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Charting Early Trajectories of Executive Control With the Shape School

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Abstract

Despite acknowledgement of the importance of executive control for learning and behavior, there is a dearth of research charting its developmental trajectory as it unfolds against the background of children's sociofamilial milieus. Using a prospective, cohort-sequential design, this study describes growth trajectories for inhibitory control and cognitive flexibility across the preschool period in relation to child sex and sociofamilial resources. At ages 3, 3.75, 4.5, and 5.25 years, children ($N = 388$) from a broad range of social backgrounds were assessed using the Shape School, a graduated measure of executive control incorporating baseline, inhibitory control, and cognitive flexibility conditions. Measures of children's proximal access to learning resources and social network supports were collected at study entry. Findings revealed substantial gains in accuracy and speed for all Shape School conditions, these gains being particularly accelerated between ages 3 and 3.75 years. Improvements in inhibitory control were more rapid than those in flexible switching. Age-related differences in error and self-correction patterns on the Shape School also suggest qualitative changes in the underlying processes supporting executive performance across early childhood. Children from homes with fewer learning resources showed a subtle lag in inhibition and cognitive flexibility performance that persisted at kindergarten entry age, despite exhibiting gradual catch up to their more advantaged peers for the nonexecutive, baseline task condition. The study provides a unique characterization of the early developmental

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pathways for inhibitory control and cognitive flexibility and highlights the critical role of stimulating early educational resources for shaping the dynamic ontogeny of executive control.

Keywords

executive function; inhibitory control; preschool; socioeconomic status; sex differences

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“Growing up” entails a progression from externally driven, disinhibited, reactive behavior to flexible, volitional, and self-regulated behavior. The cognitive processes that subserve this progression, one of which is executive control, are of principal concern for developmental science. The preschool period has attracted particular attention, this being a time of rapid, concurrent change in neural organization and self-regulation (Bell & Fox, 1992; Kopp, 1982). Drawing on the principle of the butterfly effect, even subtle individual differences in emergent executive processes at this young age may have cascading implications for long-term outcome as children enter increasingly demanding social and academic environments and behavior patterns become progressively entrenched (Thelen, 1990). Given accumulating evidence for the foundational role of executive control in academic readiness and social and behavioral competence (Clark, Pritchard, & Woodward, 2010; Espy, Sheffield, Wiebe, Clark, & Moehr, 2011; Hughes, White, Sharpen, & Dunn, 2000), specifying its true developmental course, as well as the factors that promote its optimal development, is of substantial import for early intervention, social policy, and educational remediation efforts.

Executive control can be defined as the set of top-down cognitive processes that allow an individual to regulate goal-directed behavior under conditions of novelty, distraction, or conflicting task demands (Welsh, 2002). Two skills commonly included in theoretical accounts of executive control are the ability to inhibit goal-irrelevant impulses or attention responses and the ability to adapt flexibility to changes in the environment (Anderson, 2008). In a laboratory situation, inhibitory control is measured using tasks that require the child to suppress or override a dominant response tendency. In contrast, cognitive flexibility typically is assessed using switching paradigms that require children to alter the nature of their responses to stimuli based on feedback or task-embedded cues.

Using such tasks, studies have documented substantial age-related improvements in inhibitory control and cognitive flexibility over the preschool period (e.g., Carlson & Moses, 2001; Klenberg, Korkmann, & Pekka, 2001; Stahl & Pry, 2005; Zelazo, Reznick, & Spinazzola, 1998). Notably, however, the majority of these studies use cross-sectional designs, which focus on mean differences and thus limit inferences regarding true developmental change and individual variability. The few longitudinal studies conducted in early childhood show growth as well as between-person stability in executive task performance, but have included only two assessment points (e.g., Carlson, Mandell, & Williams, 2004; Hughes, Ensor, Wilson, & Graham, 2010). Only designs that track individual progress on the same measure over more than two occasions can provide reliable information regarding the normative shape of the executive control trajectory. Such knowledge is critical for identifying periods of rapid change that might signify sensitive windows for intervention, informing developmental expectations regarding normative levels of intra- and inter-individual variability in executive control performance, and revealing aberrant pathways that may presage psychopathology. The dramatic temporal and contextual fluctuation in preschoolers' behavior also implies that repeated assessments will yield a more reliable indication of their executive control capabilities than single assessments. On a more theoretical level, comparing children's growth on tasks that tax different putative components of executive control may inform debates regarding the fundamental nature of executive control in early childhood. Arguments for a fractionated structure suggest that growth patterns for separate components may differ markedly, the emergence of more advanced skills, such as cognitive flexibility, presumably being reliant on relatively basic, foundational skills, such as goal maintenance and inhibitory control (Garon, Bryson, & Smith, 2008). For these reasons, there have been increasing calls for longitudinal studies into the developmental course of executive control (Garon et al., 2008; Mahone & Wodka, 2008).

A key advantage of longitudinal designs is the ability to examine the impact of individual differences and experiences not only on concurrent behavior but also on rates and patterns of growth within person. For instance, examining the role of sex in executive control maturation may inform developmental assessment and enhance understanding of sex-specific differences in the nature and course of disorders characterized by executive control deficits (e.g., attention-deficit/hyperactivity disorder). Neuroimaging studies offer compelling evidence for sex differences in neural structure and maturation, showing that gray matter development in the frontal regions peaks earlier in girls and myelination proceeds more rapidly in boys (Giedd et al., 1999; Lenroot et al., 2007). Nonetheless, the behavioral implications of these neural differences are unclear, some studies indicating advanced inhibitory control and overall executive control capabilities in girls relative to boys (Hughes & Ensor, 2005; Wiebe, Espy, & Charak, 2008), whereas others report no sex differences (Davidson, Amso, Anderson, & Diamond, 2006; Deák, Ray, & Pick, 2004; Wiebe et al., 2011). Inconsistent findings perhaps indicate that the impact of sex varies with age, with longitudinal research able to address this question.

Another potent factor of influence on children's development is the sociofamilial environment. Scientists have argued that the protracted development of prefrontal cortical systems that support executive control confers a heighted and extended sensitivity to social influences relative to skills that are supported by faster maturing subcortical and posterior neural regions (Hackman & Farah, 2009). Accordingly, several recent studies have demonstrated the relevance of distal indictors of socioeconomic status (SES), such as maternal education and income, as well as more proximal measures of parenting behavior and household organization, for preschoolers' executive performance (Bernier, Carlson, & Whipple, 2010; Hammond, Muller, Carpendale, Bibok, & Liebermann-Finestone, 2012; Hughes & Ensor, 2009; Noble, Mc-Candliss, & Farah, 2007). An important and understudied question concerns the temporal stability of these effects. For instance, persistent delays in executive control associated with early sociofamilial disadvantage likely warrant greater concern than transient delays that resolve over time. Tracking individual trajectories of executive control in relation to sociofamilial background factors will enhance understanding of how early experiences help to determine the overall shape and speed of children's executive skill development across early childhood.

