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UNIVERSITY OF CALIFORNIA, SAN DIEGO

A Comparison of Cue Processing and Executive Functioning in Child Task-Switching

A dissertation submitted in partial satisfaction of the requirements for the degree

Doctor of Philosophy

in

Cognitive Science

by

Anna E. Holt

Committee in charge:

Professor Gedeon Deák, Chair

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Professor Andy Kehler

Professor Marta Kutas

Professor Hal Pashler

2011

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2011

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## LIST OF ABBREVIATIONS

**+TOP** Topic Switch

**-TOP** No Topic Switch

**Advanced DCCS** Advanced Dimension Change Card Sort Task

**COMP** Completed Aspect

**DCCS** Dimension Change Card Sort Task

**PROG** Progressive Aspect

**PFC** Prefrontal Cortex

**PROCESSING SPEED** Perceptual-Motor Processing Speed

**RT** Reaction Time

**S-R** Stimulus-Response

**vWM** Verbal Working Memory

**WMS** Working Memory Span

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## ABSTRACT OF THE DISSERTATION

A Comparison of Cue Processing and Executive Functioning in Child Task-Switching

by

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Doctor of Philosophy in Cognitive Science

University of California, San Diego, 2011

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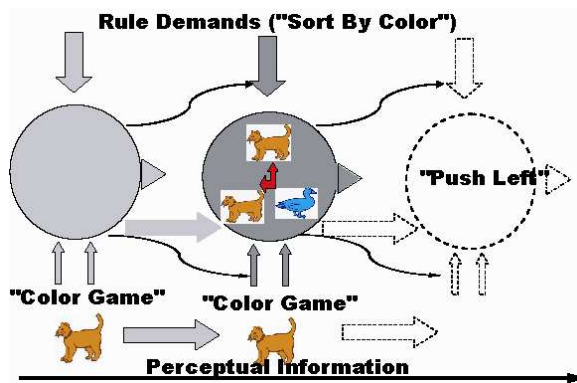
This dissertation provides a continuous, parametric study of the development of task-switch efficiency between the ages of 3-7 years. It examines the degree to which several leading explanations for switching efficiency from both the developmental and adult literature predict individual and age-related gains in accuracy and reaction time (RT) in switching tasks in early childhood. These include executive functioning (executive functions-based) accounts along with newer models of cue-processing effects. Previous work has recognized the importance of cue-processing in adult task-switch, but this dissertation provides one of the first systematic investigations of cue-processing effects in childhood. We manipulate the semantic content of verbal cues both in task-switch paradigms and in simple, no-conflict, non-switch cued matching tests. We find that differences integrating such cues can account for both individual differences

and age-related changes in flexibility. These include the catastrophic switching errors made by young children in traditional task-switch tests (and also made by older children in more complicated, indirectly or arbitrarily-cued paradigms) as well as children's switch costs. Traditional explanations for performance on card-based rule sorting tasks (such as the Dimension Change Card Sort Task, DCCS (Zelazo, 1996, 2006) do not adequately account for both performance patterns. Further, we extend the idea of cue-processing and cognitive flexibility as predictors of one kind of real-world indirect cue: discourse referents.

# Introduction

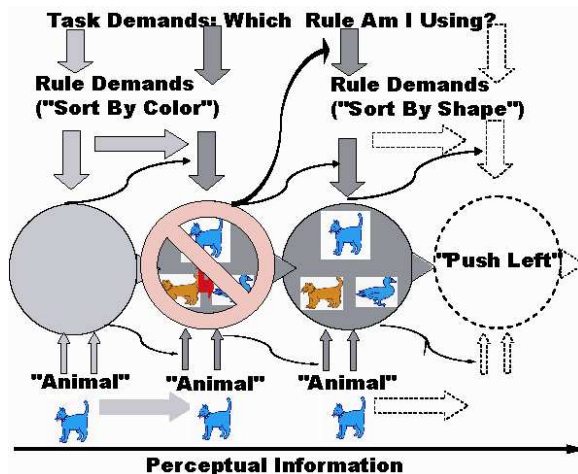
## 1.1 Definition of Cognitive Flexibility

Performing everyday tasks requires an ability to shift attention and highlight new represented information in response to changing real world information. At the perceptual level, we must recognize when external stimuli have changed. At a representational level, we must then select--from all possible responses to a new stimulus--the future response which is most in line with current goals (Figure 1.1).



**Figure 1.1:** Maintenance of rule demands in working memory without task-switch. Adapted from (Monsell, 2003).

Occasionally, we must also recognize that new perceptual information cannot be accommodated by our current rule, and thus the entire representational set in which we are operating must change. Such stimuli require a change in task (a reselection of appropriate rules) (Kharitonova, Chien, Colunga & Munakata, 2009) (Figure 1.2). This ability to make a switch between rules at a representational level given perceptual input is known more generally as cognitive flexibility (Deák, 2003; Monsell, 2003).



**Figure 1.2:** Updating of rule demands in working memory following task-switch. Adapted from (Monsell, 2003).

These changes are cognitively demanding: whereas well-practiced responses become automatized and afford divided attention, this changing of task is typically marked by slow or uncertain decisions and unitary attention to task demands.

### 1.1.1 Cognitive Flexibility and Task-Switching

Because of this close relationship between cognitive flexibility and representation switching, cognitive flexibility has typically been tested in adults in task-switch paradigms. An individual's mean RT cost ("switch cost") is used as the dependent measure. Switch costs are latency costs associated with trials that follow performance of another task.

These switch costs are robust, having been measured in a wide variety of paradigms that differ in the nature of both the task and the switch. There is no universal definition of what constitutes an appropriate task for task-switch, but most studies have attempted to control for the effects of low-level visual differences by using stimuli that afford different responses for two tasks, so called *bivalent* stimuli. This has practically limited the types of tasks used to simple Stimulus-Response (S-R) (rule-based) tasks such as sorting by (color/shape), making numerical (parity/quantity) judgments, or categorization (animal/non-animal) (Kiesel, Steinhauser, Wendt, Falkenstein, Jost, Philipp & Koch, 2010). S-R mappings may either be

assumed to be equal in difficulty (as in two sorting tasks) or highly unequal in difficulty (reading a word—an automatized response—verses naming the color of ink) (e.g. Stroop, 1935). Stimuli that afford the same motor response regardless of rule are congruent, whereas stimuli that require unique responses for each rule are incongruent. In the DCCS, a common measure of childhood cognitive flexibility, children match test cards with one of two target cards: a red rabbit or a blue boat. Test cards which are an exact match to target cards (also red bunnies or blue boats) are congruent. They are matched with the same target card regardless of rule. Test cards which share only one feature with the target cards (blue rabbits and red boats) are incongruent. They are matched with a different target card under different sorting rules. Switch costs are typically larger after incongruent stimuli for both adults (Meiran, 2000) and older adults (Kramer, 1999) in task-switch tests generally. (The traditional DCCS has only incongruent cards).

Switch costs can be measured in mixed blocks, in which mean RTs for an A trial in a fixed-order task-alternation (ABABAB) are compared with mean RT for a block of task A alone (Allport, Styles & Hsieh, 1994). These costs have been termed mixing costs or global switch costs. Outside of some debates in aging (Mayr, 2001; Witt, Daniels, Schmitt-Eliassen, Kernbichler, Rehm, Volkmann, Deuschl, 2006), measures of global switch costs are seldom used. Instead, local switch costs compare directly the costs of a task repetition (AA) to a task alternation (AB) within a single block. It is notable that switch costs are present even when the task order (e.g. ABBABB) is entirely predictable and both tasks (A and B) are easy (Koch, 2001).

### **1.1.2 Cognitive Flexibility and the Dimension Change Card Sort Task**

Many studies find that that cognitive flexibility improves dramatically between 3 and 6 years (e.g. Deák, 2003; Jacques & Zelazo, 2005). Preschoolers sometimes have great difficulty switching between simple tasks. Developmental studies have focused on a peculiar form of

inflexibility shown by 3-year-olds and some 4-year-olds. Specifically, when children are asked to switch from one simple rule to another, they sometimes perseverate on the first rule. For example, in the Dimension Change Card Sort test (DCCS; Zelazo, 2006), 3-year-olds can easily follow one simple rule (e.g. sorting pictures of red flowers and blue boats by color) or another (e.g. sorting the same stimuli by shape). However, when children are explicitly asked in a new block of trials to sort the same cards using the other rule, many children continue to sort by the old rule (Zelazo, Frye & Rapus, 1996). These perseverative errors are typically seen in at least half of middle-class, English-speaking 3-year-olds and in a substantial minority of 4-year-olds, but not in 5- and 6-year-olds.

## **1.2 Cognitive Flexibility and Executive Functions**

A body of recent work (see Hanania & Smith, 2010, for review) suggests the transition from categorical errors to correct-but-slowed switching in the DCCS is due to age-related improvement in underlying executive functions; that is, cognitive processes that control attention, planning, representation, and inference. Older theories suggest executive functions to be largely undifferentiable, typically with a prefrontal cortex (PFC) focus, and reducible to a single global executive functions, such as “only” working memory (Cohen & Servan-Schreiber, 1992; Duncan, Emslie, Williams, Johnson, & Freer, 1996; & Kimberg, D’Esposito, & Farah, 1997). Other lines of research suggest that tasks typically thought to tap executive functions broadly can, in fact, be separated using statistical modeling into distinct components with focal neural correlates (Stuss, Shallice, Alexander, & Picton, 1995).

Miyake et. al. (2000) pioneered the use of latent variable statistical modeling to differentiate executive functions components, and their respective importance in standard neuropsychological tasks. They decompose executive functions into Shifting, Working Memory and Inhibition (Miyake, Friedman, Emerson, Witzki & Wager, 2000; Friedman & Miyake,

2004). Moreover, they found that these executive function component processes differentially predicted performance on complex neuropsychological tasks that involve cognitive flexibility.

Developmental studies often find support for the same three factor model (Lehto, Juujärvi, Kooistra & Pulkkinen, 2003; Wu, Chan, Leung, Liu, Leung & Ng, 2011). Wiebe, Sheffield, Nelson, Clark, Chevalier & Espy (2011) suggested that the structural representation of executive functions may differ throughout childhood, with a single, unitary executive capacity best describing executive functions structure in preschool, but the age transition being marked by differentiation in later years.

However executive functions are conceptualized, explaining the development of cognitive flexibility depends upon elucidating the stable, functional and predictive relationships between one or more executive functions, and performance on measures of cognitive flexibility (typically the DCCS). Several leading hypotheses for the perseverative-flexible transition between age 3 and 4 have used this approach to predict or explain performance on the DCCS.

### **1.2.1 Inhibition**

One prominent account holds that the component of inhibition explains age- and individual differences in task-switch. By this account, younger children are unable to deliberately inhibit a dominant, automatic or pre-potent response. In the DCCS, for example, some researchers have suggested that younger children perseverate because they have strengthened one pair of associations between a perceptual feature (e.g., “If it’s blue...”) and a motor response (placing card 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 (Kloo, Perner, Aichhorn & Schmidhuber, 2010). Kirkham, Creuss, & Diamond (2003) found that children were more likely to perseverate on the first rule if the last cards sorted (which highlighted the pre-switch dimension) remained visible than if they were covered when the second rule began. This suggests that perceptual accessibility of no-longer relevant features

can modulate inhibitory difficulty and therefore increase the tendency of children to perseverate.

One recent formulation of the inhibition account (Diamond, 2002) postulates interaction effects among working memory span (WMS) and inhibitory demands. It is harder to inhibit a prepotent response under greater memory load. Significant correlations are found between performance on an abstract shapes task (in which participants were asked to hold and manipulate independently up to six abstract rules for picture manipulation) and a Simon test (in which participants were asked to ignore spatial location of an object and only attend to color or identity). This predictive power is greater for younger vs. older children (Davidson, Amso, Anderson & Diamond, 2006).

The effects of inhibition may be one expression of a global “all-or-none” tradeoff (Diamond, 2009). It is cognitively and metabolically expensive to change nervous system response state. Thus, response state signals (both motor and cognitive) may typically be diffuse signals. (These can be thought of as a mature, cognitive, equivalent of the motor bleed-over effects sometimes seen wherein young children cannot move a single hand in specified pattern without also moving the opposite hand). Specificity might then be achieved by a global inhibition signal. Partial changes, like those in the DCCS, which involve a dimension, but not a stimulus re-description, are then particularly difficult: it is harder to inhibit only some stimulus features (e.g. a single dimension) than to send a global inhibition signal. Thus, it is easier to respond on the same side as a stimulus than on the opposite side, but it is also easier for children and adults both to simply always respond on the side opposite the stimulus than to switch- an “all” vs. a “some” (Lu & Proctor, 1995; Davidson, et. al., 2006).

### **1.2.2 Perceptual-Motor Processing Speed**



Perceptual-motor processing speed refers to how efficiently a child can encode and process new information, and execute a response. There are predictable differences in cognitive speed with age, with largest gains in early childhood (Kail, 1991). There also are individual differences in speed across same-aged children, and these are stable across a wide variety of tasks—for example, interpreting a word or making a simple response like drawing a line (Salthouse, 2000; Cepeda, Kramer & Gonzalez de Sather, 2001). Because processing speed affects tasks like interpreting bivalent stimuli and choosing from among several possible responses, tasks with a higher order of processing complexity (e.g., following and switching rules) should be especially susceptible to differences in processing speed. Processing speed modulates the effects of executive functions on task-switch fluency (Huizinga & van der Molan, 2006). Recent developmental works suggests, though, that while processing speed globally constrains executive functions, its effects can be separately modeled using latent variable analyses (McAuley & White, 2010).

### **1.2.3 Associational Activation Strength**

Working memory differences can refer to working memory span (WMS) differences and/or to activation differences. Evidence (Zelazo, 1995; 2003) suggests that WMS differences do not adequately predict performance on the DCCS. Differences in the ease (strength) of activating a rule in working memory, however, may be important in predicting flexibility.

The “Associational Activation Strength” explanation (Munakata, 2001) suggests that in younger children, task-switch speed and accuracy are predicted by efficiency of retrieving appropriate low-level S-R associations from working memory. Morton & Munakata (2002a) postulate that tapping representations of the two dimensions of the DCCS or switching to a “harder” task vs. an “easier” task in the adult task-switch literature—so called asymmetric

switch costs (Yeung & Monsell, 2003a, 2003b)-- might depend upon innately unequal representations of the underlying cued perceptual-motor contingencies involved.

They found that children who make perseverative errors in the DCCS also tend to show weaker working memory representations of the rules (as shown by slower response times), even when those rules are tested in a non-switching task with unidimensional (1D) stimuli (Cepeda & Munakata, 2007; Blackwell, Cepeda & Munakata, 2009). If task-switch is determined by speed to activate low-level S-R association, it should be predicted by age and individual differences in 1D response matching speed.

### **1.3 Cognitive Flexibility and Context Uncertainty**

#### **1.3.1 Stimulus Uncertainty**

Experience can change the relative memory strength (activation speed) of rules (Yerys & Munakata, 2006). Contextual uncertainty also modulates the speed to activate S-R associations (rules) from working memory. Specifically, rule-conflict hinders performance: a stronger representation of the rule is required to access it given a stimulus which affords partial activation of both rules. For young children, this memory activation may be insufficient and result in perseverative errors on the DCCS (Munakata & Morton, 2002a). This also likely explains congruency effects seen generally in task-switch. A bivalent stimulus gives evidence for both possible associations. There is a latency cost to activating and selecting from multiple rules vs. a single rule, or an incorrect rule may be preferentially activated from working memory (Meiran, 2000). Cragg & Nation (2009) found that the magnitude of conflict costs (costs on incongruent switch trials) decreased with age and that young children (age 5-8) but not older children (9-11) also showed congruency costs on stay trials. These differences were independent of processing speed.

### 1.3.2 Cue Processing

A postulated mitigating factor for contextual uncertainty (though not elaborated or directly tested by Morton & Munakata, 2002a) is the semantic cues used with young children. This dovetails with emerging research from the adult literature. Previous research, (with the exception of Chevalier & Blaye, 2009) has not directly addressed the role of semantic cues in child task-switch.

Switch costs, however, are usually measured in adults and older adults (DiGirolamo, Kramer, Barad, Cepeda, Weissman, Milham, et. al., 2001; West & Moore, 2005; Kray, 2006) in cued paradigms. These cues can occur before stimulus onset (Rogers & Monsell, 1995) or via feedback. In the Wisconsin Card Sorting Task or Madrid Card Sorting Tasks (Barceló, Periañez, & Knight, 2002) there are no explicit cues to task demands. A participant initially sorts a card under one of three possible rules (sorting stimuli by shape, color or number) and receives feedback. The subject continuously reselects sorting rules until positive feedback is given. Patient populations show catastrophic failures to switch rules in these feedback-cued paradigms (Aron, Robbins & Poldrack, 2004; Kieffaber, Kappenman, Bodkins, Shekhar, O'Donnell & Hetrick, 2006). These failures have traditionally been equated with children's failure to switch on the DCCS, although the DCCS does not require the use of feedback.

Whenever task demands change in the environment, there is usually a cue to indicate these changes. This cue may be uniquely associated with one set of learned rule representations --e.g. "sort by color" -- or may only suggest a subset of possible responses (e.g. a C grade clearly indicates a need for a change in future essay-writing response, but does not in and of itself guide what new responses are best). In most cued task-switch paradigms, anytime task demands change, the cue itself changes. Early cue integration research (Mayr & Kliegl, 2003; Mayr, 2006; Forstman, Brass & Koch, 2007) reduced task-switch related costs entirely to costs

from activating a new cue-stimulus (in addition to just S-R) contingency on some trials. They found that with 2:1 mappings of cues to tasks (e.g. two cues that can signal a switch and two that can signal a task-repetition) the costs of just processing a new cue were of the same order of magnitude as the costs of task-switch demands.

The most thorough examination of cue-switch vs. task-switch costs was completed by Logan & Schneider (2007). They formalized a model (Figure 1.3) for switching behavior in which differences in switch costs can be predicted as a multiplicative (joint retrieval) effect both of the perceptual lag from visual and semantic integration of a new cue (a cost) and stimulus but also a facilitative effect from the information content of the cue guiding appropriate memory retrieval. Specifically, the cue and the target both provide evidence for a certain response, with a certain probabilistic reliability. They both function together as joint retrieval cues to activate a response in working memory. For instance, the cue “color” provides evidence for activating red and blue sorting rules, the target blue boat provides evidence for the sorting blue things to the left and for sorting boat things to the right. The combination of these yields conclusive evidence for sorting to the left. If the cue is sufficiently informative, little extra processing time is required even with stimulus uncertainty (e.g. bivalent stimuli) as overwhelming evidence already suggests efficient activation of the correct rule from working memory (Grange, & Houghton, 2010). Less transparent cues—such as the letter “s” or a black border—provide much weaker evidence for a specific effect in isolation (Miyake, 2004).

This model provides a good fit for classic alternating runs data (i.e. Rogers & Monsell, 1995). Further, it fits conceptually with the Associational Activation Strength hypothesis (though the two are not formally linked), as cues enable children to more efficiently link contextual information and stimulus features in active memory. It suggests that cue-processing should improve with age, and selectively mediate performance for young children in the

conditions with the most stimulus uncertainty—e.g. incongruent switch trials. It is notable that time to retrieve a rule given a cue would be predicted in the Logan & Schneider (2007) model to also differ even without switching (e.g. in the 1D matching tests), though Morton & Munakata (2002a) do not formally predict this.

$$RT = RT_{\text{Base}} + \exp[-CTI/\mu_C] \cdot (\mu_C + \mu_M) + \frac{1/\mu_C}{1/\mu_C - 1/\mu_M} \cdot (\exp[-CTI/\mu_M] - \exp[-CTI/\mu_C]) \cdot \mu_M$$

$\mu_c$  = cue-encoding time (time to perceptually encode cue),  $\mu_M$  = mediator retrieval time (which is the “time to instantiate a task goal” (c.f. activate an association) using a cue mediator). CTI = cue target interval.  $RT_{\text{base}}$  = the time to perceptually encode a target and to select and execute a response.

**Figure 1.3:** Cue-mediated memory retrieval. (From Logan & Schneider, 2007).

While many of these theories have not been formalized in the child literature, there are tantalizing hints that cue-processing effects may be at play in preschool and childhood cognitive flexibility. Perner & Lang (2002) found that children only perseverate in the DCCS (vs. other sorting tasks) and only when it is presented first. They speculate that previous experience with another variant of a card sort task gives children experience with the odd pragmatic instructions used in the DCCS. The DCCS is not the only mainstream measure of cognitive flexibility. In some paradigms (e.g. Shape School, Advanced DCCS) (Espy, 1997; Smidts, Jacobs & Anderson, 2004) children continue to make catastrophic errors after age 4. One potential explanation for this delayed flexibility may be found by examining a metric of “cue-directness” (the semantic relation of the cue itself to the appropriate memory representation).

At one extreme of cue-directness is the DCCS: there is no ambiguity in either task demands or rule demands in the instructions (the children are told both that they must reselect a new rule-- “We’re not playing the color game anymore! No way!”-- And they are told what responses are appropriate under the new rule. “We’re playing the shape game now!”). The Shape School and the Advanced DCCS use arbitrary cues that have no obvious semantic relationship to appropriate S-R rules. In the Shape School, children must decide when to sort by color and when to sort by shape by whether the figure is wearing a hat. In the Advanced DCCS, the presence of a black border signals a need to switch task. These cues neither indicate the appropriate rules, nor the appropriate sorting responses. 4- and 6-year-olds produce perseverative behavior in the Advanced DCCS which is comparable to that of 3- year olds on the DCCS (Zelazo, 2006).

Direct cues in adult task-switch paradigms typically do not indicate both the types of responses that are appropriate and the current rule. Instead, they typically highlight either the *transition* contingency demands without respect to the rule demands (e.g. the word “switch” but not indicating the identity of the new rule) or the *rule* contingency demands without respect to task demands (e.g. the word “color” means “pay attention to the color dimension and sort by it” but does not reinforce whether the following trial will be a change in rule from the previous game or not).

Note this implies that, as the cue is always automatically and jointed encoded with the stimulus itself in the Logan & Schneider model, cuing processing differences should be seen when a cue occurs on a task repetition, or stay, trial. Gopher, Armony, & Greenspan (2000) administered a task with a limited number of both cued switch and cued stay trials. They found both switch-related costs, and what they termed *restart costs* associated with cued stay trials relative to cued switch trials. Likewise, Gade & Koch (2007) found that reversing cue-task

mappings learned in a pre-test training period produces increased switch costs even on congruent trials.

Kray, Eber, & Karbach (2008) found that facilitation effects due to task-relevant verbalization (the differences between more semantically direct—“color” and more indirect “c” cue) were especially large in younger children and older adults. Depending upon how efficiently the cue signals the retrieval of a memory association, measurable cue-driven differences in response speed should be seen. Interestingly, because cue and stimulus uncertainty both modulate association activation time in the Morton & Munakata model, one might expect cue effects should be seen even when there are no explicit switch demands (i.e. in a 1D non-switch matching test).

#### **1.4 Our Approach to Flexibility**

The accounts listed above (inhibition, processing speed, Associational Activation Strength) that have been studied in children typically use performance in variants of the DCCS as dependent measures (Frye et. al., 1995; Frye, & Rapus, 1996; Munakata & Yerys, 2001; Kirkham et. al., 2003; Zelazo, Müller, Frye, & Marcovitch, 2003). The DCCS is, not, however, the ideal measure of flexibility in which to look for mechanisms. It is not possible with a binary outcome measure (flexible or inflexible) to judge, for instance, whether a child is perseverative because they have failed to inhibit a previous S-R association (inhibition) or failed to activate a new association in working memory (Associational Activation Strength).

