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Children's Task-Switching Efficiency: Missing Our Cue?

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In simple rule-switching tests, 3- and 4-year-olds can follow each of two sorting rules but sometimes make perseverative errors when switching. Older children make few errors but respond slowly when switching. These age-related changes might reflect the maturation of executive functions (e.g., inhibition). However, they might also reflect children's ability to use task cues. Cue-processing difficulties predict switch costs in adult task switching (Logan & Schneider, 2007). It is unknown whether they explain children's task-switching errors or slowing. The current study tested whether inhibition, cue interpretation, or both predict 3- to 6-year-old children's switch-related errors (Experiment 1) and slowing (Experiment 2). Children performed a computerized task-switching test in which most trials were preceded by an audiovisual cue that instructed them to switch rules, or to stay—that is, continue using the current rule. Interspersed control trials used no cue. In Experiment 1, 3- and 4-year-olds made as many errors on cued stay trials as on cued switch trials; however, children were significantly more accurate on uncued stay trials. The presence of cues, not switching demands, predicted errors. Accuracy was predicted by children's speed in a simpler task in which children matched stimuli on only one dimension (shape or color), with no stimulus conflict or rule switches. Additional variance was predicted by an unrelated measure of processing speed. In Experiment 2, switch costs in 4.5- to 6-year-olds were similarly predicted by speed in the simpler unidimensional matching task.

Everyday life often requires shifting between multiple tasks. It is important, for example, to be able to put aside a project report, read an incoming e-mail, and then return productively to the report. Many researchers suggest that this sort of cognitive flexibility—the ability to adaptively shift ''task set'' or responses, when circumstances demand it—is dependent upon other, related executive functions. Such switches require us to keep goals in mind, inhibit some actions, and organize other actions based on still-relevant goals and on new exigencies.

The relationship of cognitive flexibility to other executive functions, however, remains a matter of debate. Researchers do not agree about how to define various executive functions (e.g., ''inhibition''), and there is continuous progress in specifying the neurological and functional structure of cognitive control processes. These debates affect our understanding of the nature of cognitive flexibility and its limitations in children, as well as in certain psychiatric populations (e.g., Anderson, Damasio, Jones, & Tranel, 1991; Berwid et al., 2005; Cepeda, Cepeda, & Kramer, 2000).

Studies of healthy adults and a few studies of older children have inspired the proposal (Friedman & Miyake, 2004; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Miyake et al.,

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2000; Wu et al., 2011) that executive functions can be separated into at least three partly independent factors: flexibility (or switching), inhibition, and working memory. Evidence also suggests specific subdivisions and connections among the three factors. Although this model provides a useful starting point for a more elaborate theory of how adults' cognitive flexibility relates to other cognitive processes, latent variable studies in children do not uniformly support a parallel model of children's cognitive flexibility and its relation to other executive functions (Wiebe, Espy, & Charak, 2008).

One reason why tests of the three-factor model in children lag behind is that there are fewer testing methods. In addition, the most commonly used tests for young children are robust and replicable, but not sensitive enough to distinguish between the kinds of alternative models of cognitive processing that are being tested in studies of adults. Many studies of younger children (i.e., 2 to 5 years of age) have used rule-switching tests that yield qualitative, binary responses, and often, ultimately, a categorical characterization of individual children's flexibility. In these tasks, children are explicitly told to switch from one simple binary rule to another. For example, children might match a bivalent stimulus by color and then be told to switch to a different rule: Match the same stimulus by shape. The second rule requires children to reverse the responses that they had made in order to follow the first rule.

Children younger than 4 years old tend to make errors after a rule switch: Many continue to follow the first rule (Zelazo, 2006; Zelazo & Frye, 1996)—that is, to perseverate. Curiously, children who perseverate can accurately repeat the second rule (Zelazo, Frye, & Rapus, 1996), suggesting that they have encoded it. The reasons for these perseverative errors have been debated (Davidson, Amso, Anderson, & Diamond, 2006; Deák, 2000, 2003; Hanania & Smith, 2010; Span, Ridderinkhof, & van der Molen, 2004; Zelazo, Müller, Frye, & Marcovitch, 2003). The persistence of this debate might be partly due to the limited sensitivity of common rule-switching tests, which yield only one sort of ''catastrophic'' error and do not usually distinguish between degrees of flexibility or between degrees or subtypes of perseverative errors (Deák, 2003).

Other evidence suggests that when 3- and 4-year-old children are allowed more response options on each trial, they show a wider variety of flexible and inflexible response patterns. For example, Three Dimension-Changes Card-Sorting Test (Cepeda & Munakata, 2007; Deák, 2003; Narasimham, Deák, & Cepeda, 2013) imposes three rules and two task switches, as well as four choices of items, per trial. This reveals several new response patterns, including patterns of partial flexibility and of unsystematic response-switching (Narasimham et al., in review). This shows that preschoolers' rule-switching flexibility is not binary but is a more continuously varying, task-dependent skill that can reflect different underlying strategies. On a practical level, this means that we can measure preschoolers' task switching using parametric tests.

Thus far, the few studies focusing on preschool-aged children have not been fully contextualized within the larger literature on cue processing. That literature, although centered on adults (e.g., Allport, Styles, & Hsieh, 1994; Meiran, 1996; Monsell, 2003), includes a growing number of studies on children (Cepeda, Kramer, & Gonzalez de Sather, 2001; Crone, Bunge, van der Molen, & Ridderinkhof, 2006; Gupta, Kar, & Srinivasan, 2009; Karbach & Kray, 2007, 2009). Task-switching tests also use bivalent, rule- or cue-dictated task reversals; however, children aged 5 years or older, unlike 3- and 4-year-olds, make few errors. Rather, like adults, they show a slowing, or ''switch cost,'' on the first trial after a cue to switch rules. These switch costs vary in magnitude, but they seem to be ubiquitous and are typically much larger in magnitude in children than in adults (Diamond & Kirkham, 2005).

A goal of this article, then, is to bridge, and hopefully to unify, explanations for young children's categorical task-switching errors and for older children's graded switch costs. To achieve this, we designed a task-switching test that is appropriate for children as young as 3.5 to 4 years. The task uses verbal cues and simple stimuli (i.e., colored line drawings of animals) in a computer-administered procedure so that both accuracy and response time (RT) can be assessed, thus allowing direct comparison of flexibility in preschool children and in older children. This test was used to evaluate several explanations for the development of task-switching efficiency from 3 to 6 years of age.

Explanations of Perseverative Errors and Switch Costs

At least two main alternative explanations have been proposed for 3- and 4-year-olds' perseverative rule-switching errors. One is that young children fail to inhibit the habit generated during the preswitch trials. They might fail to inhibit their practiced associations between the two initially relevant perceptual features (e.g., ''If it's blue . . . '') and motor responses ('' . . . put it in the left box''). Alternately, they might perseverate because they cannot inhibit their induced bias to attend to the stimulus dimension associated with the first rule. For example, children are more likely to perseverate if the last cards they sorted under the first rule remain visible than they are if the cards are hidden (Diamond, Carlson, & Beck, 2005; Kirkham, Creuss, & Diamond, 2003), suggesting that perceptual salience can modulate inhibitory difficulty. This is consistent with arguments that switch costs are induced by the cognitive demands of suppressing the first rule (Allport et al., 1994; Wylie & Allport, 2000).

Another explanation is that with age, children can more efficiently link contextual cues and stimulus features in active memory (Morton & Munakata, 2002). This allows them to maintain current goals in the face of competing representations based on previous actions. However, rules that are less familiar are harder to activate and maintain (Munakata, 2001). Children who make perseverative errors in the Dimensional Change Card Sort task (DCCS) also show weaker representations of the rules, even when those rules are tested in no-conflict (i.e., all stimulus properties ''pull'' for the same response), nonswitching tasks (Blackwell, Cepeda, & Munakata, 2009; Cepeda & Munakata, 2007). This finding that speed of matching no-conflict, single-dimension stimuli (e.g., blue or brown color swatches) predicts switching is notable because rule-switching difficulty has been attributed to the processes necessary to adjudicate between the alternative responses that are mandated by the distinct rules (Cragg & Nation, 2009). However, the aforementioned results suggest that automation of very low-level contingencies determines higher-level, adaptive control.