Two common perspectives for studying the relation of proximal sociofamilial resources to children's development are the parental investment and parental stress perspectives (Yeung, Linver, & Brooks-Gunn, 2002). From the investment perspective, higher SES affords greater access to learning resources (e.g., books) and stimulating, educational interactions. The positive impact of such learning interactions is supported by studies showing that parental scaffolding during problem-solving tasks is positively associated with young children's executive task performance (Bernier et al., 2010; Hughes & Ensor, 2005, 2009). The complementary parental stress perspective focuses to a greater extent on parent psychological well-being and access to social supports. Stress and limited access to social support networks presumably constrain the emotional availability of the parent and decrease their ability to provide warm, contingent responses to their children. Determining whether and how proximal learning resources and social stressors relate to children's executive control acquisition is important, as these are malleable factors that may be responsive to intervention.

Here, we use growth curve modeling to describe growth trajectories on the Shape School task, a measure of inhibitory control and cognitive flexibility designed specifically for young children (Espy, 1997; Espy, Bull, Martin, & Stroup, 2006). One methodological challenge of this prospective, longitudinal design is that it confers a susceptibility to practice effects associated with repeated assessment. This issue is particularly problematic for executive control research, as executive control, by definition, is engaged in novel situations in which an automatic or habitual response is inappropriate. To address this issue, we used a lagged cohort-sequential design to parse developmental change from repeated testing effects.

A key advantage of the Shape School task is its use of multiple conditions, which pose progressively increasing demands on executive control. The first condition requires children only to name colors as quickly and as accurately as possible, whereas subsequent conditions add requirements for inhibition or flexible switching. The use of similar stimuli across conditions means that growth of specific executive control components can be isolated from growth in basic naming and processing, yielding a clearer representation of the executive constructs of interest and their relations to individual differences. The open verbal response format of the Shape School also offers an opportunity to examine children's types of errors and self-corrections, potentially providing further information regarding the nature of executive control development. Specifically, differences in the fundamental types of errors made at different ages may suggest a qualitative change in the way that children process or approach the task, whereas errors that differ only in degree might suggest quantitative gains in executive efficiency. Notably, Shape School performance predicts children's later math and reading achievement (Bull, Espy, & Wiebe, 2008). Performance also correlates with established measures of selective attention (Espy et al., 2006) and is sensitive to neurological compromise associated with preterm birth and lead exposure, supporting the psychometric properties of the task (Canfield, Kreher, Cornwell, & Henderson, 2003; Pritchard & Woodward, 2011). On the basis of cross-sectional and theoretical literature, we hypothesized that preschool children would show considerable improvement on Shape School conditions assessing inhibitory control and cognitive flexibility, coupled with an increasing tendency to self-monitor, as reflected by their self-correction of erroneous responses.

The second aim of this study was to determine the relation of individual differences, including sex, learning resources, and parent social stressors, to children's patterns of growth in inhibitory control and cognitive flexibility. Notably, some studies indicate that the relation of sociofamilial factors to executive control may be mediated by children's verbal skills (e.g., Hammond et al., 2012), whereas others have found effects even after controlling for language or IQ, suggesting a unique vulnerability of executive control to the social ecology (e.g., Hughes & Ensor, 2007). As Shape School conditions all pose similar baseline processing and response demands, examining the link between sociofamilial risk and performance on executive control conditions after controlling for baseline performance provides a particularly rigorous test of the specificity of the social context: executive control relation. Given cross-sectional evidence for weaker executive control performance in preschool boys, we hypothesized that boys would show slower gains in Shape School performance compared with girls. We expected that children with greater access to learning resources would show accelerated trajectories for executive control development, although the role of parent stress was less clear. Finally, we examined whether child sex might moderate the relations of these two dimensions of sociofamilial risk to executive control growth, based on evidence for differential vulnerability of boys and girls to sociofamilial stress in other developmental domains (e.g., Crawford, Cohen, Midlarsky, & Brook, 2001).

Method

Participants

Using a lagged, cohort-sequential design, participants (*N* = 195 girls, 193 boys) were recruited through flyers distributed at schools, childcare and medical centers, as well as by word of mouth, from two midwestern sites, a small city and a rural tricounty area. Children with known developmental disorders or English as a second language were excluded from participation via telephone screening conducted prior to recruitment. To ensure adequate variance in the sample for capturing potential sociofamilial effects, children considered to be at higher social risk were oversampled during screening so that 43% of families met federal poverty guidelines. The first cohort of participants (*n* = 228; retention to age 5.25 = 92%) was recruited at a mean age of 3 years and assessed on three additional occasions. Three additional cohorts were recruited at 3.75 (*n* = 57; 90% retained), 4.5 (*n* = 55; 100% retained), and 5.25 years (*n* = 48) in order to disentangle developmental change from repeated testing effects. Reflecting the typically developing nature of the sample, children's mean IQ on the Woodcock Johnson III Brief Intelligence Assessment (BIA; Woodcock, McGrew, & Mather, 2001) at study entry was 102.10 (*SD* = 10.41). In terms of ethnicity, 74% of the sample were White, 8% were Hispanic, 5% were African American, <1% were Asian, and 13% weremultiracial. The sample was representative of a wide range of SES, the median household income per annum being $45k (range = $2.4k–$300k) and the mean length of maternal education being 14.7 (range = 11–20; *SD* = 2.37) years.

Procedure

At study entry, two research technicians visited the child's home to obtain written, informed consent from the child's parent and to administer the Early Childhood Home Observation for Measurement of the Environment (EC-HOME; Caldwell & Bradley, 1978) and the BIA

(Woodcock et al., 2001). Within a narrow 2-week window for each follow-up point, all children attended a laboratory assessment, where they were assessed by a trained research technician on a battery of executive control tasks that included the Shape School. While the child participated in the assessment, the primary caregiver, generally the mother, was interviewed regarding the child's health and family background. Caregivers also completed several questionnaires related to the child's home environment and caregiving experiences, as detailed below. The laboratory protocol was repeated every 9 months until the child reached 5.25 years of age.