Few studies have looked at the role of executive functions in the limited other standardized categorical measures of preschool flexibility (e.g. 3DCCS, Shape School) (Espy, 1997; Smidts, Jacobs & Anderson, 2004). Limited research, however, suggests that Miyake’s executive functions do not clearly explain performance in other measures of preschool

flexibility (Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003). Further, new theories of flexibility (such as cue processing) which are of particular interest in this thesis are difficult to test using only rule-based card-sorting tasks. This disconnect has real consequences: there is a danger that over-reliance on one measure of cognitive flexibility will artificially constrain the number and types of theories to explain flexibility in childhood.

Our approach to testing the relative contributions of inhibition, processing speed, Associational Activation Strength and cue-processing to the development of cognitive flexibility is instead to adapt for use with children 3 to 7-years old task-switch methodology used with older children and adults. We use switch costs, as the primary measure. By five or six years of age children seldom make perseverative errors; however, they are much slower than middle-school children, with larger switch costs (Cepeda, Kramer & Gonzalez de Sather, 2001; Davidson, Amso, Anderson & Diamond, 2006). Such tests permit us to bridge studies of preschool children and school-aged children- another goal of this thesis.

This is an important research advantage: binary card-sorting tasks can detect only the most robust individual differences in children's rule-switching flexibility, and then only within a limited age range (approximately 3-5 years. Yet it may be the individual differences (i.e., the differences between same-age children) that are predictive of later differences in educational outcomes (Bull & Scerif, 2001; van der Sluis, de Jong, & van der Leij, 2007) and are thus of potential primary importance in the study of cognitive flexibility. Some 3-year-olds switch fluidly and accurately in the DCCS, much like a typical 5- to 6-year-old, while some 5-year-olds perseverate. Children with attention deficit/hyperactivity disorder (ADHD) (Cepeda, Cepeda & Kramer, 2000) and autistic children (Dichter, Radonovich, Turner-Brown, Lam, Holtzclaw & Bodfish, 2010) are less accurate and slower in the DCCS than their age-mates.



There is evidence from ADHD that medication—specifically catecholamine-agonist medication—mitigates these deficits (Cepeda, Cepeda & Kramer, 2000).

While it is difficult to obtain enough statistical power for a study solely of those 5-year olds who perseverate in the DCCS, it is relatively straightforward to classify children by switch cost magnitude. The utility of such task-switch tests in developmental populations has been shown by other researchers. As noted, Cepeda, Kramer & Gonzalez de Sather (2001) tested task-switch in children and adults, using a Stroop-like “what number”/“how many” test. However, because the test required number-reading, it was not intended for children younger than 6- to 7-years old. Nevertheless, the authors found expected age-related changes in switch costs. These correlated with reductions in processing speed. Dibbets & Jolles (2006) tested task-switch errors and RTs in children aged 5 through 12 years. They found the expected reduction with age in both errors and RT in both switch and non-switch trials. Notably, their test used pictorial stimuli, not symbolic stimuli like numerals, so it would be appropriate for preschool children. However, their youngest group averaged 5½ years of age, so it is unclear how the results would extend to younger children. Also, they did not administer other executive functions tests or manipulate cue content, so the results do not address reasons for their findings. Crone, Bunge, van der Molen, & Ridderinkhof (2006) successfully used a color/shape binary switching test, analogous to studies presented in this thesis. Like Dibbets & Jolles, they found robust age differences, notably in RT switch costs, but also in errors. However, their youngest participants were 7- and 8-year-olds, and they also did not administer other tests of executive functions.

Thus, prior results strongly suggest that task-switch costs and errors significantly change from 3 to 7 years. However, it remains unclear how both of these developmental changes relate to one another, and how they relate to other, parallel developing, executive skills.

Chevalier & Blaye (2009) found that amplifying the semantic relationship between an indirect cue and an S-R response (e.g. a rainbow for “sort by color”) improved children’s performance in the Advanced DCCS. However, they did not use parametric measures of flexibility, nor did they extend their findings to the types of explicit cues used in the DCCS.

In perhaps the most comprehensive study so far reported, Davidson Amso, Anderson & Diamond (2006) compared congruent, incongruent, and mixed-trial, performance on three tests by children aged 4 years through adults. In two spatial congruency tests, there was a sort of speed/accuracy trade-off, whereby 6-year-olds were more accurate than 4-year-olds on mixed blocks (i.e., where trials switched between congruent and incongruent rules); however, 6-year-olds also slowed down somewhat more. This suggests that 6-year-olds are better able to modulate their response-pace based on feedback about their accuracy in following complex, changing rules. Also, interestingly, across tests there were much higher correlations in RT than in accuracy, and RT correlated both with working memory and inhibition. Although this study used somewhat different tests that do not map directly onto task-switch tests such as those used in this thesis, it suggests two hypotheses: first, we might see different effects of age on RT switch costs than on perseverative errors. Second, RT switch costs should be more correlated than errors across tests, and they may show less distinct correlations with measures of executive functions.

### **1.5 Outline of the Dissertation**

The present thesis comprises three empirical chapters that aim to explain whether low-level association-activation differences (such as those in Associational Activation Strength and in cue-processing) can provide as good as—or better—an explanation of the development of task-switch flexibility than a more general executive functions account. Chapter Two focuses on the role of cue-processing and memory representation in predicting the transition from

perseverative to flexible switching (across the age 3- to 6-year boundary). In this, we look at whether the youngest children fail to derive pragmatic benefit from the explicit cues used within the DCCS and whether this can explain so-called perseverative errors in childhood. In Chapter Three, we systematically manipulate cue directness within a task-switch test appropriate for children aged 4- to 7-years. Finally, in Chapter Four, we address the role of cognitive flexibility in a non-traditional acquisition challenge for children: pronominal reference resolution in a discourse paradigm.

This final chapter highlights an important extension of the concept of cue information. Manipulating cue information is inherently a semantic manipulation—thus chapters 2 through 4 at least on some level demonstrate that language *facilitates* flexibility (as one means of conveying task demands; see also Deák, 2003; Bialystok & Martin, 2004). There is an increasing awareness that testing cognitive flexibility in odd, contrived experimental tasks does not accurately reflect the kinds of situations in which flexibility is important for the child in the real world (Burgess, Alderman, Forbes, Costello, Coates, Dawson, et. al, 2006). Many socio-culturally important circumstances may *hinge upon* cognitive flexibility (Cragg & Nation, 2010)—for example, following a joke which relies upon a quick revision of a temporary linguistic parse— (e.g., “why is six afraid of seven?” Because seven eight nine!) (Deák & Holt, 2008). Yet, virtually no studies have directly addressed the role of flexibility in integrating real-world language in the developmental literature (although theoretical accounts from linguistics intuitively support this idea) (e.g. Novick, Trueswell, & Thompson-Schill, 2005). Indeed, language acquisition researchers have noted the importance of inherent cue-based representations in linguistic parsings (MacWhinney, 1987). Chapter Four provides an initial attempt to relate developmental changes in cognitive flexibility mapped in Chapter Two to

individual differences in comprehension of one type of pragmatic language: pronominal reference resolution in a discourse paradigm.

All work in this thesis is presented in APA format consistent with previous or upcoming submission to peer-reviewed journal, with the modification that previously introduced abbreviations are continued without reintroduction in subsequent chapters.

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

## **Abstract**

In simple 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 still respond slowly when switching. These age-related changes might reflect the maturation of executive functions (e.g. inhibition). However, they might also relate to children's ability to use task cues to retrieve appropriate rules from working memory. Cue processing difficulties predict switch costs in adult task-switching paradigms (Logan & Schneider, 2007). They have seldom been studied as a possible explanation for children's task-switch errors. The current study tested whether inhibition, or cue interpretation, predict 3- to 6-year-old children's perseverative errors (Experiment 2a) and switch-related slowing (Experiment 2b). Children were tested in a computerized task-switching test in which most trials were preceded by an audio-visual cue that instructed them to switch sorting rules, or to continue using the current rule. Interspersed control trials used no cue. In Experiment 2a, 3- and 4-year-olds made as many errors on cued stay trials as on cued switch trials, but were significantly more accurate on uncued stay trials. Thus, the presence of cues, rather than rule switches, 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 conflict or rule switches. Additional variance was predicted by an unrelated measure of perceptual-motor processing speed (processing speed). In Experiment 2b, switch costs in 4½- and 6-year-olds were similarly predicted by speed in a unidimensional (1D) matching test.

### **Children’s Task-Switching Efficiency: Missing our Cue?**

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 email, 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 definitions of putative executive functions (e.g., “inhibition”), and there is continuous experimental progress in specifying the biological 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; Cepeda, Cepeda & Kramer, 2000; Berwid, Curko Kera et. al., 2005). Based on studies of healthy adults and a few studies of older children, there are proposals (Miyake, Friedman, Emerson, Witzki, & Wager, 2000; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Friedman & Miyake, 2004; Wu, Chan, Leung, Liu, Leung, & Ng, 2011) that executive functions can be separated into at least three partly independent factors: flexibility (or switching), inhibition, and working memory, with specific sub-divisions and connections among them. Although this model provides a useful starting point for a more elaborate theory of how adults’ cognitive flexibility relates to other cognitive processes, there is much less evidence to warrant a parallel model of children’s cognitive flexibility and its relation to other executive functions.

One reason developmental models lag behind is that there are fewer testing methods, and typical tests for young children are not sensitive enough to distinguish between possible

underlying processing models. Many studies of younger children in particular (i.e., 2 to 5 years of age) have used rule-switching tests that yield qualitative, binary responses, and often, ultimately, a binary 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 its shape. This second rule requires children to reverse the responses that they had used in order to follow the first rule.

Children younger than 4 years tend to make errors after the rule switch: many of them continue to follow the first rule (Zelazo & Frye, 1996; Zelazo, 2006), that is, to perseverate. Curiously, children who perseverate can accurately re-state the second rule (Zelazo, Frye & Rapus, 1996). The reasons for these perseverative errors have been debated (Deák, 2000, 2003; Zelazo, Müller, Frye & Marcovitch, 2003; Span, Ridderinkhof, & van der Molen, 2004; Davidson Amso, Anderson & Diamond, 2006; Hanania & Smith, 2010). The persistence of this debate is partly due to the limited sensitivity of the task, which yields only one sort of "catastrophic" error, and does not usually distinguish between degrees of flexibility, or between degrees or sub-types of perseverative errors (Deák, 2003).

Emerging 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, the 3DCCS, or Three Dimension-Changes Card-Sorting test (Deák, 2003; Cepeda & Munakata, 2007; Narasimham, Deák & Cepeda, under review) imposes three rules and two switches, and four choices of items, per trial. This reveals several new response patterns, including patterns of partial flexibility, and of unsystematic response-switching (Narasimham, Deák & Cepeda, under 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 preschools' task-switch using parametric tests.

Thus far, the few studies focusing on preschool-aged children have not been contextualized within the larger literature on task-switch. That literature, although centered on adults (e.g., Allport, Styles, & Hsieh, 1994; Meiran, 1996; Monsell, 2003), includes a growing number of studies of children (Cepeda, Kramer & Gonzalez de Sather, 2001; Crone, Bunge, van der Molen & Ridderinkhof, 2006; Karbach & Kray, 2009; Gupta, Kar & Srinivasan, 2009). Task-switch tests also use bivalent, rule- or cue-dictated task reversals; however, children 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 paper, then, is to bridge, and hopefully to unify, explanations for young children's categorical task-switch errors with older children's graded switch costs. To achieve this, we designed a task-switch 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 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-switch efficiency from 3 to 6 years of age.

#### Explanations of perseverative errors and switch costs

There are at least two major alternative explanations proposed for 3- and 4-year-olds' perseverative rule-switching errors. One is that young children fail to inhibit the habit generated



during the pre-switch 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 if the cards are hidden (Kirkham, Creuss, & Diamond, 2003; Diamond, Carlson & Beck, 2005), 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, Styles & Hsieh, 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, 2002a). 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 DCCS also show weaker representations of the rules, even when those rules are tested in no-conflict, non-switching tasks (Cepeda & Munakata, 2007; Blackwell, Cepeda & Munakata, 2009). 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 conflict that can be imposed only by stimuli that vary along both dimensions that are relevant to both rules (Cragg & Nation, 2009). However, the aforementioned results suggest that automation of very low-level contingencies determine higher-level, adaptive control.

We tested young children’s speed to activate a low-level S-R contingency by using no-conflict, unidimensional (1D) 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 controlled for all the perceptual, memory, cuing and response demands of the task-switch test. The “Associational Activation Strength” (Associational Activation Strength) explanation (Munakata, 2001) suggests that in younger children, task-switch speed and accuracy are predicted by efficiency of “1D” matching. In order to robustly test this hypothesis, younger preschool children (3 to 4.5 years) were tested in Experiment 2a, and older children (4.5 to 6 years) were tested in Experiment 2b. It is possible that low-level association strength will matter more for younger children, who might be slower to make perceptual comparisons, than older children, who should be able to quickly develop stimulus-response (S-R) associations. If task-switch is determined by speed to activate low-level S-R association, it might be predicted by 1D matching.

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, subjects make commission errors, and we expect individual and age differences in the speed threshold for children’s “No-Go” errors. Because Go/No-Go tests have not been used with 3- and 4- year-olds, however, another age-appropriate test of inhibition was administered: in Luria’s Tapping Test (Luria, 1966; Diamond & Taylor, 1996) children must inhibit the tendency to imitate an adult’s action by “doing the opposite.” If inhibitory efficiency predicts task-switch 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-switch 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 (Mayr, 2006; Arrington, Logan & Schneider, 2007; Forstman, Brass & Koch, 2007). Furthermore, one recent study indicates that cues impair task-switch performance in older children (Chevalier & Blaye, 2009). However, such effects have not been tested in younger preschool children, who might require more sustained cognitive resources to process and maintain verbal cues.

To address this possibility, our task-switch used “switch” and “stay” cues to indicate the current game. 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. To test the effects of a verbal cue per se, stay trials were compared to uncued stay-trials. (Note that there is no way to deliver uncued switch trials to young children). 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), then there would be highest accuracy/speed in uncued stay trials, medium levels in cued-stay trials, and lowest accuracy/speed in switch trials. Also, older children (5- and 6-year-olds), who seldom make rule-switching errors and should process verbal cues more easily, might not show increased cue-processing errors. However, if cue-processing remains a significant cognitive demand, these older children might show longer RTs in cued than uncued stay trials.

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 1D 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, 1D 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 life-span study that processing speed predicted a large proportion of variance in task-switch speed (see also Hale, 1990; Kail, 1991; Kail & Salthouse, 1994; Kail 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 (PPVT-III), was used to estimate general language ability. Because the task-switch and matching tests use verbal cues, speed and accuracy might correlate with receptive vocabulary.

## **EXPERIMENT 2A**

### *Method*

*Participants.* English-speaking 3-year-old ( $n = 25$ , age  $M = 3.4$  yrs., range 3.1 yrs. to 3.9 yrs., 13 girls) and 4-year-old children ( $n = 28$ , age  $M = 4.4$  yrs., range 4.0 yrs. to 4.8 yrs., 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 UC-San Diego IRB. Four 3-year-olds and two 4-year-olds were excluded because they did not complete both test sessions.

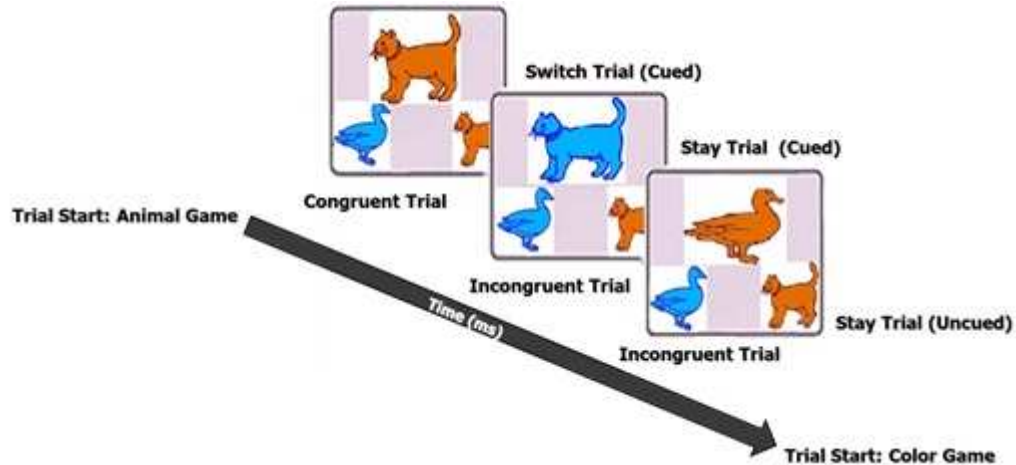
*Materials.*

*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 lay 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 (<http://www.adobe.com>, Adobe Systems Inc., Delaware, USA): 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.<sup>1</sup> Two target pictures (4 cm<sup>2</sup>), a blue cat and brown duck, were constantly present, one near each of the bottom corners of the monitor, directly above the response buttons (Figure 2.1). 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<sup>2</sup> gray box. Two of the four test stimuli matched the two target pictures (i.e., brown cat and blue duck). These congruent (i.e., non-conflict) stimuli appeared in 33% of all trials. They required the same response under any rule (i.e., either game). The other two test images (67% of trials) were incongruent (i.e., conflict); that is, they afforded different matching responses for each target, depending on which game was being played (e.g., blue cat could be matched with the blue duck or the brown cat).

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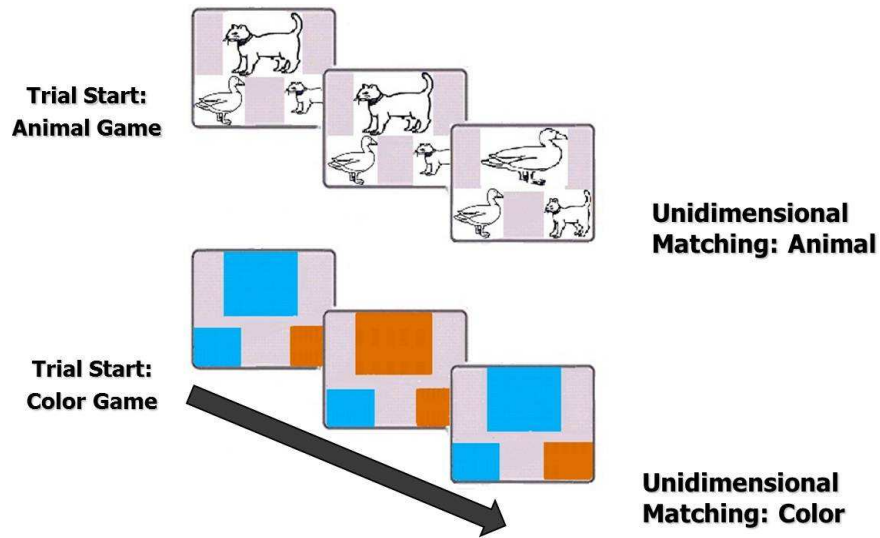
<sup>1</sup> Also, the pairs *cat* and *duck*, and *brown* and *blue*, are similar in word length and phonological complexity.



**Figure 2.1:** Task-switching design. The switch trial was always the first trial of each 3-trial same-rule (“game”) block (Experiment 2a & 2b).

Four cue videos were recorded: two switch cues (a model saying: “Now play the animal game” or “Now play the color game”) and two stay cues (“Keep playing the animal game” or “Keep playing the color game”). These were matched frame-by-frame for length (1500ms) and consistency in facial movement and intonation. An 800ms feedback video of a smiley face or frowning face was presented following each response.

*Unidimensional matching.* A one-dimension rule-matching test (see Blackwell et. al., 2009) was based on the task-switch test, but with no conflict stimuli or rule-switches. Four univalent stimuli were created based on the task-switch stimuli: black outlines of the cat and duck, and swatches of blue and brown (Figure 2.2). These were shown in the same configuration as above. The “stay” video cues (as above) and feedback videos were used. Switch cues were not used.



**Figure 2.2:** 1D matching test design (Experiment 2a & 2b).

*Inhibition, speed, and verbal tests.* The Go/No-Go test used a green circle and red circle (10 cm<sup>2</sup>) on a black background. The box completion test consists of a page with five rows of seven 3-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 show the referent of that word. Forward digit span was measured using lists from the WAIS-III (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 did Luria's Tapping Test, Box Completion, Unidimensional (1D-) matching, and Go/No-Go. In the second session, a week later, children completed Task-Switching, Digit Span, and PPVT-III. Computer tasks were programmed and delivered in Presentation 9.9 (Neurobehavioral Systems, New York CA, USA). 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 defined sorting rules. The rule changed predictably according to a video “switch” cue (1500ms) that was delivered after every three trials. The first rule was counterbalanced across participants. A matched “stay” video cue (1500ms) appeared before either the second or third trial (alternating randomly) within each three-trial block (Table 2.1). The other stay trial in the block was uncued. Stimuli appeared 700ms after the video cue. There were 16 incongruent trials of each type (switch and stay), including eight switch trials in each direction (switching color to animal and switching animal to color). There were also eight congruent switch trials and eight congruent stay trials. Trials were presented in random order, in a single block of approximately 8 min.

**Table 2.1:** Summary of task-switch cue design (Experiments 2a and 2b).



<i>Trial Type</i>	<i>Congruency</i>	<i>Stimuli</i>	<i>Cue</i>
Switch	Incongruent	Brown Duck Blue Cat	"Now play the [animal/color] game"
Stay	Incongruent	Brown Duck Blue Cat	"Keep Playing the [animal/color] Game"
Stay	Incongruent	Brown Duck Blue Cat	N/A
Switch	Congruent	Blue Duck Brown Cat	"Now play the [animal/color] game"
Stay	Congruent	Blue Duck Brown Cat	"Keep playing the [animal/color] game"
Stay	Congruent	Blue Duck Brown Cat	N/A

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 during 12 practice trials.

RT and accuracy were analyzed. For test trials, RTs less than 200ms (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. Remaining RTs were not transformed, except for outliers greater than 2 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).

*Unidimensional matching [1D matching]*. This task matched the task-switch test in event timing, motor demands, and presence of (stay) cues. There were no conflict stimuli and no need to select dimensions based on cue analysis. There were no rule switches within a block. In each block children saw either color patches only, or animal outlines only. Children were instructed to match each test stimulus by pressing the button below the correct target as quickly as possible (Figure 2.2). Children completed 16 trials per rule (i.e., color and animal). The first five trials of each rule type were considered training trials, and were not analyzed. (Excluding these trials did not affect the findings, below). RTs were trimmed and Winsorized as above; fewer than 5% of trials were affected. Children made almost no errors, so rare 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 when a "go" cue (green circle) appears, but not push if a "stop" cue (red circle) appears. In each trial, circles appeared onscreen for 250ms. Subsequently, a variable inter-stimulus interval (ISI) of at least 150ms (ensuring that children responded to the current stimulus) occurred; this interval was the critical factor. The ISI was adjusted between blocks of trials (24 trials/block) based on 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 over two consecutive blocks. The exact number of trials thus varied for each child, based on the number of blocks

needed to find the child's 50% criterion time (range: 3 to 8 blocks, or 5 to 10 min). This threshold of inhibition speed was the dependent measure.

*Tapping test [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 five 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 test trial accuracy.

*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. Finally, for the test they completed as many boxes as they could within 1 min.

*Peabody Picture Vocabulary Test-III [Receptive language]*. Children were asked to point to one of four pictures that illustrate a word. 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 sec intervals.