We tested young children's speed to activate a low-level stimulus-response contingency by using no-conflict, unidimensional stimuli (similar to Blackwell et al., 2009). Children matched either colored squares or black-and-white shapes in separate blocks of trials (i.e., without switching dimensions). This task matched all the perceptual, memory, cuing, and response demands of the task-switching task. The ''associational activation strength'' explanation (Munakata, 2001) suggests that in younger children, task-switching speed and accuracy are predicted by efficiency of ''unidimensional'' matching. To robustly test this hypothesis, younger preschool children (3 to 4.5 years old) were tested in Experiment 1, and older children (4.5 to 6 years old) were tested in Experiment 2. It is possible that low-level association strength will matter more for younger children, who might be slower to make perceptual comparisons, compared with older children, who should be able to quickly make these matches. If task switching is determined by speed to activate a low-level stimulus–response association, it might be predicted by unidimensional task switching.

To test the alternative explanation that inhibitory efficiency predicts rule-switch flexibility, we designed a go–no go test (Mesulam, 1985) for preschool-aged children. Children make speeded responses to a stimulus appearing at irregular intervals, but they must suppress a response to a rare alternative stimulus. As the task becomes faster, participants begin to make commission errors, and individual and age differences are expected in the speed limit at which children make a certain proportion (e.g., 50%) of ''no go'' errors. Because go–no go tests have only recently been used with 3- and 4-year-olds (Simpson & Riggs, 2006, 2007), however, another age-appropriate test of inhibition was also administered for breadth: Luria's Tapping Test (Diamond & Taylor, 1996; Luria, 1966). In this test, children must inhibit the tendency to imitate an adult's action by ''doing the opposite.'' If inhibitory efficiency predicts task-switching flexibility in 3- to 6-year-olds, one or both of these tests should predict switch costs.

The Role of Cues in Task Switching

Both of the foregoing explanations have implications for children's processing of task cues. The role of cues in task switching has received increasing attention in studies of adults. Some researchers attribute switch costs to the need to ''reconfigure'' or ''transition'' from the current task-set after a new cue (Arrington, Logan, & Schneider, 2007; Forstman, Brass, & Koch, 2007; Mayr, 2006). Explicit cues make it easier for participants to activate the correct rule contingency in working memory (Miyake, Emerson, Witzki, Padilla, & Ahn, 2004). They reduce the number of inferential steps between the cue stimulus and the most strongly represented contingency; moreover, they minimize any potential confusion about which task or response is indicated. Indirect cues constitute weaker evidence and thus require the participant to retrieve additional information or carry out more operations to achieve some threshold of confidence for choosing a response. Task-switch performance is better with more direct cues (e.g., ''color'' and ''shape'') than it is with less direct cues (e.g., the letters ''c'' and ''s'') especially under concurrent verbal processing demands (Miyake, Emerson, Padilla, & Ahn, 2004; Karbach & Kray, 2007). These differences in ease of cue-mediated response selection might account for the bulk of switch-cost effects (Logan & Schneider, 2007). Both children and adults fixate longer on cues when two more tasks must be alternated (or ''switched'') between in a single block versus when the task is alternated between successive blocks (Chevalier, Blaye, Dufau, & Lucenet, 2010), though there are additional fixations occurring after the stimulus.

This RT cost for indirect cues is substantial for older children (Kray, Eber, & Karbach, 2008; Kray, Eber, & Lindenberger, 2004). Moreover, explicit or ''direct'' task cues can help older children succeed at difficult switching tasks at the cusp of their developmental ability. For example, Chevalier and Blaye (2009) found that children more readily follow rule switches in the Advanced DCCS test if the cue is semantically direct (e.g., a rainbow icon to signal a color test trial) instead of indirect (a black border). However, such effects have not been tested in younger preschool children who, we hypothesize, might require more sustained cognitive resources to process and maintain even relatively ''direct'' (minimally ambiguous) verbal cues.

To address this possibility, our task-switching paradigm used task cues that explicitly indicated both the rule demands and the appropriate response demands. These task cues could directly indicate a new game requiring a switch in response or a repetition of the current game rule. All cues used the common frames, ''Now play the ___ game'' and ''Keep playing the _____ game,'' where *now* and *keep* begin the critical switch and stop cues, respectively. We henceforth refer to these as ''switch'' or ''stay'' cues for brevity, although the task cues were more analogous to the DCCS (in that they indicated both the appropriate game and the response instead of just the response demands as in typical adult paradigms). To test the effects of a verbal cue per se, our stay trials (which were cued as noted earlier) were compared to uncued stay trials. (Note that there is no way to deliver uncued switch trials to young children.) In uncued trials, there was an unspeaking face image during the interval when a video cue would appear in cued trials. If rule-switching effects are due to the demands of cue processing, verbally cued stay trials should be slower than uncued stay trials. If there is a separate, additive effect of task-set reconfiguration (i.e., switching), than we would find the highest accuracy/speed in uncued stay trials, intermediate levels in the cued stay trials, and the lowest accuracy/speed in the switch trials. Also, older children (5- and 6-year-olds), who seldom make rule-switching errors and who should process verbal cues more easily, might not show increased cue-processing errors in the cued, versus uncued, stay trials. However, if cue processing remains a significant cognitive demand, then these older children might show longer RTs in cued than uncued stay trials.

Our theoretical questions address the potential cost(s) of processing and maintaining a cue's meaning and of retrieving the appropriate response set. Preschool children may have difficulty using semantic cues to decide *what* to change. This is critical because cues always co-occur with the need to switch in traditional paradigms, while stay trials are often uncued and thus yield lesser demands for cue integration. As a result, we predict that children should show lower accuracy or longer RT on *cued* incongruent stay trials than on *uncued* incongruent stay trials, neither of which demand switching. We also expect to see differences in accessing the appropriate response set even when there is no demand for switching, as in the unidimensional matching task.

One concern is that the cue itself is a distracting stimulus that is likely to recruit children's attention to some degree, and thereby slow their responses. However, theoretical questions about cuing focus not on this simple attention-orienting demand, but on processing and maintaining a cue's meaning. Thus, if the unidimensional matching test were not controlled for the presence of verbal cues, it would eliminate not only stimulus conflict and switch demands, but also cue-based distraction. This would make it inappropriate for assessing ''pure'' effects of low-level stimulus matching. For this reason, unidimensional matching trials were preceded by stay cues (i.e., ''Keep playing the ____ game.''). Because the cue was repeated on every trial and the task remained constant, there was no semantic processing or cue maintenance demand. However, this controlled for any distracting effect of the ''mere presence'' of a cue stimulus.

Other Assessments

Children completed several brief tests to check that their general cognitive and language abilities were within the expected range for their ages. First, processing speed, which varies across age and individuals, was estimated using the Box Completion Test from the Woodcock-Johnson Battery (Woodcock & Johnson, 1989). Cepeda et al. (2001) found in a lifespan study that processing speed predicted a large proportion of variance in task-switching speed (see also Hale, 1990; Kail, 1991, 1993; Kail & Salthouse, 1994; Salthouse, 1996). Thus, speed in general, rather than cognitive inhibition or cue comprehension, might predict young children's flexibility. Also, forward digit span (Wechsler, 1981) was used as a measure of working-memory span (WMS). WMS develops considerably during early childhood, and differences between children predict other verbal skills (Gathercole & Pickering, 2000). Finally, an age-normed measure of receptive vocabulary, the Peabody Picture Vocabulary Test-Third Edition (PPVT-III), was used to estimate general language ability. Because the task-switching and matching tasks use verbal cues, speed and accuracy might correlate with receptive vocabulary.

EXPERIMENT 1

Method

Participants

English-speaking 3.5-year-old children ($n = 25$; $M_{age} = 3;5$, range = 3;1–3;11; 13 girls) and 4-year-old children ($n = 28$; $M_{age} = 4;5$, range = 4;0–4;10; 15 girls) were recruited from preschools in San Diego County. Children were fluent in English and had no diagnosed language or cognitive delays. Most children were Caucasian and middle class. All procedures were approved by the University of California San Diego Institutional Review Board. Four 3-year-olds and two 4-year-olds were excluded because they did not complete both test sessions.

