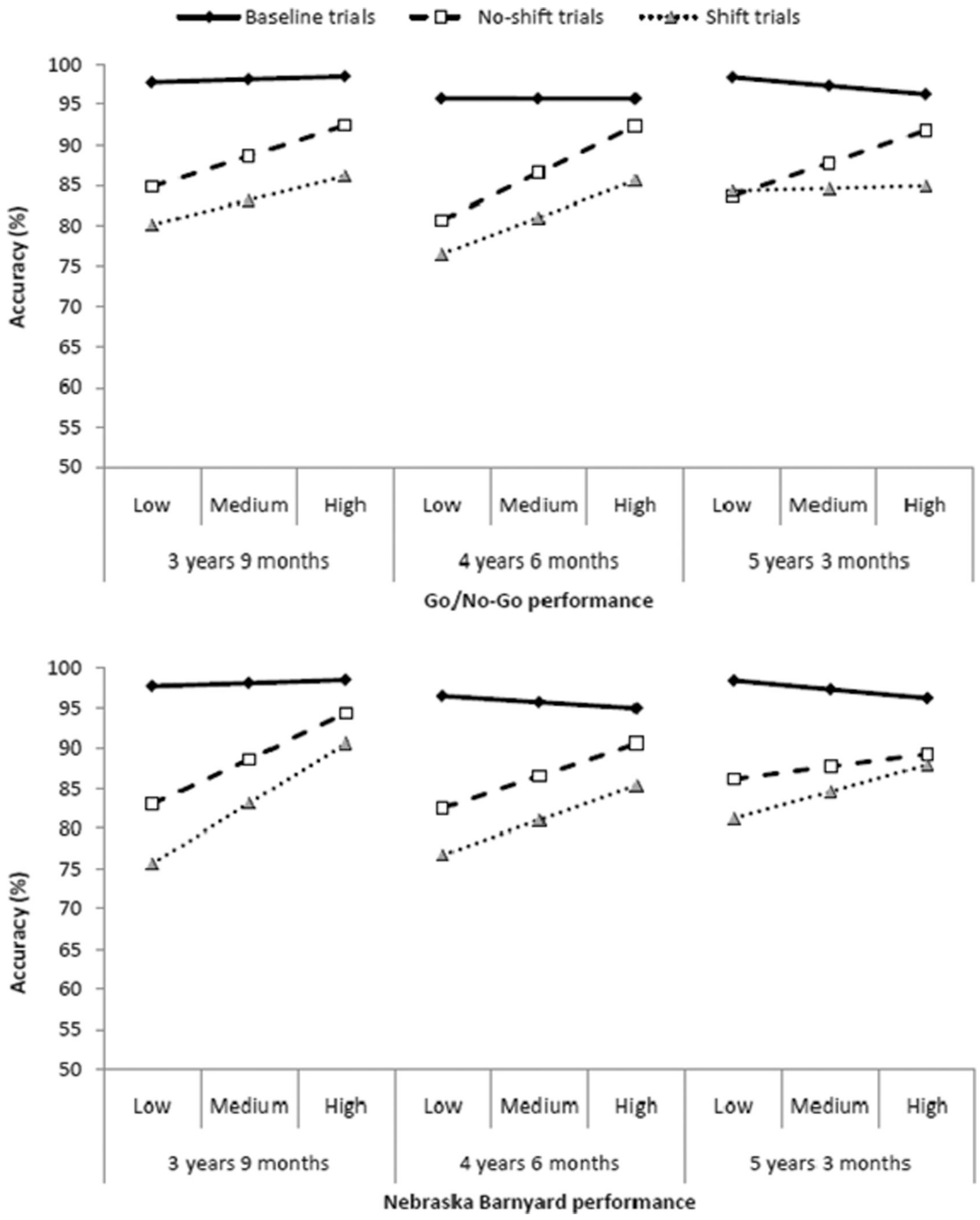

Figure 2.