### *Results*

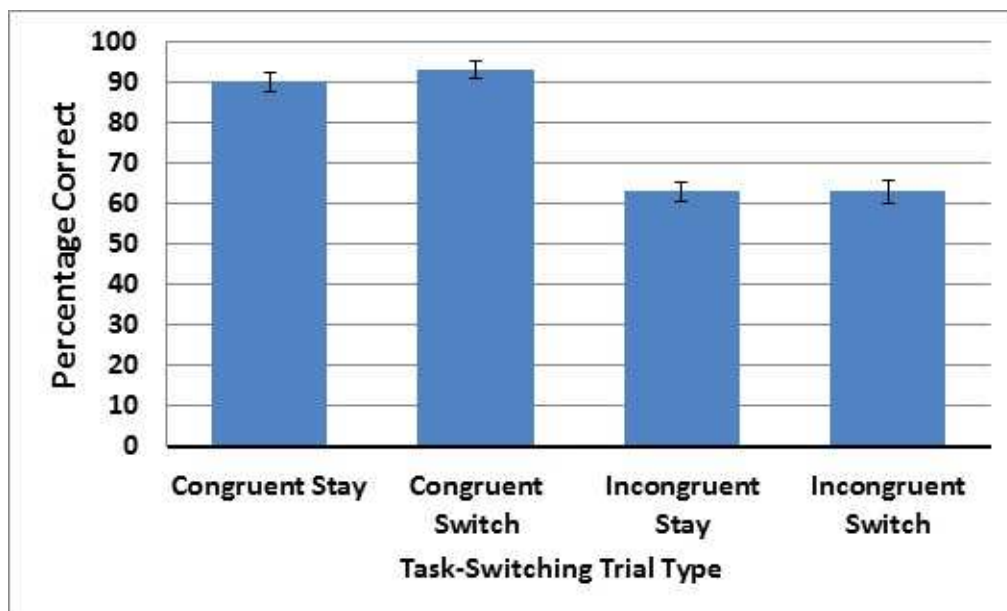
To verify that the sample had age-typical verbal abilities, PPVT-III and digit span scores were examined. Standardized PPVT scores averaged 117.3 ( $SD = 10.9$ ), which is higher than population norms ( $M = 100$ ,  $SD = 15$ ). Mean forward digit span averaged 4.1 ( $SD = 0.8$ ),

similar to other reported same-age samples (Alloway, Gathercole, Adams, Willis, Eaglen & Lamont, 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 analyses.

*Task-switching.* Three children with fewer than seven correct incongruent-stimulus trials were excluded from analyses. Accuracy in congruent trials was near ceiling for all types of trials (Table 2.2). However, accuracy varied considerably in incongruent trials. A 2 x 2 ANOVA (Cue [Switch vs. Stay] x Congruency [Incongruent vs. Congruent]), with age as a covariate, was conducted on accuracy ratios in cued trials<sup>2</sup>. There was a main effect of congruency,  $F(1,49) = 124.77, p < .0001, \eta^2 = .71$ . Children were more accurate in sorting congruent stimuli. The switch cost was not significant,  $F(1,49) = 1.34, p < .253, \eta^2 = .026$ . Errors were related to congruency, not to switching (Figure 2.3). The age covariate was only marginally significant,  $p < .083$ .

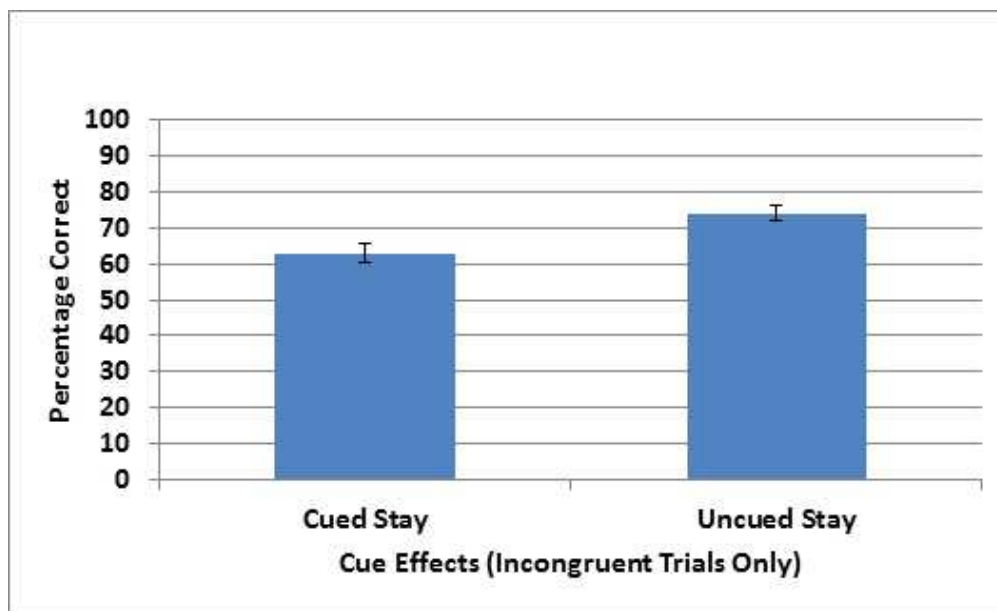
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<sup>2</sup> While game asymmetries have been reported for switch-to-animal vs. switch-to-color trials in older children (Ellefson, Shapiro, & Chater, 2006), our design did not allow for in-depth analysis for switch asymmetries, as there were only eight switch trials of each type, and only correct trial RTs were analyzed. Preliminary within-subjects t-tests for game asymmetries did not reveal any significant effects, however, so game was not included as a factor in any ANOVAs



**Figure 2.3:** Mean (with *SE* bars) task-switch accuracies of 3- and 4- year old children by trial type (Switch x Congruent) (Experiment 2a).

To assess the effect of cues in stay trials, another 2 x 2 ANOVA (Cue [Cued vs. Uncued] x Congruency [Incongruent vs. Congruent]), with age as a covariate, was conducted on stay trials only. There was a main effect of congruency,  $F(1,49) = 81.12$ ,  $p < .0001$ ,  $\eta^2 = .62$ . 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 2.4). The age covariate was not significant,  $p < .119$ .

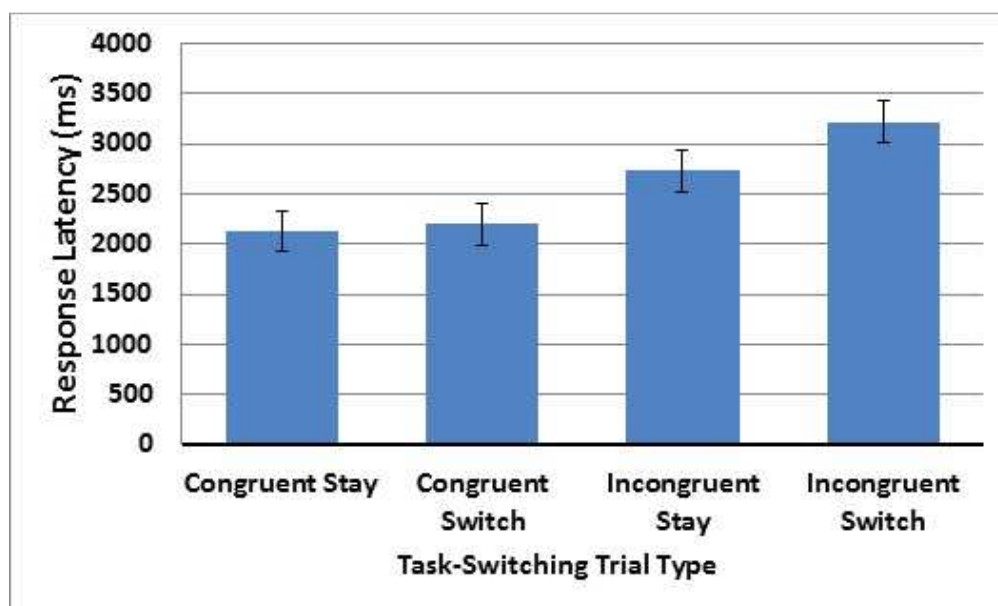


**Figure 2.4:** Mean (with *SE* bars) task-switch “stay” accuracies of 3- and 4- year-old children by cue type (Cued x Uncued) (Experiment 2a).

RTs on correct cued trials were tested for switch and incongruency costs in a 2 x 2 ANOVA (Cue [Switch vs. Stay] x Congruency [Incongruent vs. Congruent]), with age as a covariate (see Figure 2.5). 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,  $F(1,49) = 38.17, p < .0001, \eta^2 = .438$ . However, as predicted by studies of older children, there were significant switch costs,  $F(1,49) = 6.65, p < .013, \eta^2 = .120$  (Table 2.2). Thus, switch costs in 3- and 4-year-olds were measurable in latency, but not accuracy. This effect is further explored in Experiment 2b.

**Table 2.2:** Performance on accuracy and RT measures of task-switch, for 3- and 4-year-olds (Experiment 2a).

	<i>Incongruent Switch</i>	<i>Incongruent Stay</i>	<i>Congruent Switch</i>	<i>Congruent Stay</i>
3-year olds	3688ms (2072) 58.1% (3.4)	3354ms (2151) 62.3% (3.4)	2933ms (2366) 91.7% (3.7)	2602ms (1777) 88.3% (3.5)
4-year olds	2692ms (1055) 67.5% (4.0)	2224ms (1014) 63.8% (3.7)	1594ms (808) 94.4% (2.6)	1750ms (882) 91.3% (2.8)



**Figure 2.5:** Mean (with *SE* bars) task-switch RT of 3- and 4- year-old children by trial type (Switch X Congruent) (Experiment 2a).

*Unidimensional matching.* A one-way ANOVA, with age as a covariate, was used to test differences in RTs in correct animal vs. color 1D matching trials. Again, 4-year-olds were faster than 3-year-olds (3-year-olds:  $M = 2442\text{ms}$ ,  $SD = 1236$ ; 4-year-olds:  $M = 1850\text{ms}$ ;  $SD = 927.5$ ),  $F(1,49) = 216.34$ ,  $p < .001$ ,  $\eta^2 = .81$ . In addition, children were slower to match animals

than colors,  $F(1,49) = 4.63$ ,  $p < .036$ ,  $\eta^2 = .088$ . Thus, we analyzed the two rules separately in subsequent regression analyses (Table 2.3).

*Inhibition and Perceptual-motor Processing Speed.* There were significant age differences in 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 differences in the Go/No-Go test (Table 2.3).

**Table 2.3:** Performance on behavioral measures of executive functions, for 3- and 4-year-olds (Experiment 2a).

	<i>Unidimensional Matching (RI)</i>		<i>Luria Tapping (Errors)</i>	<i>Go/No-Go (Interstimulus Interval)</i>	<i>Boxes (Numbers)</i>
	<i>Animal</i>	<i>Color</i>			
3-year olds	2535ms (1177)	2349ms (1295)	9.12 (5.9)	2808ms (1579)	14 (6.5)
4-year olds	1969 (899)	1732ms (956)	4.7 (4.3)	2665ms (1574)	20.9 (7.26)

*Predicting task-switching flexibility.* Correlations among age, task-switch accuracy in cued stay and cued switch trials, and other executive functions and verbal tests, are shown in Table 2.4. Only Tapping test, Box Completion, and 1D Matching [animal] correlated with incongruent task-switch costs.



**Table 2.4:** Bivariate correlations among task-switch, measures of executive functions, 1D matching speed and language in 3- and 4- year-old children (Experiment 2a). *Note.*  $^+p < .06$ ;  $*p < .05$ ;  $**p < .015$ ;  $***p < .005$ ,  $****p < .001$ ,  $*****p < .0001$ .

<i>Pearson's Correlation</i>	Luria	Go-No-Go	Boxes	1D 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 <sup>+</sup> [.259]	-.262 <sup>+</sup>	-.269 <sup>+</sup>
Go/No-Go [Inhibition]			-.166	-.414*** [.475*****]	-.348**	-.1
Boxes [Processing]				-.462*** [-.434***]	.367**	.355**
1D Matching Color [Animal]					-.322 <sup>+</sup> [-.322**]	-.151 [-.316 <sup>+</sup> ]
Incongruent Stay Costs						.599*****

We entered age, 1D matching [animal], Box completion, and Tapping scores—all correlated with incongruent switch accuracy—into a stepwise regression of accuracy in incongruent switch trials. The only significant predictor of incongruent-switch accuracy was 1D matching [animal] ( $\beta = -.008$ ;  $R^2_{\text{adjusted}} = 0.154$ ,  $R^2_{\text{change}} = 0.188$ ,  $p = 0.012$ ).

Because switch and stay accuracies did not differ, and showed similar patterns of correlation with the other tasks, we ran a second regression on accuracy in incongruent trials, in both cued switch and cued stay trials. Accuracy in cued incongruent trials (switch and stay) might more accurately describe the source of children's errors, as the semantic integration difficulties were the same between these conditions and children did not show accuracy

differences between cued switch and cued stay. As in the previous case, 1D matching [animal] predicted accuracy ( $\beta = -.007$ ;  $R^2_{\text{adjusted}} = 0.171$ ;  $R^2_{\text{change}} = 0.188$ ,  $p = 0.002$ ). Adding Box-completion accounted for additional variance ( $\beta_{\text{uni}} = -.007$ ;  $\beta_{\text{boxes}} = .631$ ;  $R^2_{\text{adjusted}} = 0.228$ ,  $R^2_{\text{change}} = 0.072$ ,  $p = 0.038$ ).

### *Discussion*

Preschool children understand and can verbally repeat a sorting rule in conflict with their current sorting responses; however, they continue to make sorting errors under the new rule (Zelazo, Frye & Rapus, 1996). This may be because they sometimes have difficulty using semantic cues to decide *when* to change (e.g. confusion between stay and switch cues). We addressed the role of cues directly by introducing cues on  $\frac{1}{2}$  of stay trials. Strong evidence for the role of cues was found in that accuracy was lower on *cued* incongruent stay trials than *uncued* incongruent stay trials. This suggests that perseverative errors may result from difficulty using the task cue to select or activate the current rule.

This result is consistent with Chevalier and Blaye's (2009) finding that semantically ambiguous cues impaired rule-switching flexibility in older children. Both results are consistent with the rule-retrieval model postulated by Morton and Munakata (2002a): 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, and enact the appropriate response contingencies. Notably, tests of cue-processing (Miyake, Emerson, Padilla & Ahn, 2004) have shown that adults have difficulty following indirect cues (e.g. "c" and "s" for color and shape) when a working memory load is imposed. The Morton and Munakata model suggests that children's cue-processing is so inefficient that even without an added working memory load, direct cues with familiar meanings can be challenging.

The Morton and Munakata (2002a) model further predicts that children are relatively slow to activate appropriate rules even for simple, 1D stimuli. These stimuli remove stimulus-conflict and switch demands, and control for the possibly distracting presence of a cue. Response speed in the 1D animal-matching test was the best predictor of task-switch accuracy (15-20% of variance). This game asymmetry, while unexpected, may also be in line with indirect model predictions. Less well-learned rules should be harder to retrieve from working memory. Children were slower to match animals than color in 1D matching. This rule may then be considered the less well-learned rule. Speed in the better-learned rule (color) was not correlated with, nor did it predict, accuracy in incongruent switch trials. This may be because the rule is sufficiently well-learned that, without the presence of stimulus conflict or switching demands, the demands of integrating the cue are not, by themselves, great enough to prolong a response decision. Go/No-Go speed and tapping-test inhibition also did not predict task-switch. This adds to other findings that maturing inhibitory processes do not predict changes in preschoolers' cognitive flexibility (e.g., Deák & Narasimham, 2003).

1D matching is correlated with measures of processing speed. Processing speed (Box Completion) accounted for a small proportion of variance. One question is whether the matching test really measures cue integration processes, over and above speed to respond to the stimulus (i.e., processing speed). To test this more accurately, we include in Experiment 2b a new measure of processing speed. In the processing speed test, children match 1D colors or animals as quickly as possible; however, there is no cue preceding each trial. If the (cued) 1D matching test is truly capturing the demands of processing a cue's meaning, we expect the 1D matching trials to be a better predictor of task-switch than the uncued matching-speed task.

Emerging evidence suggests that cue-processing difficulties also predict older children's failures in more complex flexibility measures (e.g., Chevalier & Blaye, 2009).

Although older children seldom make the same kinds of persistent perseverative errors as young children, they sometimes show the same kinds of switch costs as adults. For example there were no accuracy differences between cued switch and stay trials in Experiment 2a, but there were emerging RT switch costs.

This raises a question about how cue-processing processes continue to play a role for children who have mastered the basic demands of the switch task. Perhaps cue processing difficulties are large when the task is at the cusp of a child's ability (as indicated by high error rates). However, when the tasks are easy enough so that there are no errors, perhaps cue integration is an insignificant factor. Although studies of adults show cue-processing effects even when error rates are quite low (< 3 percent; Arrington et. al, 2007), it cannot be assumed that cue-processing effects are similar in children, relative to other factors.

To address these questions, we administered the tasks to older children, who should not make task-switch errors but should still show robust RT effects (Cepeda et.al, 2001; Crone, Somsen, Zanolie, & Molen, 2006; Crone et. al, 2006) Thus, Experiment 2b replicates the study with older 4-year-olds to 6-year-olds, who made virtually no errors. Our primary question was whether, if the tasks and cues are easy (i.e., almost no errors), cue-perceptual-motor processing speed still predicts task-switch efficiency (i.e., switch costs).

A more basic question is whether there is continuity in task-switch abilities from 4 to 6 years of age. Do children who show larger switch costs in our task also show lower accuracy in other cued rule-switching tasks? To address this question, we also administered the Advanced DCCS (Zelazo, 2006). In this extension of the DCCS, the game to be played (shape or color) is cued by the presence or absence of a border surrounding the stimulus (e.g., black border: sort by shape; no border: sort by color). This indirect (or indirect) cue makes the task more difficult, and therefore elicits more perseverative errors from 4- and 5-year-old children (Zelazo, 2006).

In this case, however, the cue is non-verbal. It is not clear whether the demands of processing verbal cues (as in our task) will generalize to the demands of processing visual task-cues. Thus, if children who make errors in the Advanced DCCS test also show larger RT switch costs in our task-switch test, it will indicate continuity between an untimed test with non-verbal cues, the Advanced DCCS, and a timed, parametrically sensitive, verbally-cued measure of cognitive flexibility. This, in turn, will imply a fairly general task-switch capacity that varies among individual children.

## EXPERIMENT 2B

### *Method*

*Participants.* Two groups of English-speaking children were recruited: 4-year-olds ( $n = 12$ , age  $M=4.5$  yrs., range 4.2 to 4.9, 4 girls) and 6-year-olds ( $n = 12$ , age  $M=6.3$  yrs., range 6.1 to 6.9, 5 girls) with no diagnosed language or cognitive delays. Children were recruited from schools in San Diego County, CA. The majority of children were Caucasian and middle class. Three additional 4-year-old children were excluded because they did not complete both sessions. Four more were excluded from analysis because they did not fit the inclusion criteria for high switching accuracy ( $>85\%$  accuracy in switch/incongruent trials). All children completed the PPVT III-A and digit span tasks. Four-year-olds' mean PPVT-III-A score was 120.6 ( $SD = 10.9$ ); 6-year-olds' was 119.3 ( $SD = 14.7$ ). Thus, children had high vocabularies for their chronological age. One 6-year-old was excluded because his PPVT score was  $< 2 SD$  below age norms.

*Materials.* Stimuli for the task-switch, 1D matching, Go/No-Go and verbal test were the same as in Experiment 2a. Because 5-year-olds are at ceiling in Luria's Tapping test accuracy, that test was excluded. Due to concerns that our 1D matching measure was measuring

processing speed instead of cue processing, we introduced a new test of processing speed. Children saw the same stimuli as in the 1D matching test, and were told to match the test image and target. However, stimuli were uncued. Additionally, we increased the number of task-switch trials to 160 total switch trials (80 per rule), so that we could examine asymmetric switch-costs (i.e., switch-to-animal vs. switch-to-color; see Ellefson et. al., 2006).

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-switch, 1D matching and Go-No-Go tasks were the same as Experiment 2a; however, because children were recruited for an EEG study, they completed two sessions in a testing room in a neurobehavioral laboratory near the university campus.

Children completed a new test of processing speed, which was like the 1D matching test, but with no pre-stimulus cue. The stimulus appeared immediately after the matching response to the previous stimulus. After five practice trials, children completed 16 test trials, including 4 trials of each stimulus. The low 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) is 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 2a.

### *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% for incongruent switch and 94% for

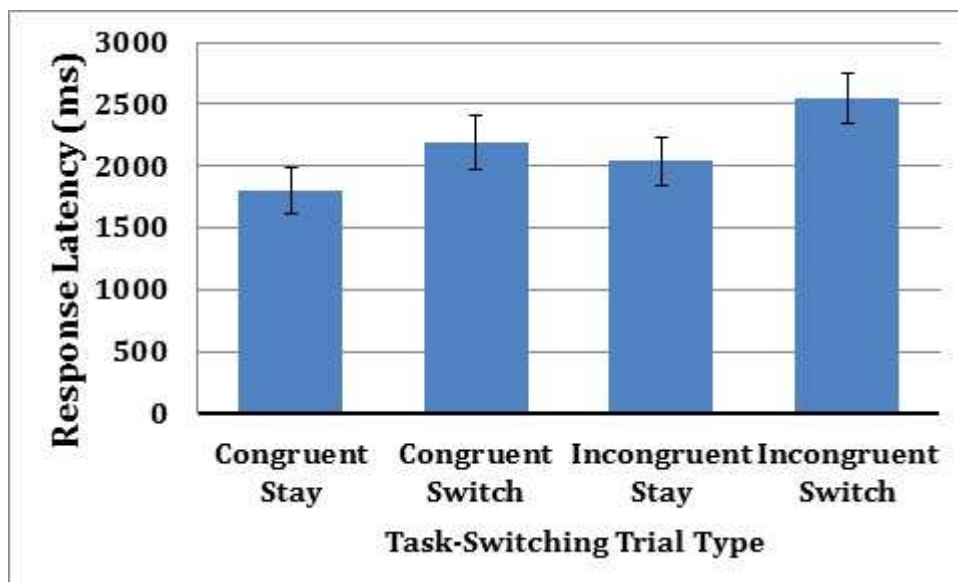
congruent switch trials. Thus, analyses focused on RT data. There were no gender differences in RT, so girls and boys are combined in all further analyses. Unlike in Experiment 2a, our data were collected from two discrete age groups. Thus, we analyzed age as a separate factor in all ANOVAs. In addition, switch game, that is, switch-to-animal or switch-to-color, was included in the ANOVAs

A 2 x 2 x 2 x 2 (Age [4 vs. 6] x Cue [Switch vs. Stay] x Congruency [Incongruent vs. Congruent] x Switch Game [Animal vs. Color]) ANOVA was performed on task-switch RTs on correct trials. There was an effect of switching,  $F(1,22) = 12.94, p < .002, \eta^2 = .37$ . RTs were slower following switch trials than stay trials. These switch costs are analogous to those seen in adults, albeit larger (Table 2.5).