Materials

Task switching. Responses and RTs were recorded on a two-button box customized for preschool children. Two large colorful buttons were mounted 24 cm apart on a padded wooden tray that was laid across the arms of the child's chair. The tray was designed to minimize children's spurious errors and to maximize their comfort and compliance. Four stimulus images were rendered in Adobe Illustrator: a brown cat, a blue duck, a brown duck, and a blue cat. Shapes and colors were chosen to be prototypical and easy to identify for children.[1] Two target pictures (4 cm^2), a blue cat and brown duck, were constantly present, one near each of the bottom corners of the monitor, directly above the response buttons (see Figure 1). The specific location of the target pictures (left or right) was counterbalanced across participants. During each trial, one of four test stimuli was displayed in the center of the monitor in a 10 cm^2 gray box. Two of the four test stimuli matched the two target pictures (i.e., brown cat and blue duck). These congruent, or ‘‘no-conflict,'' stimuli appeared in 33% of all trials. They required the same response in either game (i.e., rule). The other two test images (67% of trials) were incongruent or conflict stimuli; that is, they matched each target, but on different dimensions. Thus, children had to select one of two conflicting matches, ideally depending upon which game was being played (e.g., the blue cat could be matched with either the blue duck or the brown cat).

[1]Also, the stimulus word pairs *cat* and *duck,* and *brown* and *blue,* are similar in word length and phonological complexity.

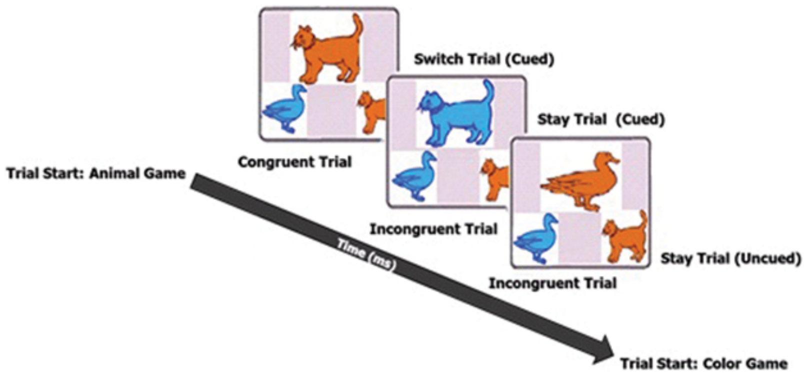

FIGURE 1 Task-switching design. The switch trial was always the first trial of each three-trial same-rule (''game'') block (Experiments 1 and 2).

There were four cue videos. Two *switch cues* showed a model saying, ''Now play the animal game'' or ''Now play the color game.'' Two *stay cues* showed a model saying, ''Keep playing the animal game'' or ''Keep playing the color game.'' All cues were matched frame by frame for length (1,500 ms) and for facial movement and intonation. An 800-ms feedback video of a smiley face or frowning face was presented after each button-press response. In uncued stay trials, a still face replaced the video cue for the same 1,500-ms interval.

Unidimensional matching. A one-dimension rule-matching test (see Blackwell et al., 2009) was based upon the task-switching test, but with no conflict stimuli or rule switches. Four univalent stimuli were created based on the task-switching stimuli: black outlines of the cat and duck and swatches of blue and brown (see Figure 2). These were shown in the same configuration as described in the Task Switching protocol in the Methods section. The ''stay'' video cues (as above) and feedback videos were used. Switch cues were not used.

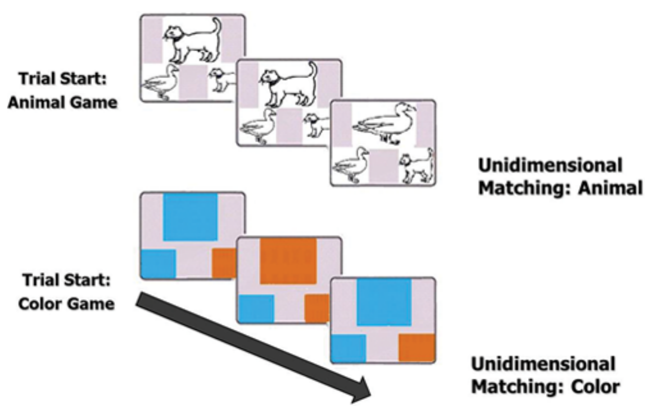

FIGURE 2 Working-memory strength test design (Experiments 1 and 2).

Inhibition, response speed, and verbal tests. The go–no go task used a green circle and red circle (10 cm^2) on a black background. The Box Completion Test consists of a page with five rows of seven three-sided squares, with one line missing from a randomly changing side. The Luria Tapping Test uses two small sticks. In the PPVT-III, participants hear progressively less frequent nouns and verbs and, for each one, point to one of four images that shows the referent of that word. Forward digit span was measured using lists from the Wechsler Adult Intelligence Scale-Third Edition (Wechsler, 1981).

Procedure

Two sessions were completed on site at three preschools in quiet rooms. Task order was fixed. In the first 45-min session, participants completed the Luria Tapping Test, Box Completion Test, unidimensional matching, and the go–no go task. In the second session, a week later, children completed task switching, digit span, and the PPVT-III. Computer tasks were programmed and delivered in Presentation 9.9 (Neurobehavioral Systems, Albany, CA). Children took breaks as needed and received a small toy after each session.

Task switching. Participants were alternately cued to play either the ''animal game'' or the ''color game.'' In both, children matched stimuli (blue cats or brown ducks) based on previously trained matching rules. The rule changed on every 3rd trial, indicated by the video switch cue. The first rule was counterbalanced across participants. The matched stay video cue appeared before either the 2nd or 3rd trial (alternating randomly) within each 3-trial block (Table 1). The other stay trial within the 3-trial block was uncued. Stimuli appeared 700 ms after the video cue terminated. In this design, on every trial, there were 16 possible incongruent switch trials, including 8 kinds of switch trials in each direction (i.e., switch from color to animal or from animal to color), defined by the specific test stimulus, which target it matched in shape and which it matched in color, and their left–right positions. For each type of incongruent stay trial (cued or uncued), there were 16 possible trials, defined by whether the trial was 2nd or 2rd in the block, the test stimulus, which test feature matched each target, and the target position. There were also 8 possible

TABLE 1
Summary of Task-Switch Cue Design, Experiments 1 and 2

Trial Type	*Congruency*	*Target stimuli*	*Test stimuli*	*Cue*
Switch	Incongruent	Brown Duck and Blue Cat	Brown Cat or Blue Duck	''Now play the [animal/color] game.''
Stay (Cued)	Incongruent	Brown Duck and Blue Cat	Brown Cat or Blue Duck	''Keep playing the [animal/color] game.''
Stay (Uncued)	Incongruent	Brown Duck and Blue Cat	Brown Cat or Blue Duck	[Unspeaking face]
Switch	Congruent	Brown Duck and Blue Cat	Brown Duck or Blue Cat	''Now play the [animal/color] game.''
Stay (Cued)	Congruent	Brown Duck and Blue Cat	Brown Duck or Blue Cat	''Keep playing the [animal/color] game.''
Stay (Uncued)	Congruent	Brown Duck and Blue Cat	Brown Duck or Blue Cat	[Unspeaking face]

Note. There are twice as many incongruent as congruent trial types because each test stimulus can correctly match either of the two target stimuli. However, congruent and incongruent trials have exactly the same rules.

congruent switch trials that differed in the direction of the switch, the specific test stimulus, and the left–right target positions. These 56 trial types were presented in random order within a single block. The task lasted approximately 8 min.

Children were initially shown how to place their hands over the buttons and were given extensive practice on the test. The experimenter provided prompts and feedback until children switched responses at least three times within a sequence of 12 practice trials.

Two measures of performance, RT and accuracy, were analyzed in two planned comparisons. First, cued switch trials were compared to cued stay trials. (As previously noted, it is virtually impossible to deliver an uncued switch trial in a rule-switching paradigm.) Second, cued stay trials were compared to uncued stay trials. RTs less than 200 ms (which would have been planned before the test image appeared) were trimmed. RTs from trials in which the child was off-task (as determined by video coding) also were eliminated. The remaining RTs were not transformed, except outlier trials greater than 2 standard deviations (*SD*) above the mean of the remaining trials within each trial type. These were Winsorized to $+2$ *SD* above the relevant mean. This affected fewer than 5% of trials of each type, which is within acceptable limits (Ratcliff, 1993).