Illustration of mixing costs (baseline trials vs. no-shift trials) and local costs (no-shift trials vs. shift trials) for non-perseverating children as a function of age and performance on Go/No-Go (top panel) and Nebraska Barnyard (bottom panel). Mean corresponds to mean scores on the Go/No-Go or Nebraska Barnyard, while low and high respectively correspond to scores one standard deviation below and above the mean (for Go/No-Go, high corresponds to the maximum score).

Table 1

Frequency, Means and Standard Deviations for Performance on Shape School, Go/No-Go, and Nebraska Barnyard.

	Age 3 years 9 months			**Age 4 years 6 months**			**Age 5 years 3 months**		
	NPers.	**Pers.**	**Combined**	**NPers.**	**Pers.**	**Combined**	**NPers.**	**Pers.**	**Combined**
N	124 (62%)	77 (38%)	201(100%)	193 (82%)	43 (18%)	236 (100%)	216 (92%)	19 (8%)	235 (100%)
Shape School									
Baseline trials (%)	90 (13)	82 (18)	87 (15)	92 (10)	85 (18)	91 (12)	95 (5)	86 (18)	94 (8)
No-shift trials (%)	87 (21)	39 (31)	69 (34)	89 (20)	38 (31)	80 (30)	91 (16)	41 (29)	87 (22)
Shift trials (%)	76 (20)	41 (17)	62 (26)	83 (18)	44 (15)	76 (23)	87 (14)	50 (15)	84 (17)
Mixing cost (%)	3 (22)	43 (36)	18 (35)	3 (19)	47 (36)	11 (29)	4 (17)	45 (33)	7 (22)
Local cost (%)	12 (22)	−2 (28)	6 (25)	7 (18)	−6 (26)	4 (21)	4 (17)	−9 (33)	3 (19)
Go/No-Go									
Correct No-Go (%)	79 (28)	73 (32)	77 (30)	89 (17)	79 (27)	87 (19)	91 (13)	80 (25)	90 (15)
Nebraska Barnyard									
Span	1.87 (.78)	1.68 (.70)	1.80 (.75)	2.54 (.92)	2.12 (.91)	2.46 (.93)	3.15 (.88)	2.37 (.90)	3.09 (.91)

Note. NPers. = Non-Perseverators. Pers. = Perseverators.

Table 2

Multilevel Modeling Parameter Estimates for Mixing Costs at Each Time Point.

Effect	Estimate	*SE*	*df*	*F*	*p*
Age 3 years 9 months					
Intercept	0.981	0.02	--	--	--
Trial Type	**−0.144**	**0.03**	**1, 393**	**23.63**	**<0.001**
Perseverator Group	**−0.282**	**0.03**	**1, 393**	**73.58**	**<0.001**
GNG	**0.004**	**0.02**	**1, 393**	**5.21**	**0.023**
NB	0.004	0.02	1, 393	2.21	0.138
GNG × Trial Type	0.033	0.02	1, 393	3.32	0.069
NB × Trial Type	0.048	0.03	1, 393	2.46	0.118
GNG × Perseverator Group	0.001	0.02	1, 393	0.01	0.938
NB × Perseverator Group	−0.007	0.03	1, 393	0.05	0.828
Age 4 years 6 months					
Intercept	0.957	0.01	--	--	--
Trial Type	**−0.119**	**0.02**	**1, 463**	**44.68**	**<0.001**
Perseverator Group	**−0.272**	**0.02**	**1, 463**	**125.38**	**<0.001**
GNG	−0.0002	0.02	1, 463	1.23	0.268
NB	**−0.008**	**0.01**	**1, 443**	**5.56**	**0.019**
GNG × Trial Type	**0.069**	**0.02**	**1, 463**	**10.13**	**0.002**
NB × Trial Type	**0.058**	**0.02**	**1, 463**	**8.97**	**0.003**
GNG × Perseverator Group	−0.044	0.02	1, 463	3.61	0.058
NB × Perseverator Group	0.018	0.03	1, 463	0.51	0.475
Age 5 years 3 months					
Intercept	0.973	0.01	--	--	--
Trial Type	**−0.111**	**0.02**	**1, 461**	**43.97**	**<0.001**
Perseverator Group	**−0.274**	**0.03**	**1, 461**	**118.65**	**<0.001**
GNG	**−0.011**	**0.02**	**1, 461**	**7.80**	**0.006**
NB	−0.011	0.01	1, 461	2.81	0.094
GNG × Trial Type	**0.054**	**0.02**	**1, 461**	**6.51**	**0.011**
NB × Trial Type	**0.034**	**0.01**	**1, 461**	**5.27**	**0.022**
GNG × Perseverator Group	0.041	0.03	1, 461	2.40	0.122