**Table 2.5:** Performance on RT measures of task-switch, for 4- and 6-year-olds (Experiment 2b).

	<i>Incongruent Switch</i>	<i>Incongruent Stay</i>	<i>Congruent Switch</i>	<i>Congruent Stay</i>
4-year olds	2498 (1182)	1989 (1332)	1837 (926)	1637 (976)
6-year olds	2391(1020)	2392 (1348)	2239 (941)	1953 (828)

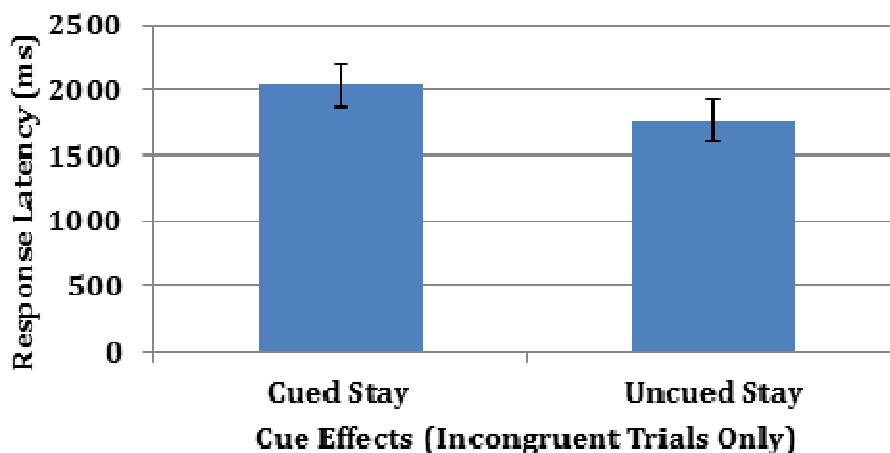
There was again a significant effect of congruency,  $F(1,22) = 9.60, p < .005, \eta^2 = .30$ . Congruent trials were faster than incongruent trials. There was no main effect of age: 4-year-olds were not significantly slower than 6-year-olds for all trial-types,  $F(1,22) = 0.55, p < .465, \eta^2 = .025$ . Children were not significantly faster to switch from animal to color or from color to animal game,  $F(1,22) = 0.55, p < .465, \eta^2 = .025$ . Both results were unexpected. There were no significant interactions among any of the factors (Figure 2.6).



**Figure 2.6:** Mean (with *SE* bars) task-switch response RTs of 4- and 6- year old children by trial type (Switch X Congruent) (Experiment 2b).

Another 2 x 2 x 2 ANOVA (Age x Cue [Cued vs. Uncued] x Congruency [Incongruent vs. Congruent]) was conducted on stay trials only. The age covariate was not significant. There was a main effect of cue type,  $F(1,22) = 6.25, p < .02, \eta^2 = .22$  and an interaction of age and cue type,  $F(1,22) = 6.29, p < .02, \eta^2 = .22$ . Children, especially 6-year-olds, were faster to respond to uncued than cued stay trials (Figure 2.7).





**Figure 2.7:** Mean (with *SE* bars) task-switch “stay” accuracies of 4- and 6- year old children by cue type (Cued x Uncued) (Experiment 2b).

*Unidimensional matching.* A 2 x 2 (Age x Rule [Animal/Color]) ANOVA compared RTs in 1D matching trials. There was a significant age-effect: 4-year-olds were slower than 6-year-olds,  $F(1,22) = 8.64, p < .008, \eta^2 = .28$ . There was also a main effect of rule type. Unlike in Experiment 2a, children were slower in color trials than in animal trials,  $F(1,22) = 8.77, p < .007, \eta^2 = .29$  (Table 2.6).

*Advanced DCCS.* Children who made 0-1 errors were classified as “flexible;” children with more errors were classified as inflexible. There was no significant age difference in mean error rates between age groups ( $p < .378$ ). Six- (M = 4;  $SD = 2.5$ ).and 4-year-olds (M = 5;  $SD = 2.5$ ) both made many errors, although they had not done so in the task-switch test (Table 2.6).

*Inhibition and Perceptual-motor Processing Speed.* Four-year-olds were slower than 6-year-olds to inhibit Go/No-Go responses,  $F(1,23) = 22.29, p < .001$ . Four-year olds were slower than 6- year olds to make an uncued matching response,  $F(1,23) = 8.604, p < .008$  (Table 2.6).

**Table 2.6:** Means (and SDs) on tests of executive functioning for 4- and 6-year-olds (Experiment 2b).

	<i>Unidimensional Matching (RT)</i>		<i>Advanced DCCS (Errors)</i>	<i>Go/No-Go (Interstimulus Interval)</i>	<i>Uncued Matching (RT)</i>
	<i>Animal</i>	<i>Color</i>			
4-year olds	938ms (231)	1233ms (513)	5 (1.9)	2725ms (992)	767ms (221)
6-year olds	701ms (231)	819ms (198)	4 (2.5)	1326ms (261)	567ms (155)

*Predicting task-switching flexibility.*

Bivariate correlations among age, task-switch accuracy in cued stay and cued switch trials, and other executive functions and verbal tests are shown in Table 2.7. Only uncued matching and 1D Matching [animal] correlated with incongruent task-switch costs. In addition, the Advanced DCCS was not correlated with switch costs.

**Table 2.7:** Bivariate correlations among task-switch, measures of executive functions, unidimensional (1D) matching speed and language in 4- and 6- year-old children (Experiment 2b). Note. + $p < .06$ ; \*  $p < .05$ ; \*\* $p < .015$ ; \*\*\* $p < .005$ , \*\*\*\* $p < .001$ , \*\*\*\*\* $p < .0001$ .

Correlation	Advanced DCCS	Go-No-Go	Uncued Matching	1D Matching Color [Animal]	Incongruent Switch Costs
Age	-.260	-.804*****	-.567***	-.561*** [-.552**]	-.386
PPVT-III	.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*
1D Matching Color [Animal]					.498** [.677*****]

We entered age, 1D matching [color], and uncued matching—the measures correlated with incongruent switch RT into a stepwise regression. As in Experiment 2a, 1D matching speed accounted for much of the variance in the incongruent switch types ( $\beta = .594$ ;  $R^2_{adjusted} = .410$ ,  $R^2_{change} = .470$ ,  $F_{change} = 9.30$ ,  $p < .001$ ). Again, adding processing speed (uncued matching) accounted for a marginal additional amount of variance ( $R^2_{change} = .08$ ,  $p < .096$ ).

## GENERAL DISCUSSION

Most attempts to investigate how executive functions contribute to young children's flexibility have only tested whether or not children persevere 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 measurement sensitivity may miss, for example, graded differences in processes such as task-cue integration, stimulus-conflict resolution, etc. Therefore, newer tests that can detect parametric behavioral differences might reveal subtle cognitive processing changes, which is critical for testing new theories from the adult and aging literature in development.

An age-appropriate, parametric test of task-switch, with controlled cues, showed that the ability to use verbal cues to quickly access and engage the correct rules strongly predicted task-switch accuracy. Even for children who did not make perseverative errors, cued rule-access predicted switch costs. By contrast, however, we did not find direct support for the popular idea in the developmental literature (Diamond, 2002; Diamond, 2009) that young children have difficulty inhibiting their prepotent responses, and that this causes switch errors. We did not find strong correlations between tests of inhibition and measures of task-switch accuracy or speed.

A strong source of evidence for a cue-processing/response-access account is that a “stay” cue also increased the task difficulty, no less than switching demands. As proof that the stay cue imposed a cost, children were reliably faster in uncued stay trials. The cued stay trials, like switch trials, required children to attend to the current cue and the stimulus, and access a corresponding response “rule” for this cue/stimulus intersection. This account fits evidence from studies of adults’ task-switch, which suggest that “true” task-switch costs are small or non-existent relative to cue-processing effects (Arrington, et. al 2007), and are related to changes in memory retrieval (Grange & Houghton, 2010).

Converging evidence for a cue-processing/response-access account was found in the strong correlation between task-switch accuracy (in switch-only trials or *all* cued trials), and 1D

matching speed for the more difficult rule. This relation was strong in children who perseverated on some trials (Experiment 2a), and in older children who were accurate in the switch task (Experiment 2b). The 1D matching test controlled for cue-processing and for stimulus and response demands, but eliminated stimulus conflict and switch demands. Thus, inhibitory demands were minimized, providing additional evidence that inhibitory demands are not the best predictors of children's rule-selection and switching abilities. These results are consistent with Morton & Munakata's (2002a) prediction that children show graded ability to activate appropriate rules from working memory, even without switching demands.

An alternative explanation for the relation between switch-task efficiency and matching speed could be that if children did not understand the cues, or could not match the stimuli accurately, they would have performed poorly in both the switching and 1D matching test. That would account for the correlation, but for a very different reason. However, this is implausible for three reasons. First, it cannot explain the results of Experiment 2b, 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, and most telling, even in Experiment 2a children (a) matched congruent stimuli in all trial-types with near-perfect accuracy, and (b) completed the 1D matching test with near-perfect accuracy. Thus, children were able to respond to the cues and perform the tasks, and were attentive and compliant.

Other, previous results are consistent with the hypothesis that cue-processing difficulties govern children's flexibility. Perner & Lang (2002) reported that children produced the standard pattern of perseveration in only one of four switching tasks (the one most similar to the DCCS), and only when it was prior to the other tasks. Thus, children may fail the DCCS (or Advanced DCCS) because they initially fail to parse the pragmatic cues. Also, Munakata & Yerys (2006) found that 3-year-olds' perseverative errors in the DCCS are sometimes due to

failure to fully comprehend the cues—even after passing the pre-test. Also, Deák (2000, 2003) found that semantic cues to word meanings differ in how strongly they imply a stimulus property, and this is reflected in flexibility in inferring multiple word meanings for an array, based on changing (weaker and stronger) semantic cues.

The results from the task-switch test have implications for other tests of executive functions. First, processing speed predicted cued task-switch accuracy and efficiency, over and above 1D speed. Thus, there seems to be a secondary contribution of general perceptual-motor decision speed, which is loosely consistent with previous reports that processing speed predicts efficiency of switching (Cepeda et. al., 2001). By contrast, there was no evidence that measures of inhibition predicted flexibility or cue integration, even though, arguably, both the tapping and Go/No-Go tests required simple cue-processing. This fits evidence that tests of inhibition do not strongly predict task-switch flexibility in children (Deák & Narasimham, 2003; Huizinga, Dolan & van der Molen, 2006). Also, the test of receptive vocabulary did not predict flexibility, further suggesting that it is not low-level semantic processing, but rather integration of current cue with stimulus properties, that affects performance. Finally, verbal working memory capacity did not predict flexibility. This confirms other evidence that span, *per se*, is not the aspect of working memory that predicts flexibility (e.g., Zelazo, et. al., 1995; 2003).

Many children in Experiment 2b failed the Advanced DCCS test. Thus, we did not replicate the single published report that 6-year-old children are flexible in this test (Zelazo et. al, 2006), even though our participants had above-average vocabulary, and performed according to age norms in all other tasks. Thus, the Advanced DCCS might be measuring a rather distinct sort of response selection, whereas our task is interpretable within the more theoretically differentiated and nuanced literature on task-switch in general. It is noteworthy that in the Advanced task, the switch cue is indirect—in essence, abstractly symbolic—rather than direct

and explicit. The cue-processing demands of this task are therefore high: the cue itself is weak evidence for rule-retrieval. This points to a limitation of our study: we manipulated the presence or absence of cues, but not the strength of the cues. We are currently addressing this topic in detail.

Several aspects of the current studies limit how far the results can be generalized. For example, our task also used frequent feedback. Bohlmann & Fenson (2005) found that feedback significantly affects preschoolers' performance on the DCCS. Thus, that factor requires future examination. Also, it is unclear how the dimensions tested in this study (and in many other studies) influence the results. For example, there is evidence that children's color-word knowledge develops surprisingly late (Bornstein, 1985), and this might contribute to the asymmetries in task strength (i.e., speed of rule-access) in our results. Notably, it was the "weaker" rule that predicted task-switch costs in both experiments, suggesting that ability to flexibly select from multiple possible rules is constrained by the "lowest common denominator"—that is, the hardest of the rules. Finally, it should be noted that our participants had relatively high receptive vocabulary. Thus, it cannot be assumed that our sample's verbal ability is representative of their chronological age.

Conclusion: These results show large individual as well as age-related differences in executive functioning, and task-switch in particular. Curiously, they shift the concern from task-switch *per se*, to the integration of multiple cues for response selection, under conflict conditions. The results show that the development of cue-task interactions in adaptable, efficient use of different rules in working memory.

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# Children's Task-Switching: A Role for Cue Integration

## Abstract

Task-switching (task-switch) costs decrease with age (Diamond & Kirkham, 2005). Age-related changes might relate to efficiency in using cues to retrieve appropriate representations from working memory (i.e., *cue-integration*) (Logan & Schneider, 2007). Alternately, they might relate to changes in executive functions. We tested whether cue interpretation, and/or specific executive functions (inhibition or processing speed) predict 4- to 6-year-old children's switching costs. Children completed four computerized task-switch tests in which verbal cues signaled a demand to either switch sorting rules, or maintain the same rule. In two games, cues specified *rule* contingencies (i.e., color vs. shape); in the other two, transition cues indicated *switch* contingencies (i.e. same vs. other). Rule cues were generally easier, but children benefitted from transition cues in the hardest switch trials. Children also showed individual differences in using cues in simple, unidimensional (1D), non-switch matching tests. These individual differences predicted switch costs. Additional variance was independently predicted by processing speed.

### **Children's Task-Switching: A Role for Cue Integration**

Cognitive flexibility is the capacity to coordinate cognitive processes to adapt to changing tasks, under conditions of uncertainty or response-conflict. Cognitive flexibility shows large age-related and individual differences throughout early and middle childhood. Measures of cognitive flexibility in childhood predict performance in high-order cognitive skills such as reading (van der Sluis, de Jong, & van der Leij, 2007), numeracy (Bull & Scerif, 2001; Clark, Pritchard & Woodward, 2010), and responsiveness to classroom instruction (Cartwright, 2002).

Much research has measured children's cognitive flexibility in a single behavioral paradigm, the Dimension Change Card Sort Task (DCCS). Children are taught a first rule, to sort colored objects according to either their color alone or their shape alone. In a post-switch phase, however, children must reclassify the same two stimuli according to the other rule. Most English-speaking 3- year-olds, and a large minority of 4-year-olds, fail to switch from one simple rule to the other (Zelazo, 2006). By age 5 or 6, children accurately switch rules. Some developmental theories have attributed this progression to the maturation of executive functions, specifically, inhibition (Kirkham, Creuss, & Diamond, 2003; Bialystok & Martin, 2004), graded working memory (Morton & Munakata, 2002a; Cepeda & Munakata, 2007) and processing speed (Cepeda, Kramer & Gonzalez de Sather, 2001). Other accounts have focused on children's capacity to hold in mind and select complex contingencies, or multiple representations (Zelazo Frye & Rapus, 1996; Kloo & Perner, 2005). Still others have focused on children's situation and discourse understanding, and on the difficulty of particular sub-tasks (Deák, 2000, 2003).

Forced-choice tests like the DCCS, however, have low sensitivity: they classify children aged 3 to 5 years as flexible or perseverative, whereas newer task-switch paradigms reveal a range of cognitive flexibility and switching "costs" in children across a wide range of

ages (e.g. Cepeda et. al, 2001; Reimers & Maylor, 2005; Kray & Karbach, 2009). For example, even though 5- and 6-year-old children are at ceiling on the DCCS, they still show response time (RT) switch costs in timed rule-switching tests (Diamond, 2005). Moreover, they still make some errors on more difficult tests of flexibility (Espy, 1997; Smidts, Jacobs & Anderson, 2004; Zelazo, 2006). Those latter tests (e.g. Shape School, Advanced DCCS) are typically harder because they add a particular kind of task demand: arbitrary cues are used to indicate the relevant stimulus, or contingency, in a given trial. For instance, in the Advanced DCCS, the presence or absence of a black border indicates whether children should sort items by shape or by color. If that sort of cue-arbitrariness, or “indirectness,” powerfully affects children’s flexibility, it would speak to the explanations listed above. For example, it is often assumed that the DCCS test cues are trivially easy for preschool children. Yet Munakata & Yerys (2001) showed that many 3-year-olds, even if they pass the pre-test for shape and color rules, do not actually fully understand the rules; moreover, those children are more likely to make perseverative post-switch errors. By age 5, those cues (e.g., the words “shape” and “color”) are fairly easy, but now indirect cues like a black border will cause similar difficulties.

If cue-processing difficulties can explain children’s errors and processing costs at different ages, in different tests, how would it address the theories listed above? One implication is that the executive functions or conceptual abilities listed above might not change *qualitatively* with age. If progressively more abstract and indirect cues elicit similar kinds of switch-costs in progressively older children, there would be no reason to propose a developmental “revolution” in, say, inhibitory skills, or in the capacity to represent more complex rule-contingencies. Also, if children show parallel cue-processing difficulties in tasks that do *not* require switching, it would disconfirm a (pure) inhibition-based account, although it would *not*, for example, disconfirm a role of working memory access in children’s flexibility.

Thus, it would be ideal to assess older children's difficulties—both in RT switch costs, and in actual response errors—on flexibility tests with easier or harder cues; that is, more or less direct cues. It is also important to test these different cues in different tests that impose greater or lesser flexibility demands: specifically, tests that impose rule-switches or not, or tests with conflict stimuli or not. Such comparisons can allow us to evaluate whether some executive functions, or capacity for conceptual complexity, are valid explanations for flexibility differences.

#### Cue integration theories of task-switching

Several studies have investigated arbitrary or indirect cues in task-switch. Results from studies of adults typically show relatively large reaction time (RT) costs following an indirect cue, compared to a more literal or obvious cue. For example, task-switch performance is better with more direct cues (e.g., “color” and “shape”) than less direct cues (e.g., the letters “c” and “s”) especially under concurrent verbal processing demands (Miyake, Emerson, Padilla & Ahn, 2004). This RT cost for indirect cues is even greater for children (Kray, Eber & Karbach, 2008). Moreover, highly explicit or “direct” task cues can help children do otherwise difficult switching tasks: for example, Chevalier & Blaye (2009) found that children more readily follow rule-switches in the Advanced-DCCS test if the cue is, semantically direct e.g., as rainbow-icon (i.e., signaling a color test trial) instead of indirect (a black border).

One possible explanation is that more explicit cues make it easier for subjects to activate the correct rule-contingency in working memory (Miyake et al., 2004). They reduce the number of inferential steps between the cue-stimulus and the most strongly-represented rule-relevant stimulus; moreover, they minimize any potential confusion about which task or rule is indicated.

Task-switch requires cue-mediated memory retrieval (Logan & Bundesen, 2004; Schneider & Logan, 2005; Logan & Schneider, 2007). These cues, combined with stimulus information, should jointly suggest one response more strongly than the other (Logan & Schneider, 2007). For instance, the word “color” activates the specific red and blue sorting rules, the blue boat image provides converging support for the ‘blue-things’ sorting rule. These cues jointly activate a single contingency. Indirect cues like the letter “s” would constitute weaker evidence, and thus require the subject to retrieve additional information, to achieve some threshold of confidence for choosing one response.

This suggests that cues which provide any information that does not directly activate the relevant sorting rule should impede performance. However, this may not always be true. In addition to rule (e.g. the word “color”) demands, cues can also signal the *transition* demands (e.g. a circle means “switch rules” but does not directly indicate *which* is the new rule). Rule cues tell you what features are relevant, but not whether you should now be doing something different. Thus, there’s no reference to one’s prior actions. Transition cues tell you how to act relative to your prior actions, but without specific reference to a feature or named rule. Thus, the two cues activate different kinds of memory representations by which children can select their current response.

Transition cues may be especially beneficial for young children, as evidence (Jamadar, Michie & Karayandis, 2010) suggests they have may difficulty relating current response options to prior actions. These difficulties may remain for older children as well as preschoolers. However, older children may mitigate such difficulties by taking advantage of co-occurrence in task-switch: typically, cues are only present in task-switch in switch trials. Thus, anytime a cue appears, it functions as a reminder of what responses are appropriate regardless of the semantic content of the cue. However, when cues can specify either switch or stay trials, children may

need contextual support to activate both sorting rules and response rules from working memory. No published studies have used *transition* cues with young (4-, 5- and 6-year-old) children. We predict that children will benefit from transition cues in the hardest kinds of switch trials: incongruent switch trials.

This account complements emerging studies on goal maintenance and goal neglect in preschoolers. Older children (aged 4 and 5) are less likely to persevere in the DCCS when they receive verbal reminders before each trial, indicating appropriate rules (Marcovitch, Boseovski & Knapp, 2007). Also, Spieler, Mayr, & LaGrone (2006) found that older adults, who are prone to goal neglect (De Jong, 2001), relied more heavily on external cues than did younger adults.

If children's switch costs are due to difficulties using cues to quickly and accurately retrieve appropriate contingencies from working memory, we should also see slow use of cues even when there are no switching demands. Holt and Deák (under review) designed a one-dimensional stimulus-matching test modeled on Blackwell, Cepeda & Munakata, 2009. Children matched stimuli that differed on only one dimension (i.e. two colored squares, or two black and white shapes). Performance in this cued 1-dimensional matching test predicted switching flexibility. We predict that, if cue processing predicts flexibility, 1) we should see differences in cue processing with more or less direct cues even without switching (i.e. in the 1-dimensional matching test) and 2) that using different cues to retrieve different (e.g. sorting rules vs. switch contingencies) should differentially predict task-switch.

We varied the cues in four 1-dimensional matching tests and in four versions of a computerized task-switch paradigm. Two versions of each type of test used transition cues, while two versions used rule cues. Our task-switch test included both cued "switch" and "stay" cues. Introducing this verbal "stay" cue increases the demands for cue processing, as cues no

longer uniquely signal switching. The need for attending to the cue in switch and stay are the same, and children must actively integrate the cue with the associated stimulus to obtain a correct contingency. If, as hypothesized, task-switch costs may be largely reduced to cue *processing* costs, we would expect to see little difference between cued switch RTs and cued stay RTs.

We also tested alternative hypotheses that general inhibition or processing speed constrains children's flexibility. Both capabilities develop with age (Kail, 1991; Diamond, 2002); however, no previous studies have directly compared whether individual differences in cue processing or executive functions better predict task-switch. We designed Go/No-Go tests of inhibition that were appropriate for preschool-aged children (see Mesulam, 1985). These used the same stimuli as the 1D-matching test. Children had to respond as quickly as possible to some stimuli (e.g. brown squares), but inhibit responses to a rare stimulus (e.g. blue squares). We also used Luria's Tapping Test (Luria, 1966; Diamond & Taylor, 1996) as an established measure of inhibition for children. To test processing speed, we designed an un-cued matching-speed test. Children saw scrambled versions of the task-switch stimuli, and had to respond by choosing the matching image as quickly as possible. In addition, we used the Box Completion Test from the Woodcock-Johnson battery (Woodcock & Mather, 1989) as an age-normed measure of processing speed.

Finally, children did several brief, age-normed tests of general cognitive and language abilities. Forward digit span was used as a measure of working memory span (WMS) (Wechsler, 1981). Also, the Peabody Picture Vocabulary Test (PPVT-III) was used to estimate receptive vocabulary. Because the task-switch and unidimensional matching tests use verbal cues, performance might correlate with receptive vocabulary.

Finally, we collected teacher reports of ADHD symptoms, and children completed a color vision test to verify that they could identify the stimulus colors.

#### Latent variable modeling of task-switch

Commonly used measures of executive functions may tap multiple sub-processes of inhibition, flexibility and working memory (Huizinga, Dolan & van der Molan, 2006). There are proposals that executive functions can be partially decomposed into at least three factors: flexibility (or switching), inhibition, and working memory (Friedman, Emerson, Witzki & Wager, 2000; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Miyake Friedman & Miyake, 2004; Wu, Chan, Leung, Liu, Leung & Ng, 2011).

Latent variable models of executive functions and cognitive flexibility have not typically been extended to children younger than age 6. Even with older children, there is disagreement about the appropriate number of latent factors. Models range from just one general executive functions component (Wiebe, Sheffield, Nelson, Clark, Chevalier & Espy, 2010) to as many as four separable components. Extant models generally include factors labeled as inhibition, processing speed, working memory updating, and WMS (McAuley & White, 2011); however, those factors are chosen and (loosely) defined *a priori*, so we should not conclude that tests of these factors are actually converging on a robust and valid structural model of cognitive flexibility. Moreover, none of the latent variable models have so far included a factor for cue-processing (as measured by, e.g., our 1D matching test), even though that variable might in fact capture most or all of the variance that is usually attributed to working memory strength. Although the relation of global processing speed to other executive functions remains a matter of debate (Cepeda et. al., 2001; McAuley & White, 2010), it should be included in latent variable models because it might mediate the face-value correlations between working memory or inhibition, and task-switch (Huizinga, Dolan & van der Molan, 2006).