Three children who made fewer than seven correct responses on incongruent trials were excluded from analyses.

Unidimensional matching. This task matched the task-switching task in event timing, motor demands, and presence of (stay) cues. There were no conflict stimuli and no need to select dimensions based on cue processing or perceptual analysis of cue features. There were no rule switches within a block. In each block, children saw either color patches or black-and-white animal outlines. Children were instructed by an audiovisual cue to match each test stimulus by pressing the button below the correct target as quickly as possible (Figure 2). Children completed 16 trials per rule (i.e., color and animal). The first 5 trials of each rule type were considered training trials and were not analyzed. (Excluding these trials did not affect the findings.) RTs were trimmed and Winsorized; fewer than 5% of trials were affected. Children made almost no errors, so the few incorrect trials were excluded from analyses.

Go–no go (inhibition). Children were told they would play a game in which ''green means 'go as fast as you can!' But red means 'stop.''' They were instructed to hold their preferred hand over one button and push it as quickly as possible if a ''go'' cue (green circle) appeared but to not push it if a ''stop'' cue (red circle) appeared. In each trial, circles appeared on screen for 250 ms. Following the response, a variable interstimulus interval (ISI) occurred, with a minimum of 150 ms to ensure that children were responding to the current stimulus. This ISI was the critical outcome variable: It was adjusted between blocks of trials (24 trials/block) based upon the proportion of no-go commission errors in the previous block. For example, if the child correctly inhibited 83% of no-go responses in one block, the ISI was reduced in the next block. This block-by-block adjustment continued until children stabilized at 50% correct for two consecutive blocks. The exact number of trials thus varied for each child, based upon the number of blocks needed to converge on the child's 50% criterion ISI (range = 3–8 blocks, or 5 to 10 min). This dependent measure, the ISI threshold, reflects an individual's inhibition speed.

Tapping task (inhibition). Children were told they would play a game with ''silly sticks.'' Following Luria (1966), the child was trained to tap once when the experimenter tapped twice, and vice versa. Training was continued until the child correctly completed 5 practice trials with feedback. Then the child completed two blocks of 10 test trials without feedback. Children were reminded of instructions after the first block. The dependent measure was the proportion of accurate responses on test trials.

Box completion (processing speed). Following Woodcock and Johnson (1989), children were told that the goal of the ''racing game'' was to close as many boxes as possible by drawing the fourth side. They then practiced on five training boxes. For the test, they completed as many boxes as they could within 1 min.

Peabody picture vocabulary test-third edition (receptive language). Children were asked to point to one of four pictures that showed the referent of a word. Across plates of pictures, words became progressively less frequent. Standard administration and scoring procedures were used (Dunn & Dunn, 1997).

Digit span (verbal memory span). Using Wechsler's (1981) administration and scoring procedures, children were asked to repeat a series of random numerals presented at 1-s intervals. The dependent measure was the largest list of digits that the child could immediately recall.

Results

To verify that the sample had age-typical verbal abilities, PPVT-IIIA Easel form and digit span scores were examined. Standardized PPVT scores averaged 117.3 ($SD = 10.9$), which is higher than population norms ($M = 100$, $SD = 15$). Mean forward digit span averaged 4.1 ($SD = 0.8$), similar to other same-age samples (Alloway et al., 2005; Gathercole & Pickering, 2000). Thus, the results might generalize to somewhat older children.

Preliminary analyses revealed no gender differences in any task, so girls and boys were combined in all further analyses.

Task Switching

Accuracy in congruent trials was near ceiling for all types of trials (Table 2). However, accuracy varied considerably in incongruent trials. A 2×2 analysis of variance (ANOVA; Cue [switch vs. stay] $\times$ Congruency [incongruent vs. congruent]) with age as a covariate compared accuracy proportions in cued trials.[2] There was a main effect of congruency, $F(1, 49) = 124.77$, $p < .0001$, $\eta^2 = .71$, with greater accuracy in congruent trials. The switch cost, by contrast, was not significant, $F(1, 49) = 1.34$, $p < .253$, $\eta^2 = .026$. Thus, errors were related to congruency but not to switching (see Figure 3). The age covariate was only marginally significant ($p < .083$).

To assess the effect of cues in stay trials, another 2×2 ANOVA (Cue [cued vs. uncued] $\times$ Congruency [incongruent vs. congruent]), with age as a covariate, was conducted on accuracy in stay trials only. There was a main effect of congruency, $F(1, 49) = 81.12$, $p < .0001$, $\eta^2 = .62$.

[2]Although game asymmetries have been reported for switch-to-animal vs. switch-to-color trials in older children (Ellefson, Shapiro, & Chater, 2006), our design did not allow for in-depth analysis for switch asymmetries because there were only eight switch trials of each type and only correct trial RTs were analyzed. Preliminary within-subjects *t* tests did not reveal any significant game asymmetries; however, game was not included as a factor in any ANOVA.

TABLE 2
Performance on Accuracy and RT Measures of Task Switching for 3- and 4-Year-Olds
(Experiment 1, All Participants Included)

	Incongruent switch	*Incongruent stay*	*Congruent switch*	*Congruent stay*
3-year-olds	3,688 ms (*2, 072*) 58.1% (*3.4*)	3,354 ms (*2, 151*) 62.3% (*3.4*)	2,933 ms (*2, 366*) 91.7% (*3.7*)	2,602 ms (*1, 777*) 88.3% (*3.5*)
4-year-olds	2,692 ms (*1, 055*) 67.5% (*4.0*)	2,224 ms (*1, 014*) 63.8% (*3.7*)	1,594 ms (*808*) 94.4% (*2.6*)	1,750 ms (*882*) 91.3% (*2.8*)

Children were more accurate in congruent trials. Children also were more accurate in uncued than in cued stay trials, $F(1, 49) = 7.15$, $p < .01$, $\eta^2 = .127$ (Figure 4). The age covariate was not significant ($p < .119$).

RTs on correct cued trials were tested for switch and incongruency costs in a 2 × 2 ANOVA (Cue [switch vs. stay] × Congruency [incongruent vs. congruent]) with age as a covariate (see Figure 5). The age covariate was significant, $F(1, 49) = 7.15$, $p < .010$, $\eta^2 = .127$: Speed declined with age. Also, there was a significant effect of congruency, $F(1, 49) = 38.17$, $p < .0001$, $\eta^2 = .438$. Moreover, as predicted based on prior studies of older children, there were significant switch costs, $F(1, 49) = 6.65$, $p < .013$, $\eta^2 = .120$ (Table 2). Thus, switch costs in 3- and 4-year-olds were seen in latency, but not in accuracy. This effect is further explored in Experiment 2.

Unidimensional Matching

A one-way ANOVA, with age as a covariate, was used to test differences in RTs in correct animal versus color unidimensional matching trials. Again, the age covariate was significant (3-year-olds, $M = 2{,}442$ ms, $SD = 1{,}236$; 4-year-olds, $M = 1{,}850$ ms, $SD = 927.5$), $F(1, 49) = 216.34$, $p < .001$, $\eta^2 = .81$. In addition, children were slower to match animals than they were to match colors, $F(1, 49) = 4.63$, $p < .036$, $\eta^2 = .088$. Because of this difference, possibly due to the difficulty of perceptual analysis/comparison of animal outlines versus color swatches, we analyzed the two rules separately in subsequent regression analyses. Mean RTs in the

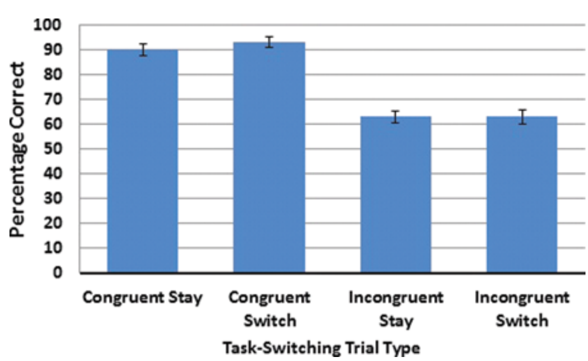

FIGURE 3 Mean (with standard error bars) task-switch accuracies of 3- and 4- year-old children by trial type (Switch × Congruent; Experiment 1).