Measures

The Shape School (Espy, 1997).—Inhibitory control and cognitive flexibility were assessed at each assessment using a computerized version of the Shape School,[1] programmed using E-Prime (Version 1.1). As part of a cover story to enhance interest, children were shown a screen depicting colorful cartoon characters playing in a schoolyard. Three basic character templates, differing only slightly in facial features and the positioning of their feet, were repeated randomly through all task conditions. Characters did, however, vary on the dimensions of color (red; blue) and shape (circle; square) and according to particular cues (happy/sad facial expression for Condition 2 and hat/no hat present for Conditions 3 and 4). Prior to each condition, children completed six practice trials, where they were provided verbal feedback on their performance. No feedback was provided during test trials. In Condition 1, *baseline color naming*, children were advised that the characters' names were their colors and were asked to name 12 characters with neutral expressions as quickly and as accurately as possible as they appeared sequentially on the computer screen. Condition 2, *inhibit* (six inhibit and 12 noninhibit trials), assessed children's inhibitory suppression of a prepotent verbal response. Children were instructed to name only the colors of characters with happy faces and to remain silent for characters with sad faces. In Condition 3, *blocked switch* (12 trials), characters were depicted with neutral expressions and wearing hats. Children were instructed to name characters with hats by their shape. In Condition 4, *mixed switching* (10 switch and five nonswitch trials), neutral characters both with and without hats were presented and children were required to flexibly shift their responses between dimensions of color and shape as cued. Children were allowed an unlimited time window in which to provide verbal responses. If children were unable to complete practice trials or name any stimuli, the task was terminated and a 0 score was allocated for remaining conditions (n = 15 at age 3, n = 2 at age 3.75).

Digital video-recordings of children's Shape School performance were coded for accuracy, response times (RTs), and error type in random order by trained research staff who were blind to study hypotheses (interrater agreement = .93 for 20% of sessions that were independently coded; range across age groups = 93%–96%). Internal reliabilities for accuracy ranged from .75 to .95. For RTs, internal reliability was generally acceptable (α = .66–.84), although it was lower for the switching conditions at 3 and 3.75 years (.47–.69), reflecting less RT consistency at younger ages. Errors were coded as *inhibit* errors, meaning

[1]While previous reports include a fifth Shape School condition, including both inhibit and switch trials, children in the younger age groups were seldom able to complete this condition. Hence, it was not considered further.

that children named the character where the response ought to have been suppressed; *switch* errors, where children responded with the opposite dimension to that required, for example, by naming color rather than shape; *within-dimension* errors, where children said the opposite shape/color to that required; *distractor* errors, where children named another pertinent characteristic of the stimulus, for example, saying the cue “hat” or “happy”; and *other errors*, including unrelated responses such as naming an arbitrary color. Reasons for missing data at each age included child refusal (n = 65 at 3; 26 at 3.75; 4 at age 4.5 years) and technical/ administration errors that prevented task coding (n = 11 at age 3; n = 9 at 3.75; n = 4 at 4.5; n = 1 at 5.25). Accuracy data from E-Prime was used for four cases at age 3.75 and four cases at age 5.3 because technical errors prohibited coding from video.

Sociofamilial background experiences.—Mothers completed *The Life Stressors and Social Resources Inventory* (LISRES; Moos & Moos, 1994) during the initial laboratory visit. The LISRES comprises 200 items of yes/no or Likert-scale format, which provide individual stress and resource scores for each of the following domains: physical health; home and neighborhood; finances; work and employment; spouse or partner relationships; relationships with children; extended family relationships; and friends or social groups. These scales have shown high internal reliability (α = .83–.84) and adequate test–retest reliability over a 1-year period (r = .67–.70; Moos, 1995; Moos & Moos, 1994). Cronbach’s alphas for scales used in this study ranged from .76 to .93. Scales assessing spousal relationships and occupational stress were not applicable for a number of parents and thus were not included in analyses. For two children who were missing one scale score from the LISRES, maximum likelihood imputation was performed based on all available social background data.

The Satisfaction With Parenting Scale (SWPS; Ragozin, Basham, Crnic, Greenberg, & Robinson, 1982), completed by mothers during the initial laboratory visit, provided a measure of parenting support sources and stress related to everyday parenting. Items (n = 17) are rated on a scale of 1–5, yielding scores for *Parental Role Satisfaction* and *Parental Pleasure*. Internal consistencies for the SWPS range from .70 to.77, and were similar in the present sample (α = .60–.77). Scores have also been shown to correlate with observational ratings of parent–child interactions (Crnic & Greenberg, 1990; Crnic, Greenberg, Ragozin, Robinson, & Basgam, 1983).

The EC-HOME (Caldwell & Bradley, 1978) provided a direct observation/interview-based measure of the quality of children’s immediate home environments. Items are rated positive if the target behavior/materials are present in the home (e.g., at least 10 children’s books visible). Items make up eight subscales, assessing learning materials, language stimulation, physical environment, responsiveness, academic stimulation, modeling of behavior, variety of stimulation, and acceptance. The EC-HOME has been used extensively in developmental research and is predictive of cognitive test performance as well as socioemotional competence (see Bradley, 1993, for a review). Research assistants administering the EC-HOME were individually trained to 100% reliability by a senior staff member, with regular monitoring to maintain administration fidelity. Unclear items were resolved by consensus during weekly supervision meetings. Using these methods, interrater reliability in our studies using the EC-HOME is consistently high (κ = .85–1). Internal reliability for this sample was .77.

Principal Factors Analysis of Sociofamilial Background Measures

Given the large number of subscales assessing children's social backgrounds, principal factors analysis (PFA) was used to identify a parsimonious, dimensional representation of the subscales for use in analyses. Scales were reverse scored where appropriate so that higher scores reflected more optimal social circumstances. To avoid colinearity between identified factors when entered simultaneously into subsequent growth models, a varimax rotation was used. The Positive Life Events, Negative Life Events, and Physical Health scales from the LISRES and the Acceptance, Responsivity, and Modeling scales from the EC-HOME were dropped during this analysis due to low communalities. Analysis of the remaining subscales yielded two factors with eigenvalues >1, which explained 94% of the variance across all subscales. Factor 1, labeled *Learning Resources* (α = .78), comprised the following subscales with associated rotated factor loadings: LISRES Financial Resources (.68), Financial Stressors (.64), and Home and Neighborhood Stressors (.45); and EC-HOME Learning Resources (.65), Variety (.58), Physical Environment (.49), Academic Stimulation (.46), and Language Stimulation (.44). Factor 2, labeled *Social Network Resources* (α = .78), comprised the LISRES Family Stressors (.61), Family Resources (.58), Child Stressors (.55), Child Resources (.52), Friend Stress (.44), and Friend Resources (.42) subscales and the SWPS Parental Role Satisfaction (.44) and Parental Pleasure (.56) scales. Factor-derived scores were computed for each child to be used in analyses.