One difficulty in interpreting competing models of cognitive flexibility and executive functions is that various tests (of, e.g., inhibition) differ in construct variance, which will modulate the correlation with flexibility (e.g., switch costs). To minimize any spurious relations among putative latent factors in the model, due to test-specific construct variance, we conducted confirmatory factor analyses (cognitive flexibilityA) around three *a priori* factors: cue-processing, perceptual-motor processing speed and inhibition.

## Method

### *Participants.*

English-speaking children, aged 4 ( $n = 38$ , mean age = 53.4 months, 19 girls), 5 ( $n = 38$ , mean age = 64.4 months, 14 girls) and 6 ( $n = 33$ , mean age = 78.4 months, 15 girls) were recruited from elementary schools within 15 km of the University of California, San Diego. Children were fluent in English, and had no diagnosed language or cognitive delays. The sample was 69% Caucasian, 9% African American, 7% Asian, 14% Hispanic and <1% percent other. Parents averaged 15.5 years of education. The procedures were approved by the UCSD Human Research Participants Protection committee. One additional 5-year-old child was excluded from analysis because he did not properly use the response button box. An additional three 4-year-olds and two 6-year-olds were excluded because they did not complete both testing sessions. One additional 6-year-old was excluded from final analysis because his PPVT score was greater than one *SD* below age norms, and one was excluded because his teacher reported ADHD symptoms.

### *Materials*

*Task-switching test.* Responses were recorded on a two-button button box customized for use with preschool children. Two large, colorful buttons were mounted 24 cm apart on a

wooden tray. The tray could be placed over a child's lap so that her or his hands rested comfortably on the buttons. The tray was designed to minimize spurious errors and to maximize comfort and compliance.

Eight experimental stimuli were created in Adobe Illustrator. Stimulus Set A included a brown cat, blue duck, brown duck and blue cat; Stimulus Set B included a green pig, grey bear, grey pig and green bear. Shapes and colors were prototypical. Each set included two target pictures (4cm<sup>2</sup>): a blue cat and brown duck (Set A), and a grey pig and green bear (Set B). These target pictures were constantly visible during a given test, one near each of lower corner of the monitor, directly above the response buttons. Left/right placement of the pictures was counterbalanced across participants. During each trial, one of four test stimuli (e.g. green pig, grey bear, grey pig or green bear) was displayed in the center of the monitor, in a 10cm<sup>2</sup> gray box. Two of these test stimuli matched the two target pictures (e.g., brown cat and blue duck). These congruent (non-conflict) stimuli required the same response under any rule or cue condition. The other two test stimuli were incongruent (e.g., brown duck): they matched one target on one dimension (e.g., color: same as brown cat), and the other target on the other dimension (shape: same as blue duck). These stimuli are critical because they create a response conflict, which should be resolved by reference to the current rule. Across trials, 33% of test stimuli were congruent, and 67% were incongruent.

Six audio-video cues (i.e., AVI files) were recorded: three switch cues (a model saying: "Play the color game," "Play the animal game," or "Play the other game") and three stay cues ("Play the animal game," "Play the color game," or "Play the same game.") These were matched frame-by-frame for length (1500ms), amount of facial movement and intonation. Also, 800ms feedback videos of a smiley face or frowning

face were presented following each response. These did not vary with stimulus set (Set A or Set B) or cue type (*transition* or *rule*).

The two versions of the task-switch test in each stimulus Set (A: [brown/blue] [cat/duck] and B: [green/grey] [pig/bear]) differed in the type of cues used. *Transition* cues emphasized the appropriate response contingency, relative to the previous trial (i.e., maintain that rule, or switch rules): “Play the same game.” or “Play the other game.” *Rule* cues emphasized the specific rule contingency (i.e., color or animal): “Play the animal game.” or “Play the color game” (Table 3.1).

**Table 3.1:** Summary of task-switch cues.

<i>Cue Type</i>	<i>Trial Type</i>	<i>Cue</i>
Rule	Cued Switch	“Play the [animal/color] game”
Rule	Cued Stay	“Play the [animal/color] Game”
Transition	Cued Switch	“Play the other game”
Transition	Cued Stay	“Play the same game”

*Unidimensional matching.* A 1-dimensional rule-matching test (see Blackwell et. al., 2009) was based on the task-switch tests, without conflict stimuli or rule-switches. Eight unidimensional experimental stimuli were modified from the task-switch stimuli described above: Set A included line drawings of a cat and a duck and swatches of blue and brown; Set B included line drawings of a pig and bear and swatches of green and grey). These were presented in the same configuration as described above. As with the task-switch test, cues corresponded to the “stay” cues in the task-switch test: “Play the [animal/color] game” (rule cue) or “Play the same game” (transition cue).<sup>3</sup>

<sup>3</sup> It is possible that two transition cues with equivalent response contingencies but different semantic forms (e.g. “same” or “another”) might be processed differently. Both the “...color” and “...animal” game cue appeared in the *Rule-cue* unidimensional matching game. However, we could not use the

*Inhibition.* The Go/No-Go tests used identical stimuli as 1D cue-integration tasks. The Tapping test used two small sticks.

*Perceptual-motor processing speed.* The uncued-matching-speed test used convolved versions of the stimuli from the task-switch and 1D-matching tests. The box completion test consists of a page with 5 rows of 7 3-sided incomplete squares, with one line missing from each, on different sides.

*Verbal ability.* The Peabody Picture Vocabulary Test-III (PPVT-III) is a normed test of receptive vocabulary (verbs and nouns). Forward digit span was measured using lists from the WAIS-III (Wechsler, 1981).

*Visual assessment.* Normal color discrimination was measured using normed H.R.R. pseudo isochromatic plates.

*ADHD assessment.* Teacher reports of ADHD symptoms were collected using the ADHD Rating Scale-P (Fairies, Yalcin, Harder, & Heiligenstein, 2001). This 18-item instrument elicits Likert-rating scores for core ADHD symptoms, based on Diagnostic and Statistical Manual-IV criteria (APA, 2000).

### *Procedure*

Two sessions were completed in quiet rooms at 18 area schools. Task order was fixed. In the first 45-60 min session, participants completed the four unidimensional matching tests (order counterbalanced), Tapping Test, a *Rule-Cue* task-switch test, the Box Completion test, and a *Transition-Cue* task-switch test. The first-session stimulus Set (A or B) was

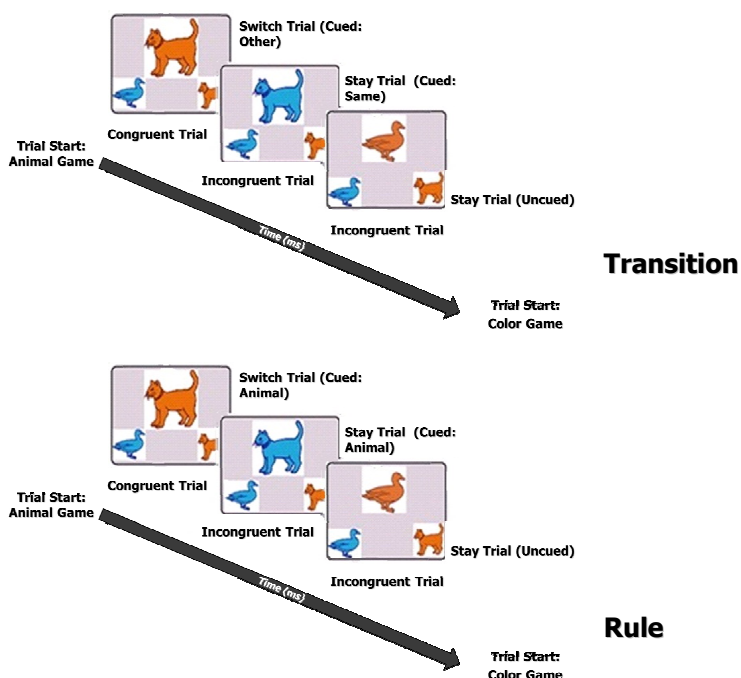
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“...other game” cue in the 1D matching trials, as there were no switch contingencies. Instead, we created a second, phonologically matched cue (“Play another one”) to use as a second cue in the 1D matching trials. Preliminary ANOVAs suggested no differences in RTs to “Play the same game” or “Play another one” trials, so we combined both types of trials in future analyses.

counterbalanced. In the second 60 min session, one week later, children completed the un-cued matching-speed test, digit span, two Go/No-Go tests, the second *Transition* switching test (using the other stimulus set), the second *Rule* task-switch test, the PPVT-III A, and the color vision test. Computer tests were programmed and delivered using Presentation v9.9 software ([www.neuro-bs.com](http://www.neuro-bs.com), Neurobehavioral Systems, New York, USA). For the computer tests, children were seated approximately 40 cm from the monitor, and were initially taught how to use the button-tray. Children were given breaks as needed. They received a small toy after each session.

*Task-switching.* In *Rule-cue* tests, participants received video cues to play either the “animal game” or the “color game.” In *Transition-cue* tests, participants received cues to play either the “same game” or the “other game.” The appropriate rule changed following a rule-switch cue after every three trials. The first game was counterbalanced across participants. A matched “stay” video cue appeared before either the second or third trial (alternating randomly) within each three-trial block (Figure 3.1). Stimuli appeared 700ms after the video cue. There were 16 total incongruent trials of each type (switch and stay) for each cue condition, and eight congruent switch and eight congruent stay trials for each task. Each switch task was presented in a single 8-10 min. block.

Children were instructed to place their hands right over the buttons. They first practiced the task, with verbal prompting and feedback, until they correctly switched games three times.

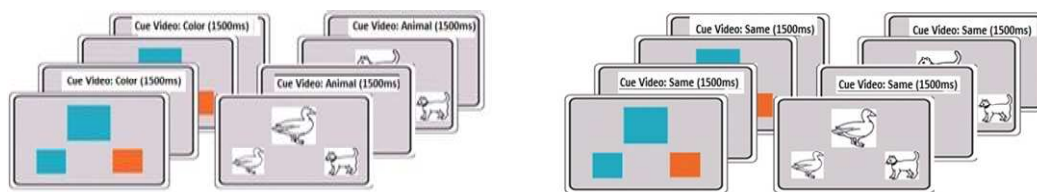


**Figure 3.1:** Task-switch design.

For test trials, RTs less than 200ms (which would have been planned before the stimulus appeared) were trimmed. Remaining RTs were log normalized. Outliers more than 2 *SD* above the mean of the remaining trials in each type were Winsorized to +2 *SD*. This affected fewer than 5% of trials, which is within acceptable limits (Ratcliff, 1993).

*Unidimensional matching.* This test was matched to the task-switch tests for event timing, motor demands, and S-R demands. The four versions used different cues and stimuli, exactly like the task-switch tests: In *Rule-cue* versions, children were reminded on every trial to play either the “animal game” or the “color game.” In *Transition-cue* versions, children were told to play either the “same game” or “another game.” Children were instructed to match each test stimulus by pressing the appropriate button, as in the other task (Figure 3.2). Children did 16 trials of each *Rule-cue* condition or *Transition-cue* condition and per stimulus set. The first five trials of each game were treated as “warm up” trials, and were not analyzed. RTs were

trimmed and Winsorized as above; fewer than 5% of trials were affected. Children made few errors, but we analyzed RT only from correct trials.



**Figure 3.2:** 1D matching design.

*Go/No-Go [inhibition]*. Children were told they would play a racing game with different colors. They were instructed to hold their preferred hand over one button, and push it as quickly as possible when a “go” cue (e.g. orange square or duck) appeared, but not push if a “stop” cue (e.g. blue square or cat; about 33% of trials, randomly selected) appeared. Stimuli were drawn from Set A and Set B. The timing was modified across blocks of 24 trials until children made errors on 50% of no-go trials in two consecutive blocks. In each trial, go cues appeared for 250ms following a 150ms “wait” period. The wait period ensured that the child was responding to the current stimulus, not the last one. Each stimulus was followed by a variable inter-stimulus interval (ISI). ISI was adjusted based on the proportion of no-go errors in the previous block. Thus, the exact number of trials varied for each child, based on the number of blocks needed to find the child’s 50% criterion time. This time was the dependent measure that indicated the child’s inhibitory efficiency.

*Tapping test [Inhibition]*. Children were told they would play a game with “silly sticks.” Following Luria (1966), the experimenter trained the child to tap twice when she tapped once, and vice versa. This was repeated until the child correctly completed five practice trials with feedback. The child then completed two blocks of 10 test trials, without feedback. The instructions were repeated after the first block. Test trial accuracy was the dependent measure.



*Un-cued matching-speed.* This test was similar to the unidimensional test, but with no cue or matching demands. Children used the button tray. They were told they would see “silly” pictures, and that they should push the button as fast as possible whenever a picture appeared. Stimuli appeared immediately following the previous response and remained onscreen until the child made a response. After five practice trials with each hand, children completed 24 test trials (12 per hand). There were four blocks of six trials each. Participants used only a single hand to respond in each block. Blocks alternated between right and left hand. The first four trials were treated as warm up trials and were excluded from further analyses.

*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. Finally, for the test they completed as many boxes as they could in one min.

*Peabody Picture Vocabulary Test-III [Receptive language].* Children were asked to point to the picture that matches a spoken word. Standard procedure and scoring was used (Dunn & Dunn, 1997).

*Digit span [Verbal memory span].* Based on Wechsler (1981), children were asked to repeat a series of numerals, spoken at 1 sec intervals. Standard procedure and scoring was used.

*Color vision assessment.* Children were asked to point to one of two hidden, colored shapes on a grey background, using a standardized procedure (Bailey, Neitz, Tait & Neitz, 2004).

## **Results**

To verify that the sample was typical of their age in some basic verbal abilities, we examined PPVT scores and forward digit span. Mean PPVT-III standard scores averaged 104.7 ( $SD = 3.2$ ) for 4-year olds, 106.9 ( $SD = 2.39$ ) for 5-year-olds, and 104.2 ( $SD = 5.29$ ) for 6-year-olds; this is comparable to population norms (mean = 100,  $SD = 15$ ). Mean forward digit span averaged 3.79 ( $SD = 0.11$ ) for 4-year-olds, 4.43 ( $SD = 0.13$ ) for 5-year olds and 4.11 ( $SD = 0.2$ ) for 6-year-olds, similar to previously reported same-age samples (Gathercole & Pickering, 2000; Alloway, Gathercole, Adams et al, 2005). Thus, the results should generalize to same-aged, or slightly older, English-speaking children.

*Task-switching.* Two ANOVAs were performed, one on accuracy and one on log-normalized correct RTs. There were no gender differences, so boys and girls were combined in further analyses. Also, there were no stimulus Set (A or B) differences, so that factor was collapsed for all further analyses.

We analyzed Session (first or second) as a separate variable of interest. Several studies suggest that practice improves adults' task-switch (Rogers & Monsell, 1995; Kray et al, 2008; Karbach & Kray, 2009); however, it is unknown how children improve with practice. We examined whether task-switch improved between the two sessions. Because the exact rules and stimuli changed between sessions, any improvement would probably be due to abstract understanding of switching demands, rather than practice with specific cue-response contingencies. Also, any individual differences in learning might be associated with differences in perceptual-motor processing speed, cue processing, or other executive functions.

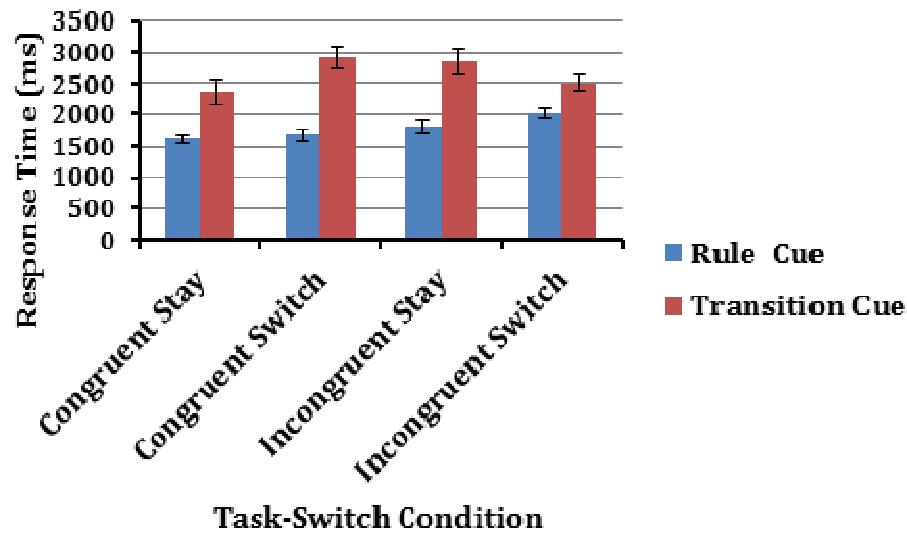
RT data were analyzed in a 3 (Age [4/5/6]) x 2 (Trial Type [Switch/Stay]) x 2 (Congruency [Congruent/Incongruent]) x 2 (Cue [*Transition/Rule*]) x 2 (Session [First/Second]) ANOVA.

There was a main effect of switching,  $F(1,107) = 19.94, p < .0001, \eta^2 = .157$ . RTs were slower following switch trials than stay trials. There was a main effect of congruency,  $F(1,107) = 64.58, p < .0001, \eta^2 = .376$ . Congruent trials were faster than incongruent trials. There was a main effect of cue type,  $F(1,107) = 103.89, p < .0001, \eta^2 = .49$ . *Transition* cued trials were slower than *rule* cued trials (though this was qualified by a Cue x Switch interaction). There was a significant main effect of Session,  $F(1,107) = 17.42, p < .0001, \eta^2 = .140$ . Children were faster in second Session. There was a main effect of age,  $F(2,107) = 44.74, p < .0001, \eta^2 = .455$ : 4-year olds were slower than 5-year olds ( $p < .002$ ), and both were slower ( $p < .0001$ ) than 6-year olds.

There was a significant interaction between switching x congruency,  $F(1,107) = 8.62, p < .004, \eta^2 = .075$ . Overall, the difference between switch and stay was less pronounced in incongruent trials. However, this effect depended on cue type (three-way interaction:  $F(1,107) = 20.77, p < .0001, \eta^2 = .163$ ). With a *rule* cue, incongruent switch trials were the hardest trial type. However, with *transition* cues, incongruent switch trials were not significantly slower than congruent trials (Table 3.2; Figure 3.3).

**Table 3.2:** Summary of task-switch descriptive statistics.

<i>Week 1</i>	<i>Cue Type</i>	<i>Incongruent Switch</i>	<i>Incongruent Stay</i>	<i>Congruent Switch</i>	<i>Congruent Stay</i>
4-year olds	Rule	2849ms (1557)	2529ms(1442)	2005ms (1566)	2075ms (999)
	Transition	3577ms (2434)	4333ms(2610)	4368ms (2345)	3956ms (1865)
5-year olds	Rule	2131ms(1111)	1759ms(1050)	1665ms(727)	1542ms (560)
	Transition	2432ms(1162)	2689ms(1451)	2839ms(1727)	1814ms (756)
6-year olds	Rule	1543ms (853)	1282ms(520)	1251ms (785)	2130ms (1129)
	Transition	1766ms (928)	1826ms(1120)	2130ms (1129)	1911ms (1378)

**Figure 3.3:** Mean (w/ SE bars) task-switch latencies of 4- 5- and 6- year-old children by trial type (Cue x Switch x Congruency).

*Unidimensional matching.* RT data were log-normalized. There were no gender effects, so boys and girls were combined in all analyses. Descriptive statistics are shown in Table 3.3.

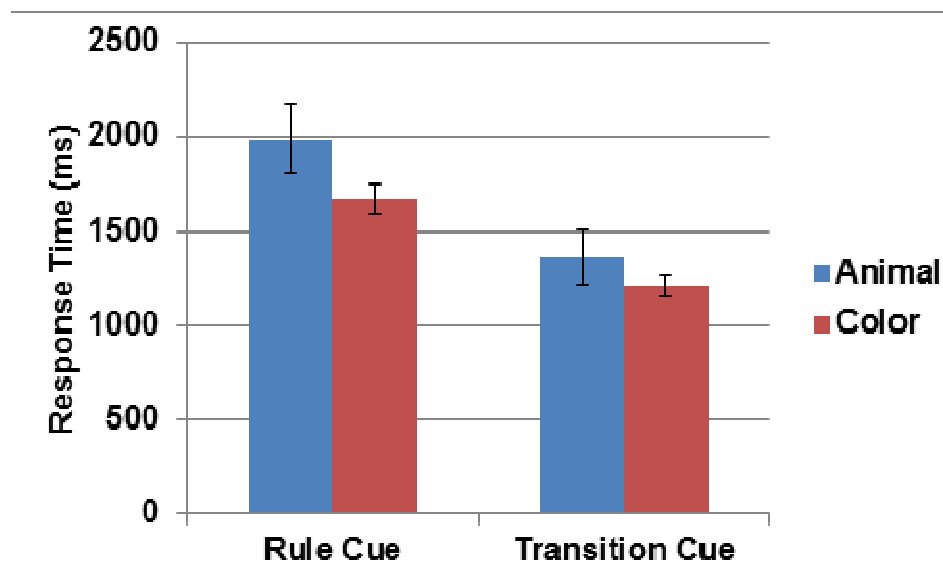
**Table 3.3:** Summary of all other behavioral statistics.

	<i>Rule Unidimensional Matching (RT)</i>		<i>Transition Unidimensional Matching (RT)</i>		<i>Uncued-Matching-Speed (RT)</i>		<i>Go/No-Go (ISI)</i>	<i>Tapping</i>	<i>Boxes</i>
	<i>Color</i>	<i>Animal</i>	<i>Color</i>	<i>Animal</i>	<i>Left</i>	<i>Right</i>			
4-year olds	2467ms (1086)	2836ms (1348)	1718ms (936)	1718ms (410)	843ms (411)	726ms (416)	1800ms (1030)	6.2 (5.8)	18.7 (7.9)
5-year olds	1354ms (539)	1650ms (567)	1051ms (410)	1254 (424)	810ms (401)	576ms (284)	1225ms (644)	1.5 (2.4)	27.7 (7.3)
6-year olds	1184ms (724)	1475ms (882)	868ms (588)	1112ms (670)	620ms (465)	499ms (334)	1094ms (865)	1.75 (2.8)	37.6 (10.9)

RTs and for accuracy in correct unidimensional switch trials were compared by 3 (Age [4/5/6]) x 2 (Rule [Animal/Color]) x 2 (Cue Type [*Transition/Rule*]) x 2 (Stimulus [A/B]) ANOVAs. RTs, showed significant age effects,  $F(2,107) = 26.65$ ,  $p < .0001$ ,  $\eta^2 = .333$ : 4-year olds were slower than either 5-year olds ( $p < .0001$ ) or 6-year olds, and 5-year olds were slower ( $p < .021$ ) than 6-year olds. There were no age differences in accuracy.

Color-matching was slower than animal-matching,  $F(1,108) = 54.736, p < .0001, \eta^2 = .338$ , and was marginally less accurate,  $F(1,107) = 3.07, p < .083, \eta^2 = .028$ .

Transition-cues were easier than rule-cues during matching: the former were faster,  $F(1,107) = 96.42, p < .0001, \eta^2 = .474$ , and more accurate,  $F(1,107) = 15.60, p < .0001, \eta^2 = .127$ , than the latter (Figure 3.4).