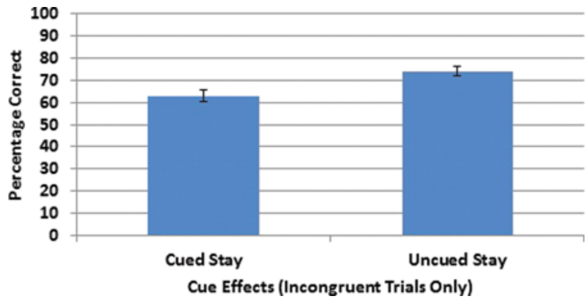

FIGURE 4 Mean (with standard error bars) task-switch ''stay'' accuracies of 3- and 4-year-old children by cue type (Cued × Uncued; Experiment 1).

unidimensional matching test and means for dependent measures on other executive function tests are shown in Table 3.

Inhibition and Processing Speed

There were significant age covariate effects for Box Completion, $F(1, 49) = 12.44$, $p < .001$, and Tapping Test accuracy, $F(1, 49) = 9.71$, $p < .003$. There were no significant age effects in the go–no go test (Table 3).

Correlates of Task-Switching Flexibility

Correlations among age, task-switching accuracy in cued stay and cued switch trials, and other executive function and verbal tests, are shown in Table 4. Only Tapping Test accuracy, Box Completion speed, and unidimensional matching speed (animal) were reliably related to incongruent task-switch costs. These variables were entered into a stepwise regression on incongruent switch-trial accuracy. The only significant predictor of accuracy was unidimensional animal-matching speed ($\beta = -.008$; $R^2_{\text{adjusted}} = .188$, $p = .012$).

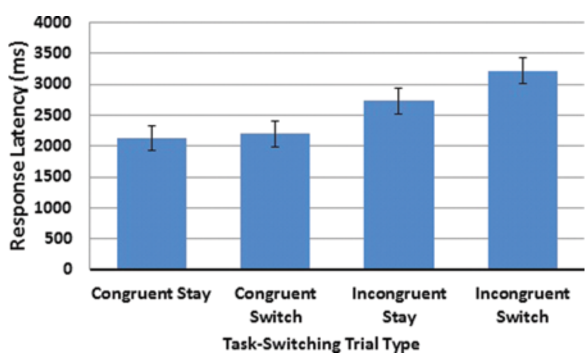

FIGURE 5 Mean (with standard error bars) task-switch response latencies of 3- and 4-year-old children by trial type (Switch × Congruent; Experiment 1).

TABLE 3
Performance on Behavioral Measures of Executive Functioning for 3- and 4-Year-Olds (Experiment 1, All Participants Included)

	Unidimensional matching (RT)		*Luria tapping*	*Go–no go*	*Boxes*
	Animal	*Color*	*(Errors)*	*(interstimulus interval)*	*(numbers)*
3-year-olds	2,535 ms (*1,177*)	2,349 ms (*1,295*)	9.12 (*5.9*)	2,808 ms (*1, 579*)	14 (*6.5*)
4-year-olds	1,969 ms (*899*)	1,732 ms (*956*)	4.7 (*4.3*)	2,665 ms (*1, 574*)	20.9 (*7.26*)

TABLE 4
Bivariate Correlations Among Task Switching, Measures of Executive Functions, Unidimensional Matching Speed, and Language in 3- and 4-Year-Old Children (Experiment 1, All Participants Included)

Pearson's correlation	*Luria*	*Go–no go*	*Boxes*	*Unidimensional matching color (animal)*	*Incongruent stay costs*	*Incongruent switch costs*
Age	$-.481^{*****}$	$-.227$	$.438^{****}$	$-.389^{***}(-.344^{**})$	.093	.147
PPVT-IIIA	$-.421$	.211	$-.048$	.175 (.282)	.160	.288
Digit Span	.081	$-.088$	.039	.016 (.161)	$-.136$	$-.026$
Luria (Inhibition)		$-.308^{*}$	$-.334^{**}$	$.276^{*}(.259)$	$-.262^{+}$	$-.269^{+}$
Go–No Go (Inhibition)			$-.166$	$-.414^{***}$ $(.475^{*****})$	$-.348^{**}$	$-.1$
Boxes (Processing)				$-.462^{***}(-.434^{***})$	$.367^{**}$	$.355^{**}$
Unidimensional Matching Color (Animal)					$-.322^{*}(-.322^{**})$	$-.151$ $(-.316^{*})$
Incongruent Stay Costs						$.599^{*****}$

Results of the unidimensional matching task are reported separately for the color game (no parentheses) and the animal game (parentheses).
$^{+}p < .06$. $^{*}p < .05$. $^{**}p < .015$. $^{***}p < .005$. $^{****}p < .001$. $^{*****}p < .0001$.

Because switch and stay accuracy did not differ and showed similar patterns of correlation with the other tasks, we ran a second regression on accuracy in all cued incongruent trials (i.e., switch and stay). Because accuracy on incongruent stay and incongruent switch trials did not differ, we also tested the relationship including the predictive value of performance on incongruent stay trials. This should be reliable if, as predicted, semantic processing is a significant cause of young children's rule-following difficulties. Importantly, semantic integration demands did not differ between cued switch and stay trials. As in the previous analysis, unidimensional animal-matching speed predicted accuracy ($\beta = -.007$; $R^2_{\text{adjusted}} = .188$, $R^2_{\text{change}} = .154$, $p = .002$). However, Box Completion speed accounted for additional variance ($\beta_{uni} = -.007$, $\beta_{boxes} = .631$, $R^2_{\text{change}} = .072$, $p = .038$).

Discussion

Preschool children understand and can restate a sorting rule, even, at times, as they make perseverative sorting errors (Zelazo et al., 1996). This may be because they have difficulty using semantic cues to decide *when* to change—that is, they might confuse stay and switch cues.

Alternately, children might struggle with the demands of processing cues when stimuli, and the cues themselves, can change from trial to trial. We tested the effect of cues on performance by introducing cues on half of stay trials. The results show that cue processing *in general* affects performance: Accuracy was lower on cued incongruent stay trials than on uncued incongruent stay trials. This suggests that perseverative errors result from difficulty in processing the cue that specifies the operative rule when there is response conflict. There was no evidence, however, that rule switches per se facilitate errors.

This result is consistent with Chevalier and Blaye's (2009) finding that semantically ambiguous cues impair flexibility in older children. Both results are consistent with the rule-retrieval model postulated by Morton and Munakata (2002): Supportive cues facilitate efficient rule retrieval from working memory. Conversely, factors like stimulus conflict can make it difficult for children to reconcile cue meaning with stimulus properties. In addition, adults have difficulty following indirect cues (e.g., ''c'' and ''s'' for color and shape) when a working-memory load is imposed (Miyake, Emerson, Padilla, & Ahn, 2004). This can be reconciled with the Morton and Munakata model, which implies that for very young children (e.g., 3 years or younger), integrating verbal cues with stimulus-response contingencies is difficult even if cues are explicit and familiar and even if overt working memory (e.g., N-Back) demands are minimized. Our results confirm this logical extension: 3-year-old children who had difficulty in the rule-switching test also were slow to match simple, unidimensional stimuli following an uninformative, repetitive cue. In fact, response speed in the unidimensional animal-matching task was the best predictor of task-switch accuracy (15%–20% of variance). This fits cue integration accounts, which stress developmental changes in working memory and semantic knowledge; however, it does not fit theories that emphasize development in cognitive complexity, conflict-based interference, or a combination of these (e.g., Zelazo et al., 2003).

This result was qualified by a difference between the stimuli that were relevant to the two rules: Children were slower to match animal outlines following a repetitive ''animal'' cue than they were to match color swatches following a repetitive ''color'' cue. Moreover, color-matching speed did not predict accuracy in incongruent switch trials in the task-switching test. One possible interpretation is that perceptual analysis was simply more challenging for animal outlines; this seems reasonable because the analysis and comparison of complex figures requires multiple saccades and fixations, each of which requires at least 200 ms (Cohen & Ross, 1978). Also, younger children require more time and effort to make such comparisons (Vurpillot, 1968). Another possibility is that the animal game cue, though repetitive and uninformative relative to the matching task, utilized more *obligatory* working-memory capacity than did the color game cue. That is, even if a cue is not difficult to process, it might necessarily recruit working-memory resources. This might increase the latency of a concurrent task (see Emerson & Miyake, 2003). Although this difference did not appear to extend to the main rule-switching task, that conclusion is tentative because it rests on a comparison of a small number of trials.