Statistical Methods

Multilevel modeling was conducted in SAS Proc Mixed using restricted maximum likelihood estimation. Maximum likelihood estimates have been shown to be robust to missing data, an intended consequence of the study's lagged-sequential design (Collins, Schafer, & Kam, 2001). First, descriptive analyses were conducted, comparing children with unplanned missing data (i.e., missing data that was not due to the lagged-sequential design) with those who did not have missing data, as well as examining correlations and changes in children's mean performance across time. Although raw RTs are presented in descriptive results for clarity, RTs were trimmed to two standard deviations above the mean for a particular trial and then log-transformed the purposes of growth analyses, given evidence for distribution skewness (> 1.7). Second, unconditional models were constructed for all Shape School conditions to ascertain the best fitting models for growth in accuracy and RT. Children's exact age was centered at the final follow-up point such that a child who attended sessions at the exact ages 3, 3.75, 4.5, and 5.25 years would have centered ages of −3, −2, −1, and 0, respectively. Fixed and random linear growth (slope) terms as well as fixed quadratic (growth acceleration/deceleration) terms were added sequentially to each of the unconditional models. Fixed effects were retained if the pertinent *p* values for estimates (γ) were < .05, whereas random effects were retained if the model log likelihood differed significantly with the addition of the random slope term, based on a chi-square difference test (Singer & Willet, 2003). For all executive conditions of the Shape School, time-varying baseline naming condition performance (*z*-scored relative to the grand mean) was entered into the unconditional and conditional models so that growth estimates reflect change in inhibitory control and cognitive flexibility performance after accounting for baseline naming skill.

A series of dummy variables was constructed for each data point, with these variables entered into growth models to isolate repeated testing effects. If a child had been administered the Shape School in a previous session, a dummy score of 1 was assigned, whereas a child who had not previously been assessed was assigned a dummy code of 0. Similarly, the impact of unplanned missing data due to noncompletion of task conditions at age 3 was modeled as a dummy variable (1 = unplanned missing data for the condition at age 3; 0 = no unplanned missing data for the condition at age 3) to determine whether children's noncompletion of Shape School conditions at an early age was related to their performance at subsequent ages.

As a third step in the analyses, time-invariant predictors, including children's sex (1 = boy, 0 = girl) and sociofamilial factor scores (*z* scores with a mean of 0) were entered into the growth models for all Shape School conditions to ascertain the relation of these individual differences to children's mean performance at age 5.25 years (the model intercept) as well as to their growth slopes across time points. All models were constructed using a backwards trimming procedure, where all possible main effects and interactions were added as a block and those with p values > .05 were removed sequentially until the most parsimonious model had been determined. Pseudo R^2 values were calculated as the change in explained variance with the addition of significant predictors (Singer & Willet, 2003).

Finally, to provide a more comprehensive picture of developing executive control, we examined children's error types and self-corrections of their error responses across age. These models were also constructed using the SAS Mixed procedure with age included on the repeated statement. Sex and the sociofamilial factor scores were entered as between-subjects factors in these models to determine their relation to children's error corrections.

Results

Analysis of Missing Data

To ascertain whether task noncompletion was related to children's social background characteristics, we conducted a series of *t* tests comparing children with unplanned missing data with children without missing data at each study time point on several background factors, including sex, maternal education, household income, and the PFA-derived learning and social network resource factors. Although missing data at older ages was not associated with these factors, children with unplanned missing data for any of the Shape School conditions at age 3 years had mothers with lower education relative to 3-year-olds without unplanned missing data, $t(226) = 2.48$, $p = .01$. Furthermore, children with missing data for the baseline naming, $t(226) = 3.51$, $p < .001$, and inhibit, $t(226) = 2.19$, $p = .03$, conditions at age 3 years had lower learning resource factor scores than those with no unplanned missing data.

Descriptive Overview of Performance on the Shape School Across the Preschool Period

Table 1 describes age-related gains in mean accuracy and RT on the four Shape School conditions for each study entry cohort. Notably, performance was similar regardless of entry cohort, indicating that changes in performance were related to true developmental growth and not to retest effects. Pearson's correlations generally indicated some stability in children's Shape School performance, with most correlations for equivalent conditions across the different age points ranging from .16 to .50 (all *p*s < .05). However, intraclass correlations for each of the Shape School conditions ranged from .03 to .09 for accuracy and from .01 to .16 for RT, meaning that only a small amount of the variance in Shape School performance across time points was between-person, whereas over 90% of this variance reflected within-person change.

Correlations between accuracy and concomitant RTs for the first three Shape School conditions revealed that higher accuracy was associated with faster RTs at ages 3–4.5 years ($r = -.17$ to $-.54$, all *p*s < .05), although less so at age 5.3 ($r = -.05$, $p = .35$ to $-.36$, $p <$ .05). In contrast to earlier conditions, accuracy and RTs for the mixed switching condition did not correlate ($r = .01$–$.04$, all *p*s > .05). Below, growth models for each of the conditions are discussed in turn for ease of interpretation.

Predictors of Change in Shape School Performance Over the Preschool Period

Condition 1: Baseline naming.—The best fitting unconditional model for color naming accuracy was a fixed quadratic model. Specifically, with each 9-month increment in age, children's mean growth in accuracy decelerated by half, $\gamma(884)_{\text{Slope}} = -.036$ ($SE = .016$), $p = .02$; $\gamma(877)_{\text{Deceleration}} = -.037$ ($SE = .005$), $p < .001$. Likewise, gains in RT decelerated over time, $\gamma(852)_{\text{Slope}} = .012$ ($SE = .029$), $p = .663$; $\gamma(891)_{\text{Deceleration}} = .094$ ($SE = .009$), $p < .001$. Children also showed significant individual variation in their rates of growth for RT, as illustrated by improved model fit with the addition of a random slope term, $\Delta\chi^2(1) = 97.3$, $p < .001$. When dummy variables for retest effects were included in the models, none was significant, indicating that changes in children's naming performance were not an artifact of repeated Shape School administration. Similarly, unplanned missing data at age 3 years was not a significant predictor, indicating that children who did not complete the color naming condition at age 3 performed similarly to their peers on the baseline naming condition at later age points.

Table 2 shows the final, conditional model for baseline naming. Girls consistently scored approximately 3% higher than boys ($p = .017$), despite maintaining equivalent RTs ($p = .652$). The effects of learning ($p < .001$) and social network ($p = .006$) resources on baseline naming accuracy diminished over time. As shown in Figure 1, although children with different levels of learning resources differed in their accuracy and RTs at the beginning of the study, performance was equivalent by age 5.25 years. The effect of social network resources on RT was moderated by sex, such that higher levels of social resources were more strongly associated with speed for boys ($p = .016$). Together, sex and sociofamilial factors explained 8% of the variance in accuracy and 1% of the variance in RTs for baseline naming over and above age alone.