**Figure 3.4:** Mean (w/ *SE* bars) unidimensional matching latencies of 4- 5- and 6 year-old children by trial type (Cue x Switch x Congruency).

Children were faster to match Set B (Pigs/Bears; Green/Grey) than Set A (Cats/Ducks; Pigs/Bunnies),  $F(1,107) = 29.84, p < .0001, \eta^2 = .118$ . These set differences were not seen in task-switch, and did not differently correlate with switch costs. Thus we did not consider them further.

A Cue x Age interaction was significant for RT,  $F(2,107) = 5.36, p < .006, \eta^2 = .091$ , and was marginal for accuracy,  $F(1,107) = 2.30, p < .098, \eta^2 = .042$ : 4-year olds showed a greater advantage for *transition* cues over *rule* cues, compared to 5- and 6- year olds.

*Inhibition and Perceptual-Motor Processing Speed.* Descriptive statistics for all inhibition and processing speed measures are shown in Table 3.3. There were significant age differences in the Tapping Test ( $F(2,107) = 16.20, p < .0001$ ): 4-year olds made more errors than 5- ( $p < .0001$ ) and 6-year olds ( $p < .0001$ ). There were also significant age differences in Box Completion ( $F(2,107) = 41.63, p < .0001$ ): all age groups differed from one another (all  $ps < .0001$ ).

A 3 (Age [4/5/6]) x 2 (Rule [Animal/Color]) ANOVA was performed on ISIs in Go/No-Go. The age effect was significant,  $F(2,107) = 8.10, p < .001, \eta^2 = .132$ . 4-year olds required longer ISIs than either 5- ( $p < .003$ ) or 6- ( $p < .0001$ ) year-olds. Rule differences (Animal/Color) were marginally significant,  $F(2,107) = 3.17, p < .078, \eta^2 = .029$ ; Animal Go/No-Go tended to be slower than Color Go/No-Go. Because stimulus differences did not reach significance, we used an average of the two measures for further analyses.

There were significant age differences in un-cued matching-speed,  $F(2,107) = 5.73, p < .004, \eta^2 = .104$ . 4-year olds were slower than both 5- and 6- year-olds.

*Confirmatory factor analysis.* All analyses were conducted with Amos 19 (<http://www-01.ibm.com/software/analytics/spss/products/statistics/amos/>, IBM, Washington, USA) using maximum likelihood estimation. Three measurement models were progressively fit to the covariance matrices. The models specified different numbers of latent factors. The one-factor model (CFA 1) included all tests, implying a developing, unitary EF construct (Wiebe, 2011). A two-factor model (CFA 2) specified separate latent factors of processing speed and inhibition. A three-factor model (CFA 3) specified separate latent factors of processing speed, 1D-matching (cue processing), and inhibition. Latent factors were assigned a scale by imposing a unit loading identification constraint (i.e., the factor loading of a reference variable was set to 1.0). Fitting of the models began with the model that had the fewest factors (CFA 1), and progressed through

more complex models (e.g., CFA 3). Factors were added until common fit indices for small samples ( $N < 150$ ) were optimized (i.e., non-significant  $\chi^2$  statistic, root *MSE* of approximation (RMSEA)  $< .06$ , comparative fit index (cognitive flexibilityI)  $> .95$ , and minimal Akaike's information criterion (AIC), Hu & Bentler, 1995; Schneiber, Stage, King, Nora & Banlow, 2006). Our final model (CFA 3) had three factors consistent with the hypothesis that perceptual-motor processing speed, cue-processing, and inhibition are separable abilities in young children. It also confirms the utility of these tests to measure different latent variable, for purposes of regression analyses. Fit indices are included in Table 3.4.

Two of the normed tests, Tapping test and Box Completion, were not predominantly associated with a single factor (Figure 3.5). Because of this non-specificity, these measures were not included in our regression analyses.



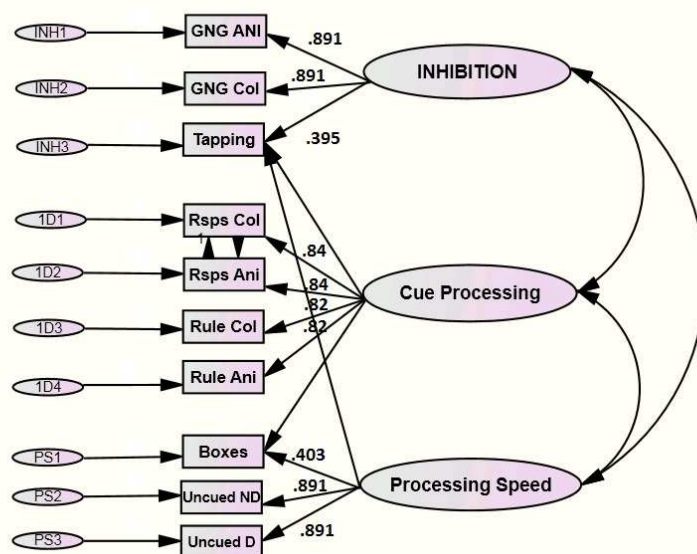
**Table 3.4:** Fit indices for models of invariance.

CFA 1= 1 Unitary EF

CFA 2= INH and PS

CFA 3 = INH, PS and Cue Integration

<i>CFA</i>	$\chi^2$	<i>P</i>	<i>RMSEA</i>	<i>CFIA</i>	<i>AIC</i>
1	37.025	.118	.058	.973	91.025
2	88.432	.0001	.135	.834	134.45
3	128.34	.0001	.169	.723	170.3



**Figure 3.5:** 3 Factor MLE model of executive measures in 4- 5- and 6- year-old children. Abbreviations: *GNG Ani* = Go-No-Go with Animal Stimuli, *GNG Col* = Go-No-Go with Color Stimuli, *Rsp Col* = 1D Matching with Transition Cues & Color Stimuli, *Rsp Ani* = 1D Matching with Transition Cues & Animal Stimuli, *Rule Ani* = 1D Matching with Rule Cues Animal Stimuli, *Rule Col* = 1D Matching with Rule Cues Color Stimuli, *Boxes* = Woodcock Johnson Box Completion Test, *Tapping* = Tapping Test, *Uncued Dom* = Dominant Hand Simple, *Uncued ND* = Nondominant Hand Simple.

*Predicting first-session task-switching efficiency.*

We examined whether unidimensional matching speed (1D matching), inhibition (Go/No-Go) or processing speed (un-cued matching-speed) predicted switch latency. Mean switch costs (each child's mean RT difference between switch trials and cued stay trials) were the dependent measure. We ran separate regressions for each task-switch cue type (*transition and rule*). Because there were significant game differences in 1D-matching (i.e., slower/less

accurate for animals than colors), we entered mean animal and color matching as separate predictor variables.

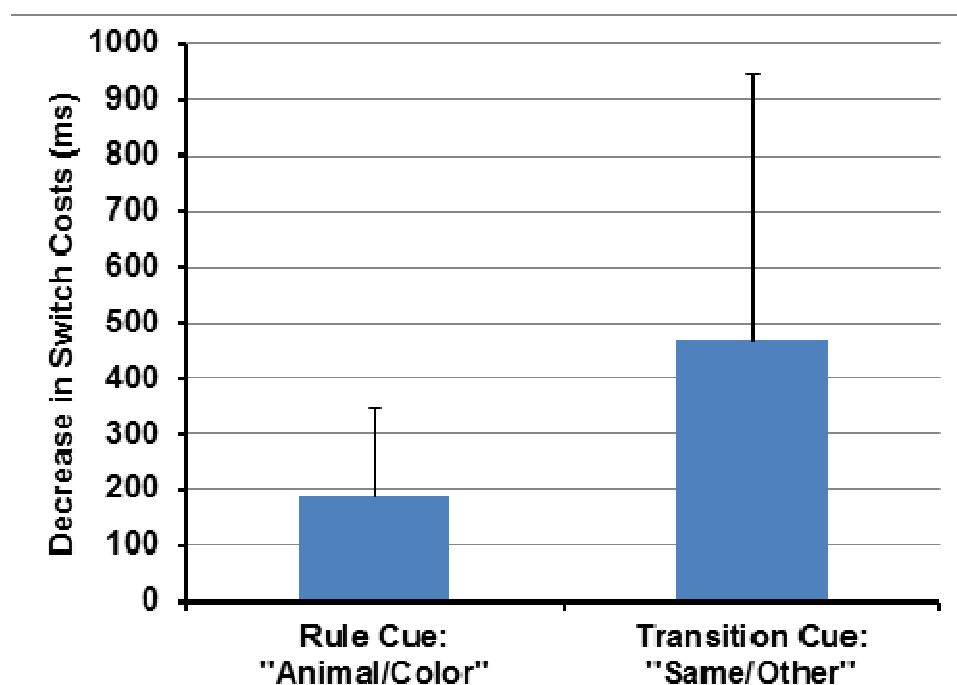
Unidimensional matching speed for the weaker cue type (*rule cue*) accounted for the most variance in switch costs, during the first session. Some additional unique variance was predicted for the stronger cue (*transition cue*) as well. This suggests that rules are activated differently in working memory depending upon the semantic information in the cue. Children may make errors either because they have weak representations of the sorting rule itself—animal or color—or because they cannot quickly select the appropriate contingency for the current rule.

Unidimensional matching speed accounted for greatest proportion of explained variance in incongruent switch trials under all cue conditions. Intriguingly, additional variance was predicted from both cue types, with the bulk coming from weaker rule in isolation (*rule* type). Perceptual-motor processing speed (un-cued matching-speed) accounted for a modest additional amount of variance. Regression results are summarized in Table 3.5.

#### *Predicting second-session task-switching gains*

Because we found a significant Session effect (i.e., faster cued RTs in Session 2), we did regression analyses on a measure of practice-related facilitation. This was the change in each child's mean switch costs from Session 1 to Session 2, for each cue condition. Recall that the actual task stimuli differed between sessions, thus any practice effects were for abstract task demands, not specific S-R contingencies. Mean switch costs change is shown in Figure 3.6. It is notable that children only showed significant switch cost declines in the *rule*-cued test—even though that rule changed between sessions, whereas the transition cue remained constant from

session 1 to 2. Thus, only rule-cued gains were used as an outcome measure for regression analyses.



**Figure 3.6:** Mean (w/ *SE* bars) decrease in switch cost (difference of switch trials from stay trials) of 4- 5- and 6 year-old children by cue type.

We then regressed the same independent variables on this measure of decline in switch costs for rule-cued task-switch. Unidimensional matching speed predicted individual differences in “practice” gains over one week (Table 3.5). To our knowledge, this is the first demonstration that differences in low-level cue-stimulus integration (cue-processing) predicts not only initial performance of a task, but also gains due to practice, independent of specific cue-stimulus or S-R associations.

**Table 3.5:** Summary of regression statistics.

	<i>Predictors</i>	<i>B</i>	<i>R</i> <sup>2</sup> <i>(after age)</i>	<i>p</i> <
TS Rule Demand Week 1	Unidimensional Rules cues	$\beta = .362$	$R^2 = 0.24$	$p < .006$
	Unidimensional Transition cues	$\beta = .508$	$R^2 = .10$	$p < .026$
	Uncued-matching- Speed	$\beta = -.266$	$R^2 = .06$	$p < .032$
TS Transition Demand Week 1	Unidimensional Rules cues	$\beta = .51$	$R^2 = .10$	$p < .01$
TS Rule Demand Week 2 (Practice)	Unidimensional Rules cues	$\beta = -.842$	$R^2 = 0.17$	$p < .01$

### Discussion

Although several studies of adults have demonstrated an important effect of the semantic properties of switch cues (Logan & Schneider, 2007), these ideas have not been systematically extended to development. This is partly because untimed, binary card-sorting tests are not sensitive enough to capture graded cue-processing effects. This is ironic, given that young children will certainly have more limited capacity to interpret semantically complex task cues. However, several studies have shown that the difficulty of specific task cues (Deák, 2003; Kharitonova, Chien, Colunga, & Munakata, 2009; Chevalier, Blaye, Dufau, & Lucenet, 2010) and children's semantic fluency (Snyder & Munakata, 2010) interact with children's task-switch flexibility.

Other studies have shown goal neglect in preschool children (Towse, Lewis, & Knowles, 2007; Marcovitch, Boseovski & Knapp, 2007; 2010) which can be mitigated by cuing, though these studies focus on the role of cues in memory maintenance, while adult accounts (e.g. Grange & Houghton, 2010) have focused on cue-driven memory activation. Previous evidence suggests that for young children, these cue-processing difficulties might extend so far as to semantically appropriate verbal cues (which explicitly indicate the appropriate goal) which are easy for older children and adults (Holt & Deák, under review). Thus, in paradigmatic, timed tests, as well as untimed tests, children show cue interpretation difficulties.

We systematically manipulated the semantic content of two verbal cues. In one, we signaled the indirect (abstract) task contingency on the impending trial (i.e., switch to new rule, or continue using the current rule). In the other, the impending sorting rule was explicitly stated (e.g., "...color game"). Notably, both cues in our task-switch paradigm were explicit—unlike the Advanced DCCS—but conveyed differing semantic information. While transition cues were less semantically related to the low-level S-R rule, these responses might be especially beneficial for conflict switch trials (Jamadar, Michie & Karayandis, 2010).

We predicted a benefit for children in switch trials using these cues, because of this switch-specific memory activation deficit. We found this result. Children received a selective benefit in trials where a change in contingency demands was critical—incongruent switch trials—showing that matching the appropriate cues to the appropriate difficulty helps.

Introduction of a "stay" cue—which increases the cue-processing demands of the traditional task-switch test because the presence of a cue no longer uniquely indicates a switch contingency—imposes accuracy costs for young children comparable to those in traditional switch trials (Holt & Deák, under review). We replicated this finding in many individuals in our

youngest age group -- 4-year olds – who showed costs associated with stay trials on the same order of magnitude as those in switch trials even with *rule* cues.

Children also have difficulty activating and maintaining the appropriate low-level S-R rules from working memory, especially under conflict conditions (Morton & Munakata, 2002a). Children who make perseverative errors in a conflict task like the DCCS also tend to show weaker memory representations of the rules (shown by slower response times (even when those rules are tested in a non-switching task with unidimensional stimuli) (Cepeda & Munakata, 2007; Blackwell, Cepeda & Munakata, 2009). More efficient cues might change the activation strength of appropriate perceptual-motor rules in working memory.

We also predicted that, in line with Morton & Munakata (2002a) we should be able to see differences in children's ability to quickly and correctly use verbal cues to access appropriate rules from working memory even when tested in non-switching tasks. These differences might underlie individual and age-related decreases in switch costs. Unlike Morton & Munakata, we additionally predicted that cue-processing effects would be present even in these low-level response-matching paradigms, as semantic processing of a cue occurs with or without stimulus conflict in adults models (Logan & Schneider, 2007).

We also found that 1D-matching speed predicted switch costs. Children showed individual differences in their ability to use verbal cues to quickly access the correct contingency rules from memory in a reduced-form, no-conflict matching test which controlled for the event timing, motor demands, and S-R demands of the task-switch test. Notably, even in this reduced conflict condition, differences in the semantic content of the cues resulted in differing performance and differing predictive value of the task-switch test. Individual differences in this unidimensional matching speed predicted individual switch costs across a wide age range. Children were reliably faster to access both color and animal rules from

working memory in the unidimensional matching test with *transition* vs. *rule* demands. Further, individual cue-processing differences predicted a hitherto untested measure of flexibility—that of improvement in flexibility with repeated exposure to a task.

Inhibitory demands were minimized in this task, providing additional evidence that inhibitory demands were not the best predictors of children’s rule-selection and switching abilities, in situations where children must retrieve and hold appropriate goals in working memory (Deák & Narasimham, 2003). Measures which purport to test common executive functions typically have a great deal of method and construct variance with each other and with task-switch tests (Beck, Schaefer, Pang, & Carlson, in press). This is particularly problematic for the 1D matching test, which shares more similarity with the task-switch tests than previous measures of inhibition or processing speed. This similarity, rather than cue-processing, may simply account for previous correlation between 1D matching and switching. We explicitly controlled for this overlap, by using the same stimuli in our measures of inhibition and processing speed.

Additionally, because cue processing effects might be largely semantic processing effects, it is important to note that early educational setting can have important impacts on children’s semantic fluency (Tombaugh, Kozak & Reese, 1999) and color rule knowledge (Bornstein, 1985). To control for these effects, we recruited children from both high and low SES schools. Children were recruited from pre-K, kindergarten and first grades which used both integrated (free-direction) curriculums, and traditional, blocked subject periods. Seven schools were on a structured subject block-based instruction day, while nine schools used an integrated curriculum and two used a hybrid model.

One important methodological limitation of our study involves interpretation of our practice effects. It is notable that we made no direct intervention in children’s flexibility. We



reported mere exposure effects. These effects are reliable, but less educationally relevant than planned interventions. Our task also used frequent feedback. Bohlmann & Fenson (2005) found that feedback significantly affects preschoolers' performance on the DCCS. Recent ERP evidence suggests neural responses do not differ whether task-switch cues precede stimulus trials (Nicholson, Karayandis, Davies & Michie, 2006) or occur as feedback (Barceló, Periáñez, & Knight, 2002). Children may show graded cue interpretation effects with feedback as well as cues preceding trials and may also show graded semantic differences processing positive vs. negative feedback (Chevalier, Dauvier & Blaye, 2010).

Conclusion: We completed the first study using multiple cues which signaled task-switch with young children. Rather than uniformly increasing processing demands, cues which signal the appropriate task demand contingencies (*transition cues*) (as opposed rule demand contingencies with *rule cues*) were selectively beneficial in incongruent switching conditions. These individual and age-related differences in switching were predicted by offline measures of cue-integration in which all demands of switching and stimulus conflict were removed. This suggests that cue-integration differences may play an important role in the development of task-switch, as they are thought to in the adult literature.

## ACKNOWLEDGMENTS

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# **Children's Resolution of Inter-Sentential Pronouns: A Role for Cognitive Flexibility**

## **Abstract**

We tested how preschool children use inter-sentential cues to resolve an ambiguous pronoun. In Experiment 4a, 3- to 5-year-olds heard brief stories in which a final ambiguous third-person pronoun could refer to one of two same-gender characters. Two variables were manipulated across vignettes: last character mentioned, and modality (Progressive/Completed) of the verb. From 3 to 5 years, children more consistently used pragmatic information from verb aspect to guide their identification of the pronoun referent. In Experiment 4b, 4- to 6-year-old children completed an expanded aspect task (manipulating modality, topic switch and last mention), as well as a timed task-switching (task-switch) test, and several additional cognitive and receptive language tests. As in Experiment 4a, children ages 4-6 reliably used verb aspect in isolation to guide their choice of referent, but, unlike older children, 4-year-old children did not do so when verb aspect is in conflict with an additional pragmatic cue (topic switch). This poor group performance masked individual differences: cognitive flexibility in the task-switch test predicted individual ability to revise pronoun interpretation in response to multiple cues. This suggests that children's integration of multiple pragmatic, indirect information from two (i.e., non-lexicalized) cues is related to more general cognitive flexibility.

### **Children’s Resolution of Inter-Sentential Pronouns: A Role for Cognitive Flexibility**

Keeping track of a pronoun’s referent across multiple sentences requires cue-based updating of understanding during discourse. Listeners need to predict how changes in the timing and content of what a speaker says can license some inferences about the speaker’s meaning. An utterance can have multiple representations (e.g. “Sarah handed a book to Jane. She smiled at her”). Frequently an appropriate conceptual mapping must be uniquely constructed from discourse cues. That is, the meanings of utterances cannot be pre-stored, nor can it even be assumed that particular cues will be available to disambiguate any given utterance. Moreover, linguistic cues can be revised repeatedly during a conversation, by virtue of additional by addition of paralinguistic cues such as speaker stress (Maratsos, 1973), prosody (Weber, Grice & Crocker, 2006), gesture, or other visual information (Tanenhouse, Spivey-Knowlton, Eberhard & Sediyy, 1995).

During the course of ongoing discourse comprehension, interpretation of a pronoun must be derived from cues such as order-of-mention, current discourse topic, recency, parallel syntactic position, and the semantics of the verb (Arnold, 2010). Cues differ in *scope*: the semantic range (e.g. intra-sentence, inter-sentence) over which a cue can constrain another element (e.g. a verb’s case; a pronoun’s referent). Discourse cues, such as topic switch, have a wider scope than lexicalized cues, such as gender. These cues are probabilistic, not definitive. In the example above, most adults interpret Sarah to be the one who is smiling, but readily accept idiosyncratic pronoun referents in nonstandard discourse (e.g. if the speaker is not fluent in the language). Speakers consistently prioritize judgments even given probabilistic discourse cues, but can revise those priorities as needed.

The Expectancy Hypothesis (Arnold, 2010) proposes a heuristic by which speakers prioritize conflicting discourse cues. Speakers learn and use cues in proportion to their probabilistic frequency of use in natural speech. If a speaker is referring to one of two

characters that differ in gender, “she” or “he” is perfectly disambiguating. Gender words in English should therefore be learned early. Indeed, by age three, children readily use gender to pick out the appropriate referent (Blakemore, 1990; Tyler, 1983). By age four, they can use gender even if the pronoun is separated by several sentences (Arnold, Brown-Schmidt & Trueswell, 2007).

Compared to lexicalized cues like gender, children acquire less reliable cues later, and they use them less consistently than adults. This is especially true when the cue is separated from its possible referent(s) by one or more intervening sentences—that is, inter-sentential resolution.

For instance, preschoolers seem insensitive to first-mention as a cue (Sekerina, Stromswold & Hestvik, 2004; Arnold, Brown-Schmidt & Trueswell, 2007). Younger children also may expect a pronoun to refer to an overtly present referent (Ackerman, 1993). A few studies have reported that preschoolers are sensitive to some probabilistic discourse cues: for example, they expect a pronoun to refer to an ongoing topic (Song & Fisher, 2005). Also, Pyykkönen, Matthews and Järviö (2009) found that even 3-year-olds can use verb transitivity to interpret an ambiguous pronoun in the subsequent sentence. Despite such findings, much research suggests that only around seven or eight years do children select and interpret pronouns using wider-scope discourse information (e.g., tracking the current topic and focus; making use of common ground with an interlocutor; Hickmann, Kail & Roland, 1995, Hickman & Hendricks 1999, Lloyd, Camaioni, & Ercolani, 1995).

Children’s cue-integrating difficulties are not limited to ambiguity in pronoun resolution. For example, young children (age 3) tend to inappropriately repeat their answers to successive forced-choice questions, if a similar discourse frame is used across the questions (Deák, 2003; Hansen & Markman, 2005). Preschool children will interpret a homophone according to its higher-frequency meaning, even if that meaning is nonsensical relative to the

questioning context (Beveridge & Marsh, 1991; Doherty, 2004). Finally, 5-year-olds have difficulty revising their initial interpretation of a noun phrase, if a restrictive modifier comes late in the sentence. For example, they do not understand that in the sentence “Put the frog on the napkin in the bowl,” the proper frog depends on the last prepositional phrase (“in the bowl”). Thus, many children choose an isolated frog instead of putting the specific frog that is on a napkin (Trueswell, Sekerina, Hill, & Logrip, 1999; Hurewitz, Brown-Schmidt, Thorpe, Gleitman, & Trueswell, 2000).

On the whole, then, the available evidence suggests that even as late as 4 or 5 years, children are learning a great deal about how to use probabilistic cues to resolve ambiguous reference—especially over wider scopes. This is not some esoteric linguistic detail: consider, for example, that children’s books, dinner table conversation, and teachers’ instructions all will rely on the ability to resolve pronoun reference over inter-sentential gaps.