This suggests that in addition to cue integration demands, children's speed to compare stimuli and select responses (with minimal conflict and working-memory load) contributes to speed in a rule-switching task. This is consistent with the claim that many cognitive skills develop as a function of generalized changes in processing speed (e.g., Kail, 1991). This is supported by our finding that speed in the Box Completion Test accounted for a modest amount of additional variance in task-switching performance. In sum, cue integration processes and response speed appear to be distinct sources of variance in preschool children's efficiency in selecting between conflicting responses to changing rules. This is consistent with results from studies of older children (Cepeda et al., 2001).

By comparison, neither inhibition test, go–no go or tapping, predicted task switching accuracy or speed. This supports other findings that maturing inhibitory processes do not predict preschool children's cognitive flexibility (e.g., Cepeda et al., 2001; Deák & Narasimham, 2003). Although administering tasks in two sessions could introduce session-wise error variance, we note that *all* of the nonswitching tasks, including the unidimensional and processing-speed tasks that were strongly related to the switch task, were administered in the first session. The fact that inhibition alone did not predict unique variance is thus unlikely to be attributed to session-wise variance.

However, a lingering question is how much children's speed in the unidimensional test depended on speed to process and match moderately complex pictorial stimuli and how much it depended upon obligatory verbal cue processing. To assess this, Experiment 2 included a new measure of processing speed. In that task, children match unidimensional colors or animals as quickly as possible, much like the cued-unidimensional test used here. However, the repetitive verbal cue preceding each trial was eliminated. If the unidimensional matching task correlates with task-switching efficiency because of basic, general processing-and-response speed differences, we should replicate the correlation. If obligatory cue processing accounts for the correlation, we should expect a reduction of this relationship in an uncued unidimensional matching task.

These results also address questions of developmental continuity in rule-switching flexibility. Cue integration difficulties *and* response speed do not strongly predict rule-switching errors in older children (who, in most tasks, make few errors), but they predict slowing (e.g., Cepeda et al., 2001; Chevalier & Blaye, 2009). We found that in a timed rule-switching test, as in untimed tests (e.g., Zelazo et al., 2003), 3- and 4-year-olds make some perseverative errors on incongruent switch trials (but not congruent trials, akin to DCCS pretest trials). In addition, however, the timed test reveals the same kinds of switch-related RT costs as in older children and adults. Thus, by examining *both* accuracy and latency in preschool children, we found that errors seem to be caused not by the switch, but by stimulus incongruency and the presence of a cue. This fails to support the theory that rule-switching errors are due to the demands of rule-contingency complexity (Zelazo et al., 2003).

The results underscore a question about how cue integration impacts cognitive flexibility as children grow older. One possibility is that cue-processing effects are large when a task is at the cusp of a child's ability, as shown here, for example, by high error rates in incongruent trials; however, when children are old enough that the task is easy (reflected by low error rates), cue integration might become an insignificant factor. Although this is an appealing hypothesis, there is evidence that, to the contrary, cue-processing effects continue (in latency) even when the task is easy. There is some evidence consistent with this possibility: Adults show cue integration effects even when error rates are very low (<3%; Arrington et al., 2007; Emerson & Miyake, 2003). However, it cannot be assumed that cue integration effects are similar in children, relative to task difficulty. Moreover, the current results, though suggestive, cannot adjudicate between these alternatives.

To address this question, in Experiment 2, we administered the tasks to older children, who should not make task-switching errors but should still show variable RT (Cepeda et al., 2001; Crone, Bunge, et al., 2006; Crone, Somsen, Zanolie, & van der Molen, 2006). Thus, we tested whether older 4-year-olds and 6-year-olds, who made virtually no errors, show cue-processing effects in task-switching efficiency (i.e., switch costs).

To further explore continuity across age in task-switching processes and performance, we considered whether 4- to 6-year-olds' RT switch costs correlate with their error rate in a more difficult rule-switching test: the Advanced DCCS (Zelazo, 2006). In this test, the game (shape or color) is cued by the presence or absence of a border around the stimulus. This indirect or implicit cue elicits perseverative errors from 4- and 5-year-old children who do not make errors in the typical explicitly cued DCCS (Zelazo, 2006). However, the border cue is nonverbal, and it is not clear whether the working-memory demands of processing verbal cues (as in our task) will generalize to the demands of utilizing an implicit visual cue (i.e., border). If children's errors in the Advanced DCCS test correlate with RT switch costs in the rule-switching test, it will indicate continuity across verbal and nonverbal cues, and across RT and accuracy effects. This will imply a relatively general task-switching capacity that varies across children (cf. Yehene & Meiran, 2007, which suggests task-specificity for switch costs).

EXPERIMENT 2

Method

Participants

Two groups of English-speaking children with no language or cognitive delays were recruited from schools in San Diego County, CA: 4-year olds ($n = 12$, $M_{\text{age}} = 4;6$, range = 4;2–4;11; 4 girls) and 6-year olds ($n = 12$; $M_{\text{age}} = 6;4$, range = 6;1–6;11; 5 girls). Most children (>90%) were Caucasian and middle class. Three additional 4-year-old children were replaced because they did not complete both sessions. Four more were replaced because they did not meet the criterion for task accuracy (>85% in incongruent switch trials). All children completed the PPVT-IIIA and digit span tasks. Four-year-olds' mean PPVT-IIIA score was 120.6 ($SD = 10.9$); 6-year olds' mean PPVT-IIIA score was 119.3 ($SD = 14.7$). Thus, children had high vocabularies for their age. One 6-year-old was replaced because his PPVT score was <2 *SD* below age norms.

Materials

Stimuli for the task-switching, unidimensional matching, go–no go and verbal tests were the same as in Experiment 1. Because 5-year-olds are at ceiling in the Luria Tapping Test, it was excluded. To separate the effects of processing/response speed and cue processing, we used a new uncued (simple) matching task to measure processing speed. This task was designed to be as similar as possible to the unidimensional matching test from Experiment 1, but without any potential effects of the presence of the cue. We created a new processing-speed task as an uncued variant of the original unidimensional test. In this new test, verbal cues were eliminated from the unidimensional matching test. Thus, RTs in the uncued (simple) matching tests are an index of fairly low-level processing and response speed differences. In the rule-switching test, we increased the number of task-switching trials to 160 (80 per rule) to more effectively test for asymmetric switch costs (i.e., switch-to-animal vs. switch-to-color; see Chevalier et al., 2010; Ellefson et al., 2006). This will also address whether cue costs (i.e., incongruent cued vs. uncued stay trial RT) interact with differences in low-level task difficulty.

The Advanced DCCS used stimuli cards (red bunny; blue boat) and standard cards (red boat; blue bunny) as specified by Zelazo (2006).

Procedure

Instructions for the task-switching, unidimensional matching, and go–no go tasks were the same as Experiment 1; however, because children were recruited for an electroencephalogram study, they completed the sessions in a testing room at a neurobehavioral laboratory.

In the uncued (simple) matching task, each stimulus appeared immediately after the response to the previous stimulus. After 5 practice trials, children completed 16 test trials, including 4 trials of each stimulus. The small number of trials was intended to minimize practice effects. Children also completed the Advanced DCCS using the procedure described in Zelazo (2006). The rule in each block (shape or color) was cued by the presence or absence of a border around the stimulus (i.e., black border = color rule; no border = shape rule).

Coding

All data were trimmed as described in Experiment 1.

Results and Discussion

Task Switching

Children were retained if their accuracy in all trial types, including incongruent/switch, was $\geq$85%. Mean accuracy was 90% in incongruent switch trials and 94% in congruent switch trials. Thus, analyses focused on RT data. There were no gender differences in RT, so girls and boys were combined in all further analyses. Because there were two discrete age groups, age was entered as a group variable, not as a covariate as in Experiment 1. Also, switch direction (i.e., switch-to-animal or switch-to-color) was entered as a within-subjects factor in analyses of switch costs.