Condition 2: Inhibit.—After accounting for children's time-varying performance on the baseline naming condition, the statistically preferred unconditional growth model for inhibitory control accuracy was a fixed quadratic model, where growth decelerated over time, $\gamma(864)_{Slope} = .003$ ($SE = .020$), $p = .893$; $\gamma(871)_{Deceleration} = -.049$ ($SE = .007$), $p < .001$. However, the slope of growth for RT was linear, indicating a consistent magnitude of change in speed throughout the preschool period, $\gamma(1023)_{Slope} = -.120$ ($SE = .010$), $p < .001$. Retest effects were not significant. However, children with unplanned missing data for this blocked condition at age 3 showed a lower accuracy intercept, scoring an average of 8% lower than their peers even at age 5.25 years, $\gamma(456) = -.077$ ($SE = .028$), $p = .006$. As shown in Table 2 and Figure 2, after accounting for baseline naming performance and for unplanned missing data at age 3, there was a main effect of learning resources, where every one standard deviation increase in learning resources was associated with a 3% increase in inhibition accuracy, $\gamma(368) = .029$ ($SE = .016$), $p = .001$. The pseudo ΔR^2 for these predictors of accuracy was 6%. Neither sex nor resources were related to RTs for this condition.

Condition 3: Blocked switch.—Similar to other conditions, growth in blocked switch performance diminished over time, $\gamma(848)_{Slope} = -.015$ ($SE = .022$), $p = .512$; $\gamma(869)_{Deceleration} = -.045$ ($SE = .008$), $p < .001$. In contrast, RTs improved at a steady rate through the preschool years, $\gamma(886)_{Slope} = -.174$ ($SE = .015$), $p < .001$. There were no retest effects. However, children with unplanned missing data at age 3 years showed lower accuracy, $\gamma(437) = -.054$ ($SE = .023$), $p = .019$ and slower RTs at subsequent assessment points, $\gamma(369) = .090$ ($SE = .041$), $p = .031$.

As shown in Table 2, boys were less accurate than their female counterparts on the blocked switch condition at age 3, $t(1015) = -3.78$, $p < .001$, but showed comparable accuracy by 5.25 years, $t(947) = 0.53$, $p = .595$. Correspondingly, girls were slower to respond than boys at age 3 years, $t(945) = 3.12$, $p = .002$, but were naming shapes as quickly as boys by age 5.25, $t(729) = -0.04$, $p = .971$. Figure 3 shows that children with lower resources showed more rapid gains in blocked switch accuracy than their peers, the positive association between learning resources and accuracy thereby diminishing over time ($p < .001$). Nonetheless, higher learning resources were consistently associated with quicker RTs for this blocked switch condition ($p = .034$). Predictors explained 13% of the variance in accuracy and 2% of the variance in RTs above and beyond age, unplanned missing data and baseline naming.

Condition 4: Mixed switching.—For the final, mixed switching condition of the Shape School, the best fitting unconditional model for children's accuracy was a fixed quadratic model, where growth tapered off over time, $\gamma(754)_{Slope} = .043$ ($SE = .018$), $p = .018$; $\gamma(758)_{Deceleration} = -.043$ ($SE = .006$), $p < .001$. Growth in RTs was linear, $\gamma(867)_{Slope} = -.034$ ($SE = .016$), $p = .032$. There were no significant retest effects. However, children with unplanned missing data for this mixed switching condition at age 3 years were, on average, 9% less accurate than their peers at later time points, $\gamma(383) = -.094$ (SE .023), $p < .001$.

Table 2 shows the final model for mixed switching accuracy, which controlled for baseline naming performance and unplanned missing data at age 3 years. Higher levels of learning resources were associated with greater accuracy in switching throughout the preschool period, although the effect was stronger at younger ages (see Figure 4). Additionally, sex moderated the association between social resources and accuracy, such that there was a 4% increase in accuracy for every standard deviation increase in social resources for boys only (p = .041). Figure 4 also shows that higher learning resources were associated with longer switching RTs at younger ages, although this effect attenuated over time (p = .002). Girls were consistently slower to respond on this mixed switching condition than boys (p = .004). Predictors explained 7% of the variance in accuracy and latency, respectively.

Changes in Error Types on the Shape School Over the Preschool Period

Table 3 shows the relative proportions of error types across the different Shape School conditions at each age point. For all conditions, the types of errors that children made varied proportionally by age. More precisely, post hoc contrasts for the baseline naming condition indicated that 3-year-old children were more likely to make “other” errors that were not related to task stimuli when compared with children of older ages. Similarly, for the inhibit, blocked switch, and mixed switching conditions, children aged 3 and 3.75 years made a greater number of distractor and other errors, whereas within-dimension errors were proportionally more common at older ages.

In addition to changes in types of errors made on the Shape School task, children showed an increase in the number of errors that they self-corrected with age, $F(3, 3301) = 150.02$, $p < .001$. Self-corrections were proportionally less prevalent for later task conditions than they were for the first two conditions, $F(12, 1658) = 1.85$, $p = .036$. Boys were more likely than girls to self-correct their incorrect responses on the baseline naming condition, $F(1, 319) = 7.79$, $p = .006$. For the inhibit, $F(1, 311) = 5.77$, $p = .017$, and mixed switching conditions, $F(1, 358) = 10.69$, $p = .001$, children with higher learning resources showed a higher probability of correcting their incorrect responses.

Discussion

This study is among the first to describe the early pattern by which executive control capabilities unfold across the preschool period using prospective, longitudinal follow-up over multiple age points. Findings highlight the period of 3–4 years as a time of accelerated gain in inhibitory control and cognitive flexibility, which possibly reflects a qualitative shift in children’s processing of executive task demands. Moreover, the study provides evidence for a sustained impact of children’s early access to learning resources on their ongoing acquisition of these executive skills. As such, this age offers a promising window of opportunity for preventive intervention, where enhanced access to stimulating learning resources and interactions may boost subsequent development of executive skills, with potentially cascading positive effects on other important abilities that have been linked to executive control, including theory of mind (Carlson & Moses, 2001), emotion regulation (Carlson & Wang, 2007), mathematics, and literacy (Bull et al., 2008).

Between 3 and 3.75 years, children’s accuracy on the Shape School inhibit condition improved from below 40% to over 70%. This rapid change is in keeping with previous studies, one of which is that of Carlson (2005), who reported pass rates of 45% for 3-year-olds and 70% for 4-year-olds on a battery of inhibitory control tasks. Such similarities across different tasks support the idea that inhibitory control growth is occurring at the construct, as opposed to the task, level. The abrupt rise in inhibition accuracy to almost ceiling levels in this short time frame suggests a qualitative shift in children's conceptual understanding of task demands and application of complex rule systems. Correspondingly, the linear trajectory of growth for RTs on the inhibit condition is consistent with studies showing gains in speed on inhibition tasks in later childhood and supports the idea that it is the efficiency with which children are able to inhibit a response, rather than their basic ability to suppress a response, that continues to improve through later preschool and perhaps middle childhood (Best & Miller, 2010).