#### Cognitive flexibility in child and adult language

Perhaps the late development of discourse-cue sensitivity is due to slow experience. It might take years to experience enough instances of various cues in various contexts. However, considering the range of cue-processing difficulties that have been documented in 3- to 6-year-old children, it is also possible that some general cognitive abilities place a developmental limitation on children’s cue-processing. One possible factor is cognitive flexibility.

Cognitive flexibility may be important at multiple levels in children’s higher-level language skills (Deák, 2003), including ambiguity resolution. In the most direct role, learning to use a probabilistic, indirect cue (topic switch, verb semantics, etc.), may be predicated on having the representational flexibility already present in working memory. Alternatively, cognitive flexibility may play a role not in *learning* an indirect cue, but in integrating multiple indirect cues into a single discourse representation and in guiding referent update at critical

points in an ongoing dialogue. Using probabilistic cues across multiple sentences may thus require flexibility in a way that learning the probabilistic nature of those cues does not.

There is evidence that cue knowledge alone cannot explain age-related patterns in cue use. Children speaking Korean (a head-final language) should not show a kindergarten path in a sentence such as “Pick up the frog on the napkin in the box” because the verb, appearing at the end of the sentence, uniquely specifies the appropriate response. However, children make errors both in this condition and in the truly ambiguous “Put the frog on the napkin in the box.” This, the authors argue, suggests that something (possibly cognitive flexibility) must additionally be involved. Children actually override the most probabilistically reliable cue (verb semantics) (Choi, & Trueswell, 2010).

#### Probabilistic cue integration: Gender, order-of-mention, topic and verb aspect

To address these questions, we inquire how children use changeable cues, within multi-sentence short stories, to determine the referent of a pronoun. We use personal pronouns (“he”, “she”) as ambiguous words. The test uses an ecologically common task (i.e., hearing and grasping a story) to test cognitive flexibility and it uses probabilistic cues that are common in everyday speech. We use cues which at least some evidence suggests preschoolers can use (topic switches, most-recently mentioned actor, and verb semantics).

Because we wanted to use all probabilistic cues, we introduced one particular type of verb semantics guided pronoun shift: verb aspect. Verb aspect gives information about the completion, duration or repetition of an action. In English, verb aspect is a discourse level cue, with wide scope. However, in other languages (notably Slavic languages), aspect is a lexicalized property of a verb. Cross-linguistic evidence (Vinnitskaya & Wexler, 2001) suggests that Slavic children acquire and use the conceptual mappings associated with aspect with few errors by age

6. Because aspect is a discourse cue in English, we might expect later, and less consistent, use of inter-sentential aspect cues by English-speaking children.

Aspect also licenses a host of conceptual information about a discourse. These subtle shifts of references can have important consequences for listeners' comprehension. They judge a traveler to be further from his ultimate goal immediately after reading a progressive vs. simple past verb tense (Matlock & Spivey, 2010). Matlock (2010) explored how shifting verb aspect could shift listener's comprehension of a political message. In some stories, participants heard a description of poor U.S. economic performance described using progressive verb aspect ("Employment numbers are weakening") vs. completed aspect ("Employment numbers weakened"). Participants were more likely to claim they would vote a fictitious politician out of office after the progressive trials. The authors speculate that implied temporal overlap from the progressive verb aspect highlighted the ongoing link between politician and economic state. Recent work also suggests that aspect cues can influence the choice of pronoun referent (Rohde, Kehler & Elman, 2006).

This has interesting implications when multiple actors (and multiple actions) occur together within discourse. For instance, in the story stem:

Aladdin wanted to go shopping.

The car was outside.

Aladdin motioned to Genie in the store.

**Progressive:** He was walking over.

The progressive aspect suggests that the action in the final sentence (walking over) occurred in parallel with the action from the previous sentence (motioning). Thus, it is less plausible for Aladdin to be the referent of both. This implies listeners should prefer Genie as the referent of "he" in the last sentence. However, with a completed action, the motioning action is



completed before the walking action begins and Aladdin is a more plausible referent. We tested these expectations for adults and children in Experiment 4a.

We examined children's use of aspect in Experiment 4a in the context of two additional cues: gender and recency. Gender, as noted above, should be a hard constraint on children's pronoun interpretation (when two characters differ in gender). Last-mention is a cue in multiple languages (Huang, 2000). Thus, last-mention may provide a referential lure for children. Children may either fail to use aspect until later childhood (indication that they do, in fact, learn less reliable cues later) or might underweight these cues relative to other, more familiar, potential sources of information (e.g. last mention). In Experiment 4b, we examine whether cognitive flexibility mediates children's understanding of aspect and additional probabilistic cues in multi-cue stories. We administered an expanded version of the stories in Experiment 4a, now also including information from a topic switch. We also administered a set of behavioral measures of cognitive flexibility. One or more of these measures of flexibility (task-switch, inhibition, processing speed, or working memory span) might predict children's ability to use single discourse cues or integrate multiple cues in an ongoing discourse.

## EXPERIMENT 4A

### *Method*

*Participants.* English-speaking 3- to 5-year-old children ( $n = 15$  per group,  $M_3 = 3.2$  years, 5 girls,  $M_4 = 4.4$  years, 8 girls,  $M_5 = 5$  year age 5.4 years, 7 girls) were recruited from preschools in suburban and rural Illinois. Children were fluent in English, and had no diagnosed language or cognitive delays. The majority of children were Caucasian and middle class. An additional 18 English-speaking adults from the same region ( $M_a = 33.8$  years) were recorded for

control judgments. All procedures were approved by the UC San Diego Human Research Participants Protection committee. All children completed the study session.

*Materials.*

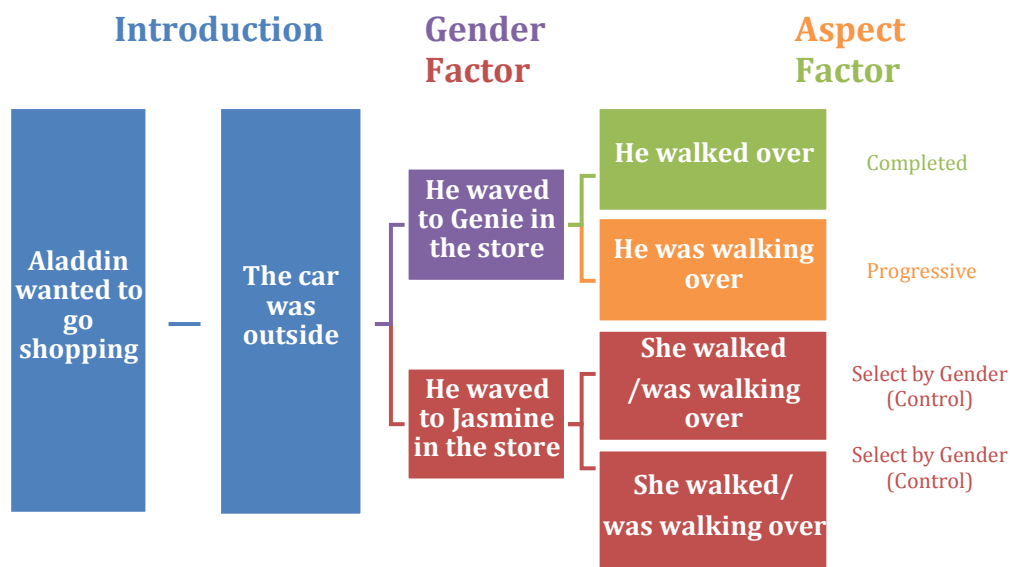
*Pronoun Comprehension.* We created a series of 24, four sentence stories. In these stories, we varied 1) gender of the two characters (i.e. either the same gender or different genders) 2) verb aspect (Progressive: PROG or Completed: COMP) in the probe sentence and 3) the last explicitly-named character in the third sentence. An additional set of 6 filler stories included a pair of characters as either the first or the second introduced character (different-number).

Each story involved two actors who participated in a short action sequence. The first three sentences introduced the characters and set up a shared activity. The fourth (probe) sentence followed the format: Pronoun [Past progressive/Simple past] intransitive verb (e.g. “He was **walking/walked** over”). Trials of interest were those in which both characters were of the same gender. In these trials, the pronoun in the final sentence (e.g. “he”) could only be disambiguated using cues deriving from last-mention and/or verb aspect. These trials determined whether participants’ used aspect and last-mention as discourse cue.

In different-gender trials (where “he” or “she” referred to the sole boy/girl in the story), we did not expect children to use either information from verb aspect or last-mention. The gender cue alone disambiguated the final pronoun. However, if children incorrectly weighted information when there were multiple cues, we might expect some gender errors in these trials.

In the different-number condition (6 stories), three characters appeared. Two were consistently grouped together pictorially. The pronoun in the final sentence, “(s)he” or “they,” could uniquely identify the referent. These stories acted as filler stories. We did not expect

children to use either information from verb aspect or last-mention. The number cue alone disambiguated the final pronoun (Figure 4.1).



**Figure 4.1:** Story Manipulation (Experiment 4a).

Pictures of characters were rendered in Adobe Illustrator. All were taken from public domain websites. Cartoon characters were anthropomorphic entities easily identified by gender.<sup>4</sup> Informal pilot testing suggested children as young as three could reliably identify the gender of each character. Test stimuli were displayed at 180<sup>2</sup> pixels on a white background in Microsoft PowerPoint. Each story included a series of three screens. In the first, the first-mentioned character was shown in the center of a white background. In the second screen, the second-mentioned character was shown alone in the center. In the third screen, both characters appeared, spatially separated, with the first character always shown on the left side of the

<sup>4</sup> Character names varied from 2-4 syllables. However, when stories were constructed, character pairs were matched for syllabic length within a single story. Each character appeared in a story with another character only once. Each character appeared in two stories total, appearing once as the first introduced character and once as the second introduced character. Character names varied from 2-4 syllables. However, when stories were constructed, character pairs

screen. If a pair of characters were introduced second (i.e., different-number condition), the pair appeared together on the left or right. Another object from the story (e.g. a ball, in a basketball story) appeared in the middle of the screen, equidistant from both characters. This was intended to serve as a mnemonic cue to the content of the story. This screen remained until the child answered the comprehension question (Figure 4.2).



**Figure 4.2:** Display screen for Pronoun Comprehension (Experiment 4a & 4b).

The experimental and filler stories were pseudo-randomly ordered into two lists. Each list was administered in either a forward or a backward order, for a total of four presentation orders. Each character appeared with another character only once throughout the test, and appeared equally as first or second mentioned character. Prior norming with 25 adults ensured that verb choices were standardized for likelihood of completion by female or male characters.

*Verbal ability.* The Peabody Picture Vocabulary Test (PPVT-III) was administered as a normed test of receptive vocabulary. It has 208 plates, each depicting four line drawings of referents of verbs or nouns.

*Procedure.* Children were tested in their homes, in a quiet area without distraction. The child sat approximately 20 cm from the screen of a laptop computer. Children were told that

they would hear some simple stories, and should listen carefully because they would be asked a question. They were encouraged to point onscreen to the appropriate picture to answer the question. In each trial, the experimenter began by displaying the first screen, depicting the first character. The experimenter introduced the character by saying “This is \_\_\_\_\_. Can you say his/her name?” The experimenter then introduced the second character on the screen. When the child showed that they could identify both characters, the experimenter advanced the screen and read the story at a natural pace. Children were then asked to identify the character that performed the action in the last sentence (e.g. “Who was falling?”). A second experimenter recorded the response. Children completed three practice stories, in which the final sentence did not contain an ambiguous pronoun, to ensure that children were comfortable in responding and that they knew character names. After each trial the child was prompted to identify one of the two characters (chosen randomly), to ensure that children remembered the character-name mappings. Trials with naming errors were excluded from further analysis (< 5% of trials). After each trial, the child was told, “Good job. Thank you.” Testing took between 25-35 minutes.

Following the pronoun comprehension test, the child was administered the PPVT-III-A according to standard instructions.

### *Results*

To verify that children had age-typical receptive language, we examined PPVT III-A scores. Mean standardized scores averaged 106.25 ( $SD = 11.8$ ) for 3-year-olds, 110.68 ( $SD = 12.2$ ) for 4-year-olds, and 106.43 ( $SD = 9.8$ ) for 5-year-olds.

Preliminary analyses found that participants’ own gender did not significantly impact performance in any analyses. Thus, data from boys and girls were combined in all analyses.

Adults performed at ceiling in different-gender and different-number trials as expected.

A 2 (Aspect [PROG/COMP]) x 2 [Last-Mention (First Character/Second Character)] ANOVA was conducted on mean choice percentage (for the first character) for adult controls. There was a main effect of aspect: adults choose the second - mentioned character more in the progressive than in the completed aspect trials,  $F(1, 18) = 14.87, p < .001, \eta^2 = .14$ .

For instance, in a story such as:

Aladdin wanted to go shopping.

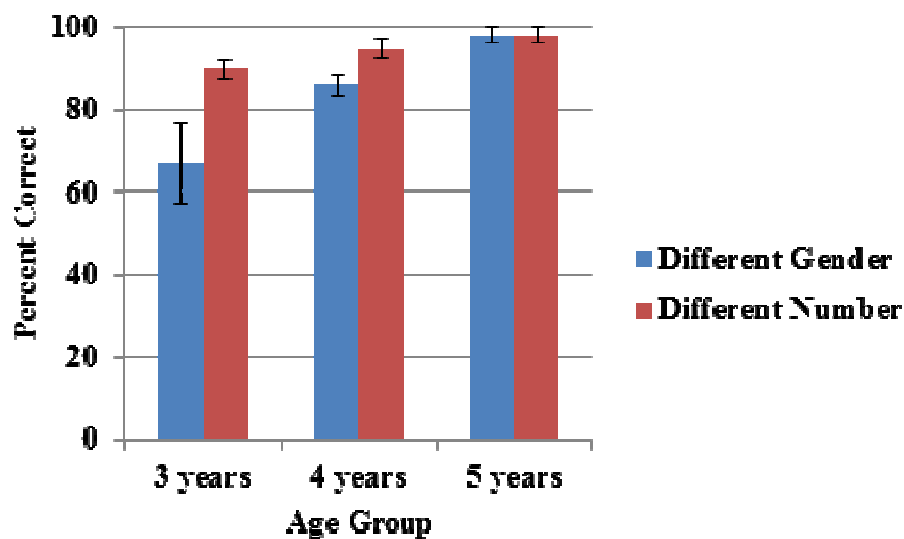
The car was outside.

Aladdin waved to Genie in the store.

**PROG:** He was walking over.

Adults chose Genie as the referent significantly more than Aladdin. These responses were not binary- adults still chose the first-mentioned character 27% of the time, showing that preferences, while strong, were probabilistic. The last-mentioned character did not significantly guide adults' choice of referent.

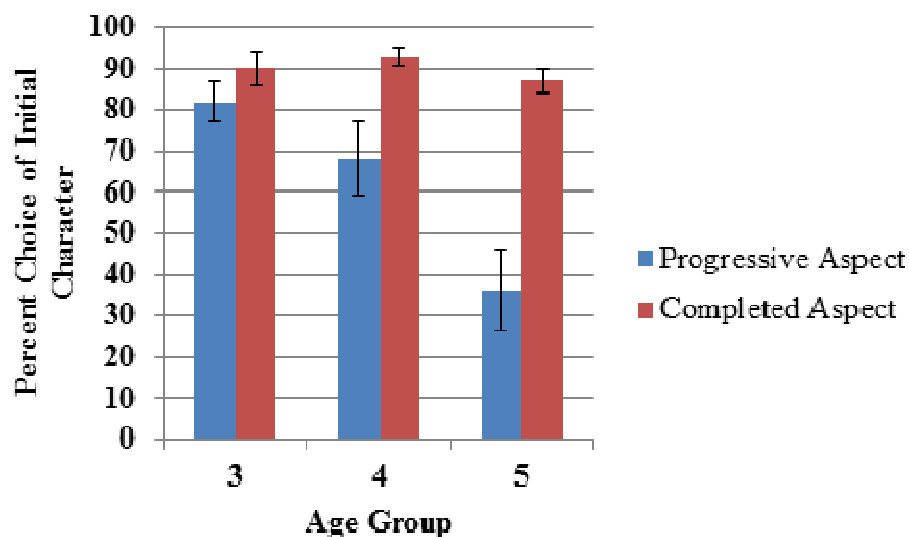
Like adults, all children performed near ceiling on the number filler trials. This indicates that even 3-year-olds were on task, and that task demands were not too difficult. Surprisingly, however, 3-year-olds did not perform at ceiling on the different-gender trials. Specifically, 3-year-old children made errors in trials where the last mentioned proper name conflicted with pronoun gender in the final sentence (Figure 4.3). Post-hoc analyses showed that gender-assignment errors did not interact with verb aspect: 3-year-olds miss-assigned gender whether the verb aspect was completed or progressive. This was an unexpected effect, which we will examine in follow-up experiments. Split-half analyses did not reveal any tendency to make more gender errors towards the end of the experiment, thus suggesting that fatigue or off-task performance cannot explain these results.



**Figure 4.3:** Percentage Correct Choices in Different-Gender and Different-Number Conditions, By Age (Experiment 4a).

For same-gender stories, a 3 (Age) x 2 (Aspect [PROG/COMP]) x 2 (Last [First Character/Second Character]) ANOVA was conducted on percent choice of the first character. There was a main effect of aspect: children preferred the first character less in trials with progressive aspect,  $F(1, 42) = 30.534, p < .0001, \eta^2 = .421$ . There was a significant interaction between age and aspect. Children became more sensitive to verb aspect with age,  $F(2, 42) = 7.240, p < .002, \eta^2 = .256$  (Figure 4.4). 5-year-olds were more likely than 3- ( $p < .0001$ ) and 4-year-olds ( $p < .033$ ) to use aspect to guide a pronoun switch. Choices with both verb aspects differed from chance performance, which would be 50% choice of each character in both same-gender/different-aspect conditions: PROG  $t(44) = -2.26, p < .029$ ; COMP  $t(44) = -22.29, p < .0001$ . (Chance-level performance for three pictures, including the distractor, would be 33%. However, children were not included in analyses if they picked the distractor more than 5% of the time and trials where children picked the distractor were not analyzed).

There was an interaction of age and last-mention,  $F(2, 42) = 5.250, p < .009, \eta^2 = .2$ . Three year olds' were more likely to choose the last named character.



**Figure 4.4:** Percentage Choice of Initial Topic, by Aspect Condition, by Age (Experiment 4a).

#### *Discussion*

Four- and 5-year-old children showed increasing sensitivity to verb aspect, using progressive verb aspect to infer that an ambiguous pronoun was more likely to refer to a non-topical character. Three-year old children showed relatively little sensitivity to aspect. This is the first demonstration of such sensitivity in English-learning children, as research even on adult verb aspect is nascent. Moreover, the results suggest that sensitivity to verb aspect develops with age at a time when children show large individual differences in cognitive flexibility. Notably, most tests of cognitive flexibility require children to select and integrate multiple probabilistic cues, in situations where there is some kind of mapping or response conflict.

As previously noted, some 3-year-olds made unexpected errors using gender cues. Over half (60%) made one or more gender assignment errors in trials where the last-mentioned proper name was the opposite-gender character. We did not further explore this gender effect in Experiment 4b because it was outside of our initial questions. These errors, however, suggest



that scope errors are obtained even in cases where a certain cue conflicts with a probabilistic cue. This is unexpected: previous research suggests that children can use gender as a cue even in discourse contexts. Interestingly, though, Arnold (2007) found that 3-year-old boys made gender errors when the gendered pronoun matched the last-mentioned actor. This is somewhat in contrast to the results we found—where 3-year olds tended to match gendered pronoun to the last mention even when this led to incorrect assignment. However, both suggest that the youngest children cannot reliably weight a salient, but weak, discourse cue (last-mention) as less reliable than a lexicalized cue. Instead, for example, younger children may over-weight a cue simply because it occurred *first* out of several cues. This sort of problem can also explain why 3-year-olds were not very sensitive to aspect cues.

These errors may be construed as perseveration on an initial syntactic parsing. That is consistent with previous findings of perseverative interpretations of multi-sentence paradigms. For example, Deák (2000) tested how children infer meanings of different words for an array, based on changing linguistic cues. Children heard three words for each of six sets of novel objects, described by a unique novel word that followed one of three phrase cues: “looks like a(n)\_\_\_\_,” “is made of\_\_\_\_,” or “has a(n)\_\_\_\_.” Children had to generalize each word to a comparison object, based on an inference about the word’s meaning that was implied by each phrase. Many 3-year-old children tended to perseverate on the meaning implied by the first phrase cue they heard. Similarly, many 3-year-olds will perseverate in choosing the answer to a series of distinct forced-choice questions with the same choices (Deák, 2003, 2006).

In Experiment 4a, only 3-year-old children ignored a lexicalized, determinate cue (i.e. gender) when it conflicted with a prior, but uncertain cue—specifically, last-mentioned character in the previous sentence. This error shows that 3-year-olds’ ability to use gender cues

in isolation can be compromised by a more complex cue context, even when other cues are “weak.”

To better understand the effects of multiple cues for pronoun resolution, including aspect and last-mentioned character, it would be informative to find a cue which is typically more salient than aspect, but which still shows developmental variability in the age range of interest. That is to say: last-mention was sufficiently salient to override gender cues, but only for the youngest children. In older children (i.e., 4- and 5-year-olds), we might find similar conflict effects when two probabilistic cues are in conflict. A logical contextually interactive cue with aspect is topic. That is, *topic* tends to push one character to prominence, and topic switches can change that spotlight. Aspect also can shift the focus from an active character to another character completing a concurrent action, if verb semantics imply that the two actions are unlikely to be simultaneously carried out by one character. For this reason, topic switch was added as a co-varying cue in Experiment 4b.

Although a few psycholinguistics have begun to mention cognitive flexibility and related general cognitive factors (e.g., processing load, competition and selective attention; e.g., (Novick, 2005; Gollan & Ferreira, 2009; Arnold, 2010), almost nothing is known about how factors like cue competition might impact pronoun resolution in children. If cognitive flexibility plays a role, we would expect not only age differences, as outlined above, but also individual differences. There is ample evidence of individual differences among 3- to 6-year-old children in cognitive flexibility, from sufficiently sensitive tests (Diamond & Kirkham, 2005). There is some evidence that these individual differences predict discourse comprehension. Performance on conflict-inhibition tasks, for instance, correlates with the ability to infer shared information during online discourse (e.g., to which of two possible referents a speaker is referring) (Brown-Schmidt, 2009).

We explore this possibility in Experiment 4b in two ways. First, we modified the stories in Experiment 4a, varying three discourse-level cues: topic switch, verb aspect and last-mention. This enabled us to test whether, and how, young children integrate those cues. Second, we administered a set of age-appropriate tests of rule-switching flexibility and related executive functions (EFs). The purpose was to examine whether age and individual differences in cognitive flexibility in 4- to 6-year-olds can predict individual's tendency to use combinations of inter-sentential cues to pronoun reference.

### **EXPERIMENT 4B**

Children in Experiment 4a showed developing adult-like use of aspect cues from 3 to 5 years. It also showed that a discourse cue (last mention) can interfere with 3-year-olds' use of a strong, determinate cue (i.e., gender). In Experiment 4b we explored the role of cognitive flexibility in these sorts of changes in the ability to select discourse cues. Do individual differences in non-syntactic measures of cognitive flexibility (e.g., rule-switching) predict children's ability to resolve ambiguous pronouns based on multiple, probabilistic cues?

The stories in Experiment 4b parametrically varied progressive or completed verb aspect (PROG/COMP), whether or not there was a previous topic switch (+TOP/-TOP), and whether the last character mentioned was the initial topical or non-topical character. Unlike in Experiment 4a, all of these cues are discourse-level (not lexicalized), and are probabilistically "weaker." Older children (aged 4 and 5) did not make gender errors, but might experience more conflict with the topic switch cue.