Cued trial RTs (on correct responses) were compared in a $2 \times 2 \times 2 \times 2$ ANOVA (Age [4 vs. 6] $\times$ Cue [switch vs. stay] $\times$ Congruency [incongruent vs. congruent] $\times$ Switch Game [animal vs. color]). The switching effect was significant, $F(1, 22) = 12.94$, $p < .002$, $\eta^2 = .37$. RTs were longer on switch trials than on stay trials. This is analogous to data from adults, albeit switch costs were larger (Table 5). There was also a significant effect of congruency, $F(1, 22) = 9.60$, $p < .005$, $\eta^2 = .30$. Congruent trial RTs were faster than incongruent trial RTs. This shows continuity with the younger children in Experiment 1 and with many studies of older children

TABLE 5
Mean RT (*SD*) on All Four Trial Types in the Task-Switching Test for 4- and 6-Year-olds (Experiment 2)

	Incongruent switch	*Incongruent stay*	*Congruent switch*	*Congruent stay*
4-year-olds	2,498 (*1, 182*)	1,989 (*1, 332*)	1,837 (*926*)	1,637 (*976*)
6-year-olds	2,391 (*1, 020*)	2,392 (*1, 348*)	2,239 (*941*)	1,953 (*828*)

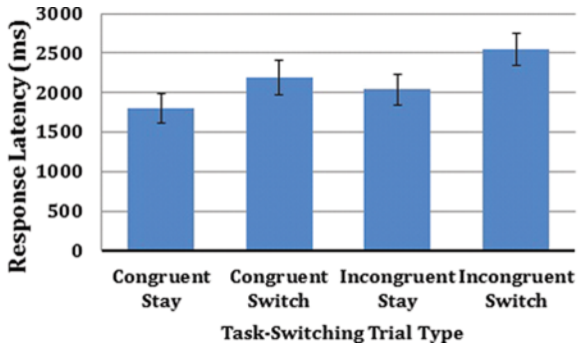

FIGURE 6 Mean (with standard error bars) task-switch response accuracies of 4- and 6-year-old children by trial type (Switch × Congruent; Experiment 2).

and adults (e.g., Cepeda et al., 2001). The main effect of age was not reliable: 4-year olds were not significantly slower than 6-year olds in any trial type, $F(1, 22) = 0.55$, $p < .465$, $\eta^2 = .025$. The switch direction effect also was not reliable: Children were not faster to switch to the color game than to switch to the animal game, $F(1, 22) = 0.55$, $p < .465$, $\eta^2 = .025$. Thus, there was no evidence of asymmetric switch costs (Monsell, Yeung, & Azuma, 2000). There were no significant interactions among any of the factors (see Figure 6).

Stay trial RTs (correct responses) were compared in a 2 × 2 × 2 ANOVA (Age × Cue [cued vs. uncued] × Congruency [incongruent vs. congruent]). Neither age nor congruency had a significant effect. However, cues did have a significant slowing effect, $F(1, 22) = 6.25$, $p < .02$, $\eta^2 = .22$. Also, the interaction of age and cuing was significant, $F(1, 22) = 6.29$, $p < .02$, $\eta^2 = .22$. Children, especially 6-year-olds, were faster to respond to uncued than to cued stay trials (Figure 7). The other interactions were not significant.

Unidimensional Matching

A 2 × 2 (Age × Rule [animal/color]) ANOVA compared RTs in cued and uncued unidimensional matching trials. Four-year-olds were significantly slower than were 6-year-olds,

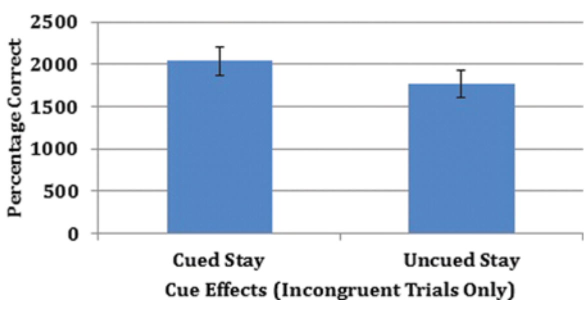

FIGURE 7 Mean (with standard error bars) task-switch ''stay'' accuracies of 4- and 6-year-old children by cue type (Cued × Uncued; Experiment 2).

TABLE 6
Means (and *SD*s) on Tests of Executive Functioning for 4- and 6-Year-Olds in Experiment 2

	Unidimensional matching (RT)		*Advanced DCCS*	*Go–no go*	*Uncued*
	Animal	*Color*	*(errors)*	*(interstimulus interval)*	*matching (RT)*
4-year-olds	938 ms (*231*)	1,233 ms (*513*)	5 (*1.9*)	2,725 ms (*992*)	767 ms (*221*)
6-year-olds	701 ms (*231*)	819 ms (*198*)	4 (*2.5*)	1,326 ms (*261*)	567 ms (*155*)

$F(1, 22) = 8.64$, $p < .008$, $\eta^2 = .28$. There was also an effect of rule type; however, unlike in Experiment 1, children were slower in *color* trials than they were in animal trials, $F(1, 22) = 8.77$, $p < .007$, $\eta^2 = .29$ (Table 6).

Advanced DCCS

There was no significant age difference in mean postswitch error rates. Six-year-olds averaged 4.0 correct ($SD = 2.5$); 4-year-olds averaged 5.0 correct ($SD = 2.5$). Notably, the same children were very accurate in the task-switching test (Table 6).

Inhibition and Processing Speed

In the go–no go test, 4-year-olds were slower than 6-year-olds to inhibit no-go responses, $F(1, 23) = 22.29$, $p < .001$. In the uncued (simple) matching test, 4-year-olds were slower than 6-year-olds, $F(1, 23) = 8.604$, $p < .008$ (Table 6).

Predicting Task-Switching Flexibility

Bivariate correlations among age, incongruent task-switching accuracy, cued stay trials, switch trials, and the inhibition, speed, and verbal tests are shown in Table 7. Only unidimensional matching speed and uncued (simple) matching speed correlated with task-switch costs.

TABLE 7
Bivariate Correlations Among Task Switching, Measures of Executive Functions, Unidimensional Matching Speed, and Language in 4- and 6-Year-Old Children (Experiment 2, All Participants Included)

Correlation	*Advanced DCCS*	*Go–no go*	*Uncued matching*	*Unidimensional matching color (animal)*	*Incongruent switch costs*
Age	−.260	−.804*****	−.567***	−.561*** (−.552**)	−.386
PPVT-IIIA	.051	−.146	−.168	−.239 (−.189)	−.298
Digit Span	−.113	−.319	−.339	−.229 (−.122)	.089
Advanced DCCS		−.474*	−.109	.086 (.278)	−.085
Go–No Go (Inhibition)			.016	.210 (.455*)	−.023
Uncued Matching (Processing)				.344* (.409)	.475*
Unidimensional Matching Color (Animal					.498** (.677****)

$^{+}p < .06$. $^{*}p < .05$. $^{**}p < .015$. $^{***}p < .005$. $^{****}p < .001$. $^{*****}p < .0001$.

We entered age, unidimensional matching (color), and uncued (simple) matching into a stepwise regression on incongruent switch RT. As in Experiment 1, unidimensional matching speed accounted for a significant unique variance in switch RT ($\beta = .594$; $R^2_{\text{adjusted}} = .470$, $R^2_{\text{change}} = .410$, $F_{change} = 9.30$, $p < .001$). Again, adding processing speed (simple matching speed) accounted for some additional unique variance ($R^2_{\text{change}} = .08$, $p < .096$).

GENERAL DISCUSSION

Most tests of preschool-aged children's rule-switching flexibility, and its relation to other developing cognitive capacities and executive functions, have relied on perseverative errors in binary, untimed, rule-switching tests such as the DCCS. However, such tests provide limited information to adjudicate between alternative theories. Binary, forced-choice tests have low sensitivity: Children are often, for example, classified as flexible or perseverative. This lack of sensitivity might miss graded differences in processes such as task-cue integration, stimulus-conflict resolution, response speed, etc. Other tests that can detect parametric behavioral measures (e.g., RT) and simultaneously exact greater procedural control (e.g., timing of trial-by-trial events and the delivery of cues) might reveal subtle cognitive-processing differences. This is necessary for testing new theories from the literature on adults' task switching, determining whether they pertain to children's flexibility, and thus inferring whether there is continuity of cognitive factors from early childhood to later life.