Effect	**Estimate**	***SE***	***df***	***F***	***p***
NB × Perseverator Group	0.037	0.03	1, 461	1.62	0.204

Note. Trial Type: Baseline trials (Switch Condition) [reference] vs. no-shift trials (Color & Shape Baseline Conditions); Perseveration: Non-Perseverators [reference] vs. Perseverators; GNG = Go/No-Go task; NB = Nebraska Barnyard; SE = Standard Error. Significant effects appear in bold characters.

Table 3

Multilevel Modeling Parameter Estimates for Local Costs at Each Time Point.

Effect	**Estimate**	***SE***	***df***	***F***	***p***
Age 3 years 9 months					
Intercept	0.887	0.02	--	--	--
Trial Type	**−0.055**	**0.02**	**1, 198**	**5.43**	**0.021**
Perseverator Group	**−0.444**	**0.04**	**1, 195**	**144.15**	**<0.001**
GNG	**0.038**	**0.02**	**1, 195**	**7.20**	**0.008**
NB	**0.056**	**0.02**	**1, 195**	**4.44**	**0.036**
GNG × Trial Type	−0.008	0.01	1, 198	0.33	0.566
NB × Trial Type	0.019	0.02	1, 198	0.58	0.449
GNG × Perseverator Group	−0.013	0.02	1, 195	0.43	0.513
NB × Perseverator Group	−0.053	0.04	1, 195	2.08	0.151
Age 4 years 6 months					
Intercept	0.866	0.01	--	--	--
Trial Type	**−0.043**	**0.01**	**1, 233**	**9.89**	**.002**
Perseverator Group	**−0.414**	**0.03**	**1, 230**	**199.37**	**<0.001**
GNG	**−0.059**	**0.02**	**1, 230**	**4.14**	**0.043**
NB	**0.040**	**0.02**	**1, 230**	**11.72**	**.001**
GNG × Trial Type	−0.013	0.02	1, 233	0.64	0.424
NB × Trial Type	0.003	0.01	1, 233	0.04	0.848
GNG × Perseverator Group	−0.048	0.03	1, 230	3.01	0.084
NB × Perseverator Group	0.023	0.03	1, 230	0.55	0.459
Age 5 years 3 months					
Intercept	0.878	0.01	--	--	--
Trial Type	−0.032	0.02	1, 232	4.06	0.045
Perseverator Group	**−0.399**	**0.03**	**1, 229**	**158.69**	**<0.001**
GNG	0.041	0.02	1, 229	3.24	0.073
NB	**0.016**	**0.01**	**1, 229**	**4.48**	**0.036**
GNG × Trial Type	−0.038	0.02	1, 232	3.59	0.059
NB × Trial Type	0.018	0.01	1, 232	1.62	0.204
GNG × Perseverator Group	0.016	0.03	1, 229	0.23	0.630

Effect	Estimate	*SE*	*df*	*F*	*p*
NB × Perseverator Group	0.029	0.04	1, 229	0.61	0.436

Note. Trial Type: No-shift trials (Switch Condition) [reference] vs. shift trials (Switch Condition); Perseveration Group: Non-Perseverators [reference] vs. Perseverators; GNG = Go/No-Go task; NB = Nebraska Barnyard; SE = Standard Error. Significant effects appear in bold characters.