One clear advantage of this study was the ability to compare growth in inhibitory control with that of switching, with findings indicating dissimilar growth trajectories for these skills. For the inhibit and blocked switch conditions, gains in accuracy showed similar trajectories, perhaps indicating that the ability to inhibit prepotent responses and to make a single, global shift from one task set to another rest on similar underpinning substrates. In contrast, children's accuracy for the mixed switching condition was approximately 10% below that of other conditions even by age 5.25 years. Diamond (2009) has argued that this type of mixed switching is particularly difficult because neural systems operate at a gross level, making it easier to invoke a global shift in behavior and continue to exercise this response repeatedly than it is to invoke different response sets that then are differentially implemented across trials on the basis of cues. The higher goal representation and abstractive demands in the mixed switching condition may also pose a challenge, as children must decide which task is relevant and recognize a change in these requirements, relative to blocked switching, where they need only hold one explicitly stated goal in mind throughout the condition (Chevalier et al., 2012). Recent studies suggest that goal representation is difficult for preschoolers, especially when task cues only arbitrarily relate to the response requirements of the task (Blaye & Chevalier, 2011). In sum, subtle differences in the trajectories for different Shape School conditions hint at different underlying demands and perhaps portend a separation of different executive control components, as is commonly reported in adults (Miyake et al., 2000).

Changes in children's error patterns and self-corrections also suggest a qualitative shift in the processes they apply to executive control tasks. The error types of older children were more organized and systematic, often centered on the actual switching demands of the task. In contrast, younger children made more random errors related to distracting or irrelevant task features, perhaps indicating that their difficulty was not in inhibiting or switching based on a particular dimension but actually in attending selectively to the relevant cues or dimensions that support effective Shape School performance. Much of the difficulty for young children may therefore relate to the suppression of bottom-up interference. This pattern is consistent with evidence that young children perform better on card sorting tasks when requirements on selective attention are dampened (Hanania & Smith, 2010). High levels of self-correction reveal a surprisingly high level of volitional self-monitoring in this young age range, perhaps facilitated by children's rapid gains in inhibitory control.

Importantly, findings suggest that children's early access to learning resources facilitates their growth in executive control. A major advantage of the Shape School is the ability to examine the added "cost" of executive demands after taking into account baseline performance with the same stimulus features. The developmental lag in baseline naming abilities for children with fewer learning resources suggests that much of the impact of the environment on executive control is mediated by more general processes, such as language and processing speed, that are rallied by prefrontal cortical circuits to support executive task performance. Presumably, familiarity with concepts such as color and shape assists performance by increasing representational salience and decreasing the load on cognitive resources needed to process this basic information when switching between complex rules. Nonetheless, even after accounting for baseline naming performance, lower resources were associated with a persistent discrepancy in inhibition and switching accuracy across all ages. Although the more restricted range of performance accuracy at age 5.3 may have attenuated the variance associated with predictors at later age points, there was still significant interindividual variance in the intercept for all Shape School conditions, making it unlikely that findings are attributable to ceiling effects. Moreover, children with fewer learning resources were less likely to self-monitor by correcting erroneous responses on executive conditions. In essence, these findings indicate that greater access to learning resources affects the entire trajectory of executive skill development, conferring a specific advantage for executive capabilities over and above baseline processing skills, which is still apparent at kindergarten entry. There are several potential explanations for this independent association of learning resources with executive control. Children with greater exposure to learning resources may have more opportunities to practice holding information "online" or integrating concepts and relations. Event-related potential studies (e.g., Stevens, Lauinger, & Neville, 2009) have also indicated that basic neural responses related to attention control may be disrupted in children from homes with lower SES, which in turn may impact on the development of higher order executive control. It is important to note that effect sizes were relatively small, a one standard deviation rise in learning resources contributing a 2%–8% advantage in accuracy at age 5.25 years. Nonetheless, even slight delays in inhibitory control and flexibility skills are likely to undermine children's school readiness, with ongoing implications for classroom behavior and learning.

Findings hint at subtle differences in the rate of executive control growth for girls and boys. Girls were more accurate than boys in baseline naming and also showed a more accelerated slope of growth for the Blocked Switch condition, perhaps reflecting a faster maturation of language abilities in girls. Interactions between sex and social resources for the baseline naming and mixed switching conditions also indicate a potential vulnerability in males to social network-related stressors in terms of their early cognitive flexibility development. Interestingly, boys were quicker to respond on the switching conditions, perhaps suggesting that girls are slowing their performance on tasks demanding high performance monitoring where boys are not.

Knowledge of normative patterns of growth in executive control gained from longitudinal studies like this one can inform developmental assessment and intervention. For instance, given high levels of accuracy on the Shape School by age 4.5 years, low accuracy in a child of this age may warrant further evaluation and monitoring. Unexpectedly, findings indicated that children who were unable to complete conditions of the Shape School at age 3 may represent those with most cause for concern, as their mean accuracy on subsequent test occasions was 4%–9% lower than the mean. These findings complement those of Pritchard and Woodward (2011), who reported that children born very preterm were less likely than children born full term to complete executive Shape School conditions at age 4 years, with task noncompletion being prognostic of academic and language delays 2 years later. Although the pattern of catch-up growth for baseline naming skills in children with fewer learning resources is encouraging, the clear, persistent relation between early learning resources and executive control skills in this study has policy implications, highlighting a pressing need to facilitate access to high-quality early educational experiences if we are to improve school readiness in children from disadvantaged backgrounds. This is all the more important when one considers that children in the United States from the most economically disadvantaged environments are also the least likely to attend quality preschool programs (Wright, 2011). As the children in this study mature, continued monitoring of their performance on similar tasks may shed new insight into how normative and atypical biological and social experiences affect executive control growth and ultimately determine the course of children's development.

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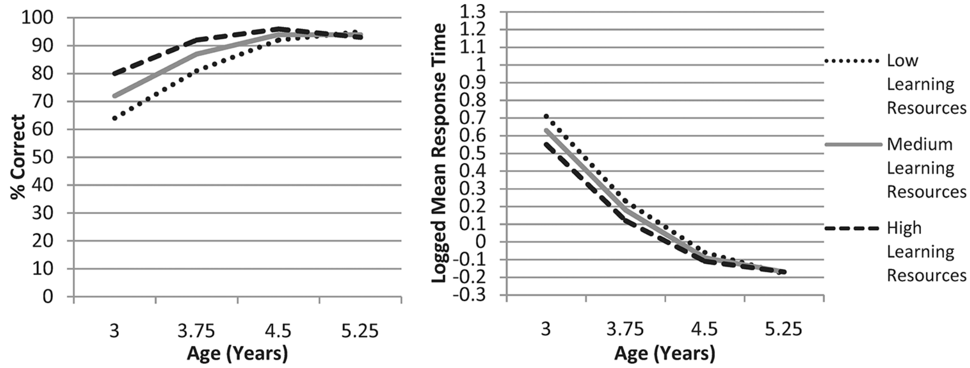

Figure 1.