An age-appropriate, parametric test of task switching, with controlled delivery of stimuli and cues, showed that children's task-switching accuracy was strongly related to their ability to use verbal cues to quickly access and execute the correct rule. Even among children who did not make errors, cued performance in the unidimensional matching task predicted switch costs. By contrast, there was no support for the popular idea (cf. Diamond, 2002, 2009) that young children make rule-switching errors because they have difficulty inhibiting prepotent (i.e., previous) responses or representations. There was no correlation between any tests of inhibition and any measure of task-switching accuracy or speed in either younger (Experiment 1) or older (Experiment 2) children. Although insufficient to rule out a role for inhibition in and of itself, our result is in accordance with multiple experiments (see also, e.g., Cepeda et al., 2000; Deák & Narasimham, 2003), which together suggest the inhibitory explanation is less viable.

As evidence for a cue integration/memory access account, cues increased task difficulty even on stay trials and were arguably responsible for younger children's errors, whereas there was no evidence that *switch* demands increased errors. Moreover, a nonswitch cue imposed RT costs (compared with uncued trials). Cues seem to obligatorily garner children's processing resources, even if there is no stimulus/response conflict. This fits evidence from studies of adults' task switching, which suggest that ''true'' switch costs are small or nonexistent, whereas cue integration processes that demand working-memory processes have a substantial effect (Arrington et al., 2007; Grange & Houghton, 2010).

Converging evidence for a cue integration/working-memory account was seen in the correlation between switching accuracy and unidimensional matching speed for the slightly harder rule. This relation was strong both for children who sometimes perseverated and for older children who did not. The unidimensional matching task controlled for cue integration and for stimulus and response demands, and eliminated stimulus conflict and switching, thereby minimizing inhibitory demands. This is further evidence that inhibitory difficulties do not explain children's task-switching errors. These results do, however, support Morton and Munakata's (2002) prediction that children show graded activation of rules from working memory, even without switching demands. The results also suggest that semantic properties of the cue are critical in determining how children activate rules to carry out task goals (see Munakata & Yerys, 2001).

An alternative explanation for the correlation between switching efficiency and matching speed could be that if children did not understand or encode the cues or could not match stimuli accurately, they would perform poorly in both the switching and matching tasks. However, this is implausible for three reasons. First, it cannot explain the results of Experiment 2, where accuracy was uniformly high. Second, children had extensive practice and would have been excluded if they did not show that they had learned the tasks. Third, even in Experiment 1, children were nearly perfectly accurate in all trial types on congruent trials and in the unidimensional task. Thus, children understood the cues and tasks and were attentive and compliant.

Other previous results converge on the conclusion that children's rule-switching difficulties are related to cue-processing difficulties. Perner and Lang (2002) reported that children produced perseverative errors in only one of four switching tests—the one similar to the DCCS—and only when it was the first of the four tests. Thus, DCCS errors might reflect an initial failure to know how cues should be utilized (or integrated) when an adult imposes an unfamiliar, unexpected, and arbitrary rule switch (see also Bohlmann & Fenson, 2005). Also, Munakata and Yerys (2006) found that 3-year-olds who make errors in the DCCS often fail to fully comprehend the cues, even after passing the pretest. Also, Deák (2000, 2003) found that children's flexible use of semantic cues to word meanings depends largely on how strongly those cues imply a related stimulus property. Finally, as noted, Chevalier and Blaye (2009) found that cue difficulty modulates children's rule-switching accuracy.

These converging findings support our interpretation that cue-processing demands, with indirect cues and even direct or explicit cues, impede children's cue-based response selection when there are conflicting options. This converging evidence mitigates a limitation of the current data: Specifically, in our switch test, the very presence of a cue was a cue itself. Some cues preceded switch and stay trials with equal likelihood. By contrast, a ''still'' or uninformative cue window always preceded a stay trial. Therefore, after some period, children could learn that when the face in the cue window did not speak, they could retrieve the last rule to generate a response. Unfortunately, we cannot determine how much the difference between cued and uncued stay-trial RT was due to cue processing *per se* and how much was due to the perfect cue validity of the still cue. However, the fact that in Experiment 2 unidimensional matching responses were slower than simple matching responses suggests that cue-processing effects *per se* were significant. Moreover, a cue validity account cannot easily explain why one game cue, but not the other, predicted rule-switch effects. Nonetheless, to resolve these issues, in ongoing studies, we are using modified tests to separate the effects of cue processing and cue validity using transition cues, which indicate only the response demands (e.g., ''switch'' or ''stay'') but not the appropriate rule.

The results also point to other relations between rule switching and executive functions. Processing/response speed in simple tests predicted rule-switching accuracy and speed, over and above unidimensional matching speed. Thus, there seems to be a contribution of general response speed. That confirms previous reports that generalized processing speed predicts task-switching efficiency (Cepeda et al., 2001). By contrast, the finding that tests of inhibitory speed (go–no go) and accuracy (tapping) did not predict flexibility confirms previous findings (Deák & Narasimham, 2003; Huizinga, Dolan, & van der Molen, 2006).

Cue-processing accounts imply that receptive language skills will contribute to rule-switching flexibility, and there is some evidence to support this (Munakata & Yerys, 2001). However, receptive vocabulary as measured by the PPVT-Revised did not predict flexibility. This suggests that it is not merely low-level semantic knowledge, but rather the interpretation or integration of the current cue with stimulus properties, that affects performance. Also, verbal memory span did not predict flexibility, suggesting that children's rule-switching flexibility is limited by active working-memory processes, not by memory span capacity. This confirms other evidence that memory span is not the critical factor (Zelazo et al., 2003).

Many children in Experiment 2 failed the Advanced DCCS. Thus, we did not replicate the single published report that 6-year-old children are flexible in this test (Zelazo et al., 2006; Zelazo, Frye, & Rapus, 1996), even though our participants had above-average vocabulary and matched age norms in all other tasks. Thus, the Advanced DCCS might not be reliable across samples. Moreover, accuracy did not correlate with any measure of flexibility in our rule-switching paradigm. This suggests that the Advanced DCCS is measuring a unique sort of response selection. By contrast, our rule-switching test was modeled after tests used in many studies of adults' task switching to adjudicate between relatively well-differentiated and nuanced hypotheses. Our results are consistent with patterns of data from older children and adults, indicating some convergent validity. One possible reason that the Advanced DCCS does not produce convergent results is that the switch cue is implicit—in essence, an unfamiliar, abstract symbol—not a semantically explicit cue. Thus, the task has different memory demands, including memorization and retrieval with minimal cues, and therefore might be more of a test of rule *learning* than rule-switching *flexibility*. However, little is known about how children process cues that are relatively explicit/transparent or implicit/abstract. We are currently investigating this question.

Several aspects of this study limit how far the results can be generalized. For example, our task used frequent feedback. Bohlmann and Fenson (2005) found that feedback greatly reduces 3-year-olds' errors on the DCCS. This factor requires future investigation. Also, it is unclear how the use of shape and color as stimulus dimensions, in this and most other studies, affects the results. For example, children's color-word knowledge develops surprisingly late (Bornstein, 1985), and this might contribute to the somewhat confusing asymmetries in task strength between our experiments. Notably, the ''weaker'' (i.e., slower) rule predicted switch costs in both experiments, suggesting that the ability to flexibly select and utilize a rule is constrained by the ''lowest common denominator''—that is, the hardest of the possible rules that might be activated. Finally, it should be noted that our participants had high receptive vocabularies, so we cannot assume that our sample is fully representative of their age cohort.

Conclusion

These results show large individual and age-related differences in task-switching efficiency, in speed of response to conflicting stimuli following verbal cues, and in other executive functions and verbal skills. The results shift our focus from children's task switching *per se*, to their ability to select, integrate, and adapt to multiple cues to choose responses under conflict. The results further call for a theoretical shift from inhibition-based theories to explanations that focus, first, on active working-memory processing of verbal cues, and second, on generalized processing speed.

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