Relations between learning resources and growth in performance on the Shape School baseline naming condition. Figures illustrate the estimates derived from growth models for a child exposed to learning resources one standard deviation below the mean (low), within one standard deviation of the mean (average), and one standard deviation above the mean (high), holding all other model predictors constant.

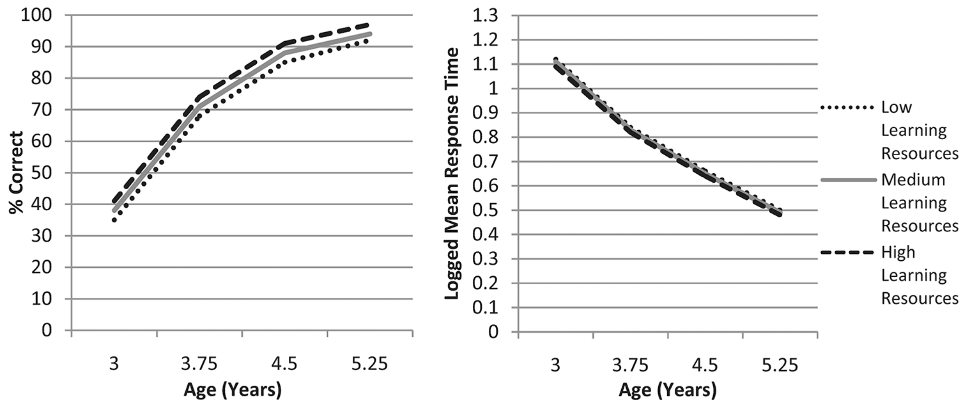

Figure 2.

Relations between learning resources and growth in performance on the Shape School inhibit condition.

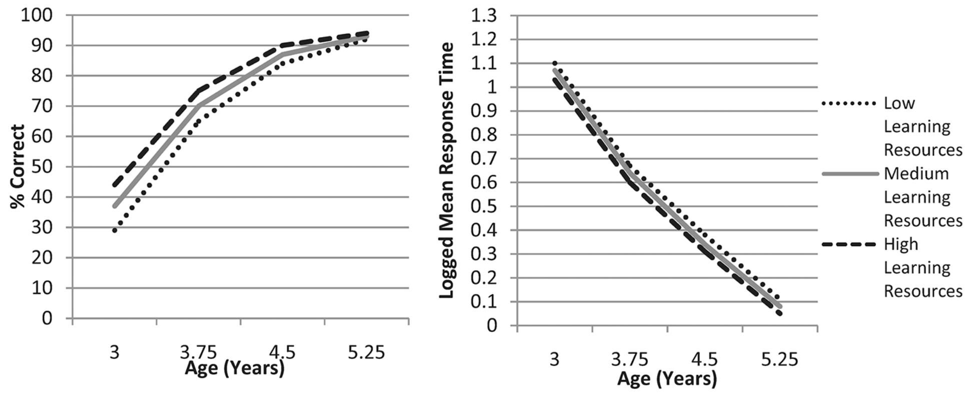

Figure 3.

Relations between learning resources and growth in performance on the Shape School blocked switch condition.

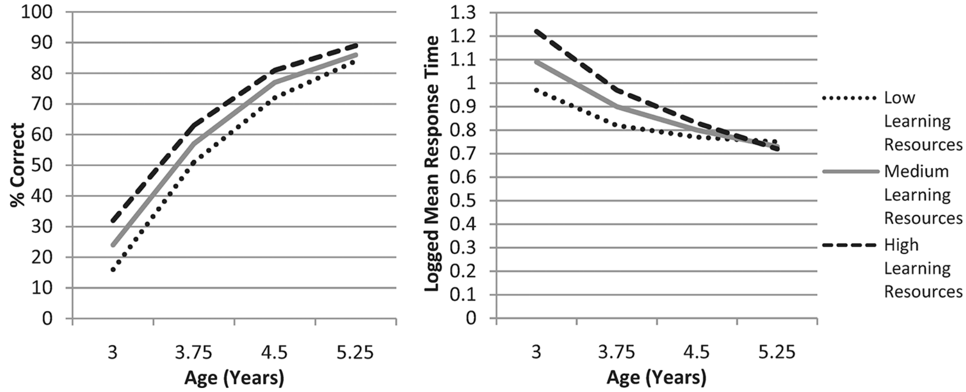

Figure 4.
Relations between learning resources and growth in performance on the Shape School mixed switching condition.

Table 1

Mean Performance Over the Preschool Period on Four Conditions of the Shape School

Condition	*M (SD)* accuracy by age 3	3.75	4.5	5.25	*M (SD)* response time(s) by age 3	3.75	4.5	5.25
Baseline naming								
Cohort 1	.71 (.33)	.89 (.18)	.93 (.12)	.95 (.07)	2.18 (1.52)	1.23 (.60)	.99 (.31)	.89 (.28)
Cohort 2		.86 (.22)	.92 (.15)	.96 (.06)		1.24 (.52)	.98 (.34)	.84 (.21)
Cohort 3			.93 (.10)	.94 (.13)			1.03 (.39)	.82 (.18)
Cohort 4				.94 (.07)				.85 (.18)
Inhibit								
Cohort 1	.38 (.34)	.73 (.32)	.86 (.26)	.94 (.14)	3.37 (2.03)	2.50 (.87)	1.92 (.52)	1.67 (.36)
Cohort 2		.72 (.33)	.92 (.15)	.96 (.06)		2.37 (.85)	1.93 (.62)	1.71 (.34)
Cohort 3			.89 (.22)	.95 (.10)			2.10[a*] (.79)	1.71 (.34)
Cohort 4				.97 (.06)				1.75 (.35)
Blocked switch								
Cohort 1	.42 (.42)	.76 (.33)	.86 (.26)	.92 (.16)	2.78 (1.91)	2.19 (1.43)	1.49 (.71)	1.17 (.53)
Cohort 2		.75 (.31)	.89 (.22)	.95 (.07)		2.04 (1.36)	1.44 (.60)	1.12 (.45)
Cohort 3			.84 (.22)	.89[b*] (.20)			1.66 (.93)	1.15 (.34)
Cohort 4				.93 (.12)				1.19 (.38)
Mixed switching								
Cohort 1	.27 (.27)	.59 (.30)	.76 (.25)	.84 (.18)	3.83 (3.15)	2.86 (1.47)	2.54 (.94)	2.28 (.68)
Cohort 2		.62 (.27)	.75 (.25)	.89 (.14)		3.16(1.97)	2.43 (.98)	2.21 (.58)
Cohort 3			.73 (.22)	.85 (.21)			2.74 (1.05)	2.19 (.64)
Cohort 4				.88 (.15)				2.17 (.47)

[a*] $p < .05$ versus Cohort 1.

[b*] $p < .05$ versus Cohort 2.

Table 2

Predictors of Preschoolers' Growth in Accuracy and Response Time for Four Conditions of the Shape School

	Shape School condition							
	Baseline color naming		Inhibit		Block switch		Mixed switch	
Variable	Accuracy	RT	Accuracy	RT	Accuracy	RT	Accuracy	RT
Fixed effects								
Intercept	.954*** (.011)	−.157a*** (.019)	.927*** (.015)	.571*** (.018)	.885*** (.018)	.195* (.032)	.859*** (.015)	.898*** (.028)
Condition A performance			.100*** (.007)	.141*** (.011)	.105*** (.009)	.208*** (.018)	.057*** (.008)	.153*** (.018)
Unplanned missing data at age 3			−.066* (.028)	.053 (.033)	−.043 (.023)	.077 (.041)	−.085*** (.022)	.038 (.037)
Sex	**−.029*** (.012)	−.012 (.023)	−.013 (.016)	−.005 (.018)	−.012 (.023)	−.006 (.040)	−.024 (.017)	**−.084*(.029)**
Learning resources	−.008 (.010)	.002 (.016)	**.029**** (.094)	−.012 (.011)	.011 (.0134)	**−.034*** (.028)	**.026*** (.013)	−.018 (.023)
Social resources	−.010 (.010)	**−.060**** (.019)	.002 (.009)	.005 (.010)	.009 (.010)	−.001 (.018)	−.009 (.014)	−.012 (.023)
Sex × Social Resources		**.079**** (.027)					**.042*(.020)**	
Linear slope	−.038* (.016)	.015 (.027)	.001 (.020)	−.121*** (.010)	−.001 (.023)	−.204*** (.020)	.035 (.015)	−.029 (.015)
Slope × Sex					**.042**** (.014)	**.051*** (.025)		
Slope × Learning Resources	**−.030***** (.005)	**.029*** (.012)			**−.021**** (.008)		**−.016*** (.006)	**−.047**** (.016)
Slope × Social Resources	**−.015***** (.005)							
Quadratic slope	−.037*** (.005)	.094*** (.009)	−.050*** (.007)	.009 (.026)	−.049*** (.008)		−.047*** (.006)	
Stochastic effects								
Residual	.029*** (.001)	.077*** (.005)	.047** (.002)	.074*** (.004)	.055" (.002)	.134*** (.008)	.016*** (.002)	.145*** (.008)
Intercept	.004*** (.001)	.008 (.006)	.006*** (.002)	.005* (.002)	.005*** (.002)	.030*** (.007)	.036*** (.002)	.019*** (.006)
Slope		−.002 (.003)						
Slope intercept covariance		.013*** (.003)						
Fit statistics								
−2 log likelihood	−639.9	721.1	−61.7	351.3	86.8	1,009.3	−184.1	1,028.2
AIC	−635.9	729.1	−57.7	355.3	90.8	1,013.3	−180.1	1,032.2
BIC	−628	745	−49.8	363.2	98.7	1,021.2	−172.2	1,040.1

Note. RT = response time; AIC = Akaike's information criterion; BIC = Bayesian information criterion. Significant effects of sex, learning resources, and social network resources are in bold. Standard errors are in parentheses.

[a]The reaction time intercept is negative as a result of logging the distribution for reaction times.

*$p < .05$.

**$p < .01$.

***$p < .001$.

Table 3

Proportions of Error Types for Different Conditions of the Shape School Over the Preschool Period

	Age (years)					
Shape School condition	**3 (1)**	**3.75 (2)**	**4.5 (3)**	**5.25 (4)**	$F_{(\text{Age} \times \text{Error Type})}$	**Contrast**[a]
Baseline color naming (*N*)	144	152	167	166		
Switch error	.24 (.38)	.23 (.38)	.27 (.42)	.29 (.42)		
Within-dimension error	.43 (.44)	.62 (.44)	.65 (.44)	.67 (.44)		1 < 2, 3, 4
Distractor error	.01 (.08)	.01 (.05)	.01 (.09)	.03 (.17)		
Other error	.32 (.40)	.14 (.30)	.07 (.23)	.01 (.05)	13.64[***]	1 > 2 > 3, 4
Errors self-corrected	.32 (.41)	.51 (.44)	.67 (.43)	.76 (.40)	37.02[**]	1 < 2 < 3 < 4
Inhibit (*N*)	149	172	163	152		
Inhibit error	.33 (.26)	.30 (.35)	.27 (.38)	.29 (.41)		
Switch error	.01 (.05)	.01 (.04)	.01 (.07)	.01 (.09)		
Within-dimension error	.11 (.21)	.25 (.38)	.40 (.46)	.55 (.47)		1 < 2 < 3 < 4
Distractor error	.38 (.34)	.36 (.40)	.20 (.39)	.12 (.31)		1, 2 > 3 > 4
Other error	.17 (.25)	.08 (.18)	.05 (.20)	.03 (.15)		1 > 2, 3, 4
Errors self-corrected	.15 (.28)	.33 (.40)	.52 (.46)	.70 (.43)	77.68[***]	1 < 2 < 3 < 4
Blocked switch (*N*)	95	158	194	168		
Switch error	.38 (.44)	.30 (.42)	.25 (.40)	.25 (.39)		1 > 3, 4
Within-dimension error	.28 (.40)	.45 (.45)	.63 (.44)	.71 (.42)		1 < 2 < 3 < 4
Distractor error	.12 (.28)	.06 (.21)	.03 (.15)	0 (.02)		1 > 3, 4
Other error	.23 (.35)	.19 (.35)	.09 (.25)	.03 (.15)	20.29[***]	1, 2 > 3, 4
Errors self-corrected	.16 (.32)	.37 (.44)	.57 (.45)	.72 (.41)	65.19[***]	1 < 2 < 3 < 4
Mixed switching (*N*)	96	207	249	266		
Switch error	.64 (.35)	.77 (.29)	.82 (.29)	.81 (.30)		1 < 2 < 3, 4
Within-dimension error	.05 (.10)	.10 (.19)	.09 (.22)	.05 (.17)		
Distractor error	.19 (.29)	.06 (.18)	.02 (.10)	01 (.07)		1 > 2 > 3, 4
Other error	.12 (.22)	.07 (.17)	.05 (.16)	.03 (.10)	14.34[***]	1 > 3,4
Errors self-corrected	.11 (.22)	.23 (.34)	.34 (.39)	.50 (.43)	50.16[***]	1 < 2 < 3 < 4

Note. Values reflect the proportion of all errors that fell into the error category.

[a] Describes contrasts between age groups that were significant at $p < .05$.

** $p < .01$.

*** $p < .001$.