Stories with no topic switch essentially replicated items in Experiment 4a. Stories with just progressive verb aspect were expected to potentiate a switch from the initial topic to the second character. Stories with just a topic switch were also expected to potentiate a switch from

the initial topic to the second character. These both represent single-cued switches. Of interest is when information from both from both a topic switch and progressive aspect occur together. In these instances, we expect the combination of two cues (topic switch and progressive aspect) is expected not to potentiate a switch from the initial topic to the second character. Information from the topic switch suggests a temporary pronoun switch; however the progressive aspect reinforces the salience of the first character.

Last-mention did not govern older children's performance in Experiment 4a, so it was not expected to "outweigh" aspect. However, Huang (2000) found that last-mention can affect adults' reference assignment; moreover, it has not been established whether last-mention interacts with topic switch in children. Furthermore, last-mention should produce proactive interference, which might require cognitive flexibility. Thus, it makes sense to further investigate the last-mention factor.

We chose one main test of cognitive flexibility, and several other executive function tests. To test task-switch, we used two computerized task-switch tests which required children to alternate between brief series of color-rule and shape-rule trials (c.f. Zelazo, 2006). Children saw pictures of colored animals, and were asked to "sort" the pictures by pushing the button below the target picture that matched on the appropriate dimension. In order to general executive capability, we selected or adapted several tests that have been used with developmental or neuropsychiatric populations. We adapted a Go/No-Go test of perceptual-motor suppression response speed from Mesulam (1985) and Tapping Inhibition Task adopted from Luria (1966). These tasks tap inhibition and require participants to respond in unnatural or less-practiced ways on some trials, thereby requiring a suppression of stronger response tendencies. To test general neural processing speed, we adapted the Box Completion Test from the Woodcock-Johnson test (Woodcock & Mather, 1989). Participants are asked to draw in the

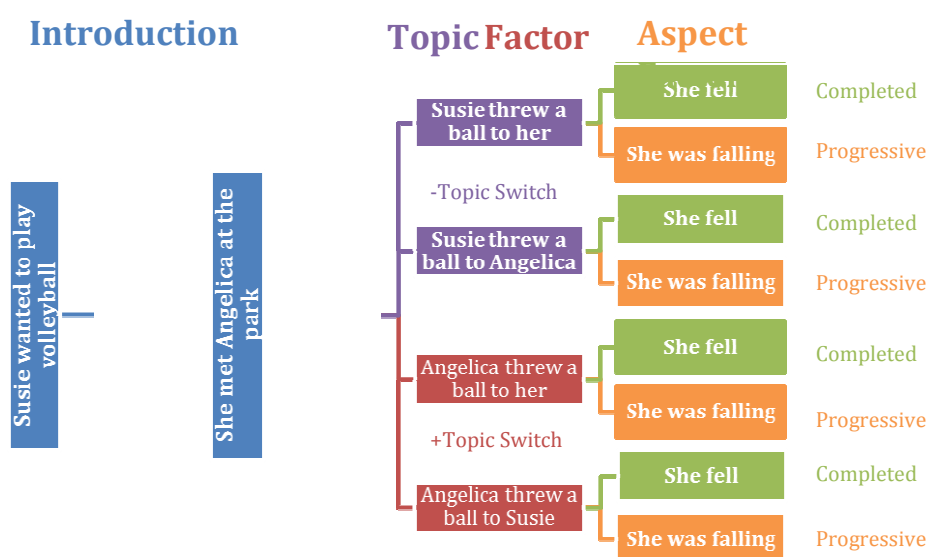
missing sides of a series of open squares rotated in different directions, as quickly as possible. We also included several age-normed measures of verbal working memory (vWM). These measured working memory in different ways. The Woodcock –Johnson memory for sentence test asks participants to remember sentences of increasing length and syntactic complexity. The Nonword Repetition test asks participants to remember and repeat phonologically varying non-words of differing syllabic length. Finally, digit span asks participants to remember a series of numbers spoken at 1 second intervals. Children completed an age-normed measure of receptive vocabulary, the Peabody Picture Vocabulary Test (PPVT-III) as in Experiment 4a.

### *Method*

*Participants.* 24 4-year-old children (mean age = 4.4 years, range 4.0 to 4.9, 19 girls), and 28 5- and 6-year-olds (M = 79.8 months, 14 girls) were recruited from preschools within 15km of UC San Diego. Children were fluent in English, and had no diagnosed language or cognitive delays. The majority of children were Caucasian and middle class. In addition, 24 undergraduate students were recruited from the University of California San Diego ( $n = 24$ , mean age = 20.4 years, 12 women). All participants were monolingual native English speakers, and had no diagnosed language or cognitive delays. All procedures were approved by the UCSD Human Research Participants Protection committee. Two more 4-year-olds and two 5-year-old children were excluded from analyses because they did not complete both sessions. Four 4-year-olds and one 5-year-old were excluded from analyses because they picked the distractor item on more than 5% of all trials. All children were given the PPVT III-A, forward Digit Span, Non-word Repetition test and the Woodcock Johnson Memory for Sentences Test.

### *Materials.*

*Pronoun Comprehension.* We created a series of 40 5-sentence short stories in which we varied 1) topic switch (+TOP/-TOP) in the 3rd sentence; 2) verb aspect (PROG/COMP) in the probe sentence; and 3) whether the last-named character was the same as the current topic-character. With the exception of an added introductory sentence, stories followed the same format as in Experiment 4a. This introductory sentence explicitly named the two characters appearing in the stories. Unlike in Experiment 4a, half the stories in the third sentence had a topic switch (Figure 4.5).



Decision: Who Fell?/Who was falling?

**Figure 4.5:** Story manipulation (Experiment 4b).

Pictures of characters were prepared as in Experiment 4a<sup>5</sup>. Test stimuli were displayed at 180<sup>2</sup> pixels on a white background using Matlab with Psychtoolbox toolkit. Unlike in

<sup>5</sup> Character names varied from 2-4 syllables. However, when stories were constructed, character pairs were matched for syllabic length within a single story. Each character appeared in a story with another character only once. Each character appeared in four stories total, appearing twice as the first introduced character and twice as the second introduced character. Presentation lists were structured so that the same character did not appear on two successive trials in any position.

Experiment 4a, no related thematic elements (e.g. pictures of balls) were displayed onscreen. Audio files were edited using Praat software ([www.fon.hum.uva.nl/praat/](http://www.fon.hum.uva.nl/praat/), Paul Boersma, University of Amsterdam). Each sentence file was edited to sound natural with a duration of 1600ms, and a maximum pitch window of 400 Hz for proper names and 300 Hz for pronouns. There was an empty 500ms between sentences. Character mentions in sentences of interest (four and fifth) had standard naming onsets.

After the first 15 trials, children were told they would take a break and “do something different.” They then were administered the Tapping Test. After the second 15 trials, they completed the Box Completion test, and then the remaining ten trials. These breaks encouraged child compliance and comfort.

The experimental and filler stories were pseudo-randomly ordered into two lists as in Experiment 4a.

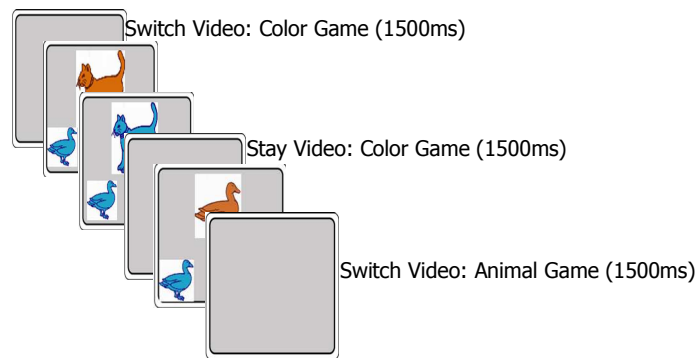
*Task-switching.* Responses and RTs were recorded on a two-button box customized for preschool children. Two large, colorful buttons were mounted 24 cm apart on a padded wooden tray that lay across the arms of the child’s chair. The tray was designed to minimize spurious errors and to maximize comfort 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<sup>6</sup>. Two target pictures (4 cm<sup>2</sup>), a blue cat and brown duck, were constantly present, one at each of the bottom corners of the monitor, directly above the response buttons (Figure 4.6). The side of these target pictures (left or right) was counterbalanced across participants. During each trial, one of four test stimuli was displayed in the center of the

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<sup>6</sup> Also, *cat - duck* and *brown - blue* match in word length and, roughly, phonological complexity.

monitor, in a 10 cm<sup>2</sup> gray box. Two of the four test stimuli matched the two target pictures (i.e., brown cat and blue duck). These congruent (non-conflict) stimuli appeared in 33% of trials. They required the same response under either rule condition (see below). The other two images (67% of trials) were incongruent (conflict) stimuli; that is, they afforded two different matching responses for each target, one based on color and one based on shape (e.g., a blue cat could be matched with the blue duck or the brown cat).



**Figure 4.6:** Task-switch manipulation (Experiment 4b).

Four cue videos were recorded: two switch cues (a model saying: “Now play the animal game” or “Now play the color game”) and two stay cues (“Keep playing they animal game” or “Keep playing the color game”). These were matched frame-by-frame for length (1500ms) and consistency in facial movement and intonation. In addition, 800ms feedback videos, a smiley face or frowning face, were presented following each response.

*Inhibition and perceptual-motor processing speed.* The Go/No-Go test used a green circle and red circle (10 cm<sup>2</sup>) on a black background. The box completion test used of a page with 5 rows of 7 3-sided incomplete squares, with one line missing from different sides. The Luria Tapping test used two small sticks.



*Verbal ability.* Four verbal tasks were administered. The Peabody Picture Vocabulary Test-III (PPVT-III), and several measures of verbal Working Memory (vWM): the Woodcock-Johnson memory test, with 32 sentences of progressively increasing length, the Non-word Repetition task (40 nonwords, 10 each of 2, 3, 4, and 5 syllables), and forward Digit Span from the WAIS-III (Wechsler Adult Intelligence Scale, 1981).

*Procedure.*

Tasks were completed on-site at three Montessori schools near UC San Diego, in two 1-hour sessions, in a quiet location away from other children. Order of tasks was fixed for all children. In the first session, participants completed: 1) Pronoun Comprehension 2) Tapping Test 3) Box Completion 2) Go/No-Go In the second session, one week later, children completed: 4) Task-Switching 5) Woodcock-Johnson Memory for Sentences 6) Digit span, 7) PPVT-III, and 8) Non-word Repetition. Executive function tasks were programmed and delivered using Presentation v9.9 software ([www.neuro-bs.com](http://www.neuro-bs.com), Neurobehavioral Systems, Albany, CA, USA). The Pronoun Comprehension Test was delivered using Matlab v.14 software ([www.mathworks.com](http://www.mathworks.com), Mathworks, Boston, MA, USA) with the Psychtoolbox suite. Children were seated approximately 40 cm from the monitor, and were given breaks whenever as needed. Children received a small toy after each session.

*Pronoun Comprehension.* The experimenter encouraged the child to sit about 20 cm from a portable laptop computer. Children were told that they would hear some simple stories, and would have to listen carefully because they would be asked a question. A custom-built keyboard cover was placed over the laptop keyboard, leaving only three keys exposed. Each key was located directly underneath one of the three pictures located onscreen (two characters mentioned in the story and one distracter). Children were trained to push the button underneath the appropriate picture, in response to a question. Children first completed three practice stories,

with an unambiguous final pronoun, to ensure that they could understand the task and remember character names.

Stories were presented over three screens. In the first screen, children were told the name of the first character (“Here’s Susie!”) and saw a picture of the corresponding character on the left hand side of the screen. On the second screen, children were told the name of the second character (“And here’s Angelica!”) and saw a picture of the corresponding character on the right hand side of the screen. The third screen displayed both characters as in Experiment 4a and was up for the duration of the story. Children pushed the button underneath the appropriate character of their choice. Children received neutral feedback (e.g. “good job”) at staggered intervals.

*Task-switching.* Participants were alternately cued to play either the “animal game” or the “color game.” Both require matching stimuli (blue cats or brown ducks) according to previously defined sorting rules. The rule changed predictably with a video “switch” cue (1500ms) after every three trials. (The first rule was counterbalanced across participants). A matched “stay” video cue (1500ms) appeared before either the second or third trial (alternating randomly) within each three-trial block. Stimuli were either incongruent (32 trials), requiring a different response depending on the game, or congruent (16 trials), requiring the same response in either game. Details are described elsewhere (Holt & Deák, under review).

*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 when a “go” cue (green circle) appears, but not push if a “stop” cue (red circle) appears. The timing was modified between blocks of 24 trials until children accidentally responded to 50% of no-go cues in two consecutive blocks. Details are described elsewhere (Holt & Deák, under review).

*Luria's Tapping test [Inhibition]*. Children were told they would play a game with “silly sticks.” Following Luria (1966), the experimenter trained the child to tap twice when she tapped once, and vice versa. This was repeated until the child seemed to grasp the rules, and then correctly completed five practice trials with feedback. Then the child completed two blocks of 10 test trials, without feedback. Children were reminded of the instructions after the first block. Accuracy in the test trials was the dependent measure.

*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. Finally, for the test they completed as many boxes as they could in one min.

*Verbal Ability.*

*Peabody Picture Vocabulary Test-III* was administered as in Experiment 4a.

*Digit span [Verbal memory span]*. Based on Wechsler (1981), children were asked to repeat a series of numerals, spoken at 1 sec intervals. Standard procedure and scoring was used.

*Woodcock-Johnson Memory for Sentences*. Children were first shown a small picture of a car. They were instructed to point to the item and repeat the word “car.” If children did this, they moved on to a block of 15 sentences, increasing in word length. The experimenter read the sentence at a natural pace. Children repeated sentences, and received one point for perfect recitation. In a second block of up to 16 trials, children heard sentences of increasing length presented using Adobe Audition (<http://www.adobe.com>, Adobe Systems Inc., Delaware, USA). Children received two points for perfect recitation, one point for one mistake and zero points for anything else. Presentation continued until the child received a score of zero on four consecutive trials (Woodcock & Johnson, 1989).

*Non-word Repetition.* Children were told that they would hear some “funny alien words” which they should try to say. The child heard 5 blocks of 8 nonwords each. Nonwords were presented using Adobe Audition. The child was allowed 3 sec to make each repetition attempt. After 3 seconds the experiment prompted the child for a response; these trials, however, were not included in the final score. The next nonword in the sequence was spoken by the experimenter after a repetition attempt for the previous item. Children received 0 points if a second experimenter judged that the child had produced a sound that differed from the target nonword by one or more phonemes and 1 point if the repetition was judged to be phonologically accurate. In accordance with published administration guidelines (Gathercole, 1995), children received credit for a phonological substitution if it was clear from spontaneous speech that this substitution reflected a generalized, regional phonemic substitution.

### *Results*

Children’s performance on measures of receptive vocabulary and verbal memory abilities are given in Table 4.1.

**Table 4.1:** Performance on measures of language comprehension in young children.

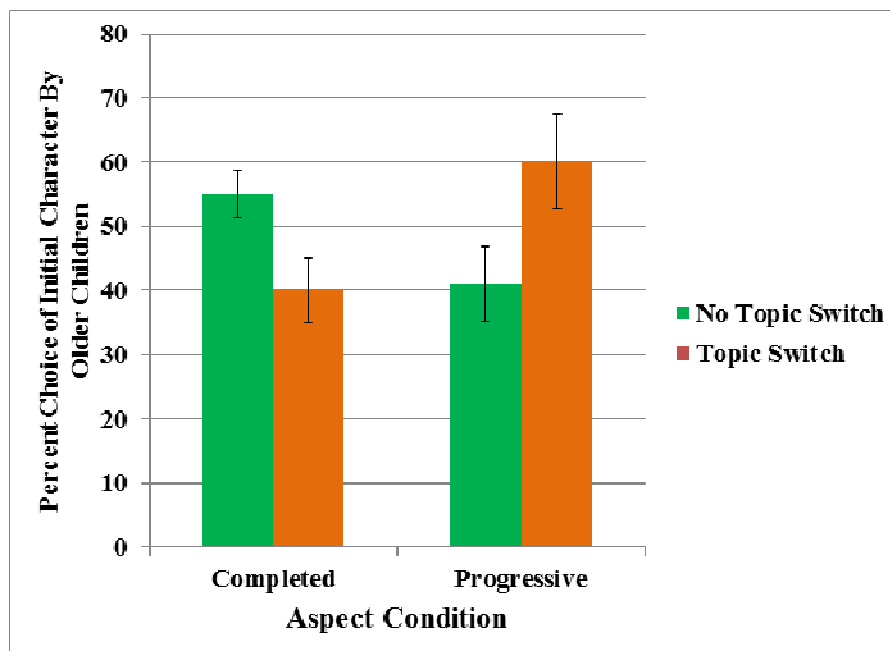
<i>Measures of vWM</i>	<i>PPVT III-A</i>	<i>Nonword Repetition</i>	<i>Woodcock-Johnson Memory for Sentences</i>	<i>Digit Span</i>
4-year-olds	117.3 (10.9)	35.5(6.6)	18.6(7.6)	4.05(.55)
5&6-year-olds	116.5(13)	40.2(5.5)	24.5(8.1)	4.01(.92)

*Pronoun Comprehension.* Children's choices in each condition were scored as the mean percentage of first-introduced character choices. Thus, where cue information (e.g. verb aspect; topic switch) is expected to guide a pronoun switch, the percentage choice of first-named character should be low. Preliminary analyses showed that participants' gender did not significantly impact performance. Thus, data from boys and girls were combined in all analyses.

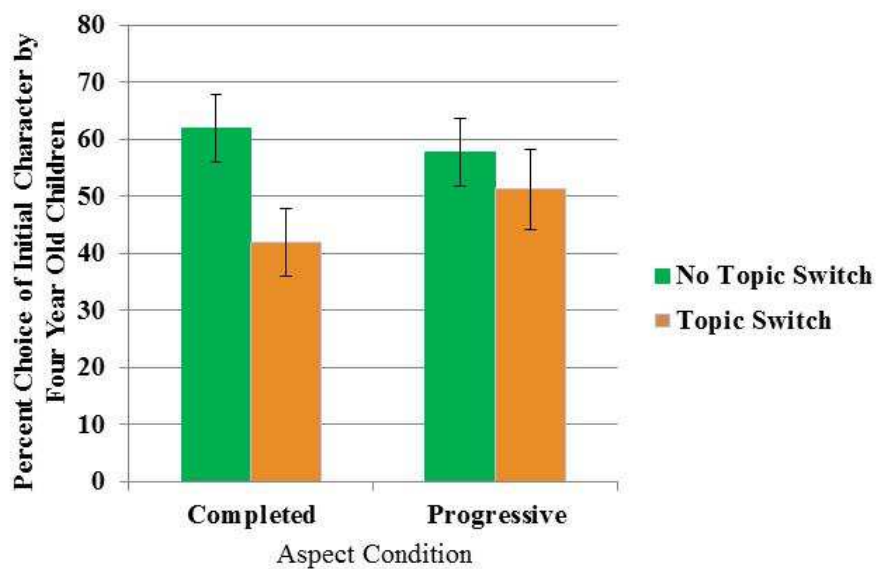
Adult Choice ratios were entered into a 2 (Aspect [PROG/COMP]) x 2 (Topic [+TOP/-TOP]) x 2 (Last-Mention [First-Character/Second-Character]). There was a significant Aspect X Topic interaction,  $F(1, 23) = 18.61, p < .001, \eta^2 = .244$ . No effects of last-mention were found. Adults consistently used information from both *topic* and *aspect* to ascribe a pronoun's

referent. Both the presence of a topic switch or the use of progressive aspect guided adults' to prefer the second-introduced character (a switch of referent). When information from both a topic switch and progressive aspect was present, adults' generally preferred the first-introduced character. We interpret this as using both cues to guide a switch of preferred pronoun referent, effectively revising an initial preference for a pronoun switch.

A 3 (Age) x 2 (Aspect [PROG/COMP]) x 2 (Topic [+TOP/-TOP]) x 2 (Last-Mention [First-Character/Second-Character]) ANOVA was performed for children's choice of pronoun referent. There was an interaction of topic x aspect,  $F(1, 50) = 19.986, p < .0001, \eta^2 = .286$ . Overall, older children integrated information from both topic and aspect to choose in a relatively adult-like fashion (Figure 4.7). There was, however, an interaction of topic x age,  $F(1, 50) = 8.950, p < .0001, \eta^2 = .152$ . Unlike older children and adults, 4-year-olds only showed clear choice preferences in cases without topic switch (-TOP). Post-hoc t-tests revealed that 4-year olds did not choose significantly differently from chance when there was a topic switch ( $p > .05$ ) (Figure 4.8). This chance-level performance by age was subjected to additional analyses below.



**Figure 4.7:** Percent Choice of Initial Topic, by Condition, in Pronoun Comprehension Test (Age 5-6).



**Figure 4.8:** Percent Choice of Initial Topic, X Condition, in Pronoun Comprehension Test (Age 4).

*Other Measures of Executive Function.* Descriptive statistics for each measure of executive function are shown in Table 4.2. Note that results from rule-switching tasks, measures of Tapping errors, Box completion test, are comparable to other published studies, including those from this lab. Most notably, children are slower to sort stimuli in the rule-switching task when the trials immediately follow a change (switch) in sorting rule. Further, 4- year old children showed variable accuracy as well as RT in these conditions, which enabled post-hoc classification of the younger children into “flexible” and “inflexible” groups.

**Table 4.2:** Performance on measures of executive functioning (Experiment 4b).

	<i>Task-Switching (Accuracy)</i>		<i>Task-Switching (RT)</i>		<i>Luria Tapping (Errors)</i>	<i>Go/No-Go (Interstimulus Interval)</i>	<i>Boxes (Numbers)</i>
	<i>Switch</i>	<i>Stay</i>	<i>Switch</i>	<i>Stay</i>			
4-year-olds	79% (13.46)	76% (13.03)	2685ms (1208)	2180ms (1022)	6.39 (5.91)	2648ms (1499)	19.97 (7.2)
5&6-year-olds	95% (2.46)	96% (2.03)	1452ms (451)	1334ms (454)	1.25 (1.93)	927 (651)	29.85 (9.99)

*Relationship of Executive Functioning to Performance on Pronoun Comprehension Test.*

To investigate whether individual differences in EFs would predict variance in choice preference in the Pronoun Comprehension test, we ran exploratory bivariate correlations between all tests of executive functioning and choice data in conditions with two cues (+TOP + PROG) (Table 4.3). Only task-switch accuracy showed a significant correlation with choice data, though there were marginal correlations with one measure of inhibition (Tapping Test). We divided four year olds children into two groups, based upon flexibility category in the computerized task-switch test.



**Table 4.3:** Bivariate correlations of measures of executive functioning and story conditions in the pronoun comprehension test (Experiment 4b).

		Aspect + Topic Switch Conditions	Aspect - Topic Switch Conditions
Luria Tapping Test	Pearson Correlation	-.384	.067
	Sig. (2-tailed)	.064	.757
	N	24	24
Box Completion	Pearson Correlation	-.089	-.276
	Sig. (2-tailed)	.680	.191
	N	24	24
Stop Signal ISI	Pearson Correlation	.141	.377
	Sig. (2-tailed)	.510	.069
	N	24	24
Mean Incongruent Task-Switch Trial Accuracy	Pearson Correlation	.412*	.087
	Sig. (2-tailed)	.045	.687
	N	24	24
Flexible or Inflexible?	Pearson Correlation	.452*	.130
	Sig. (2-tailed)	.026	.545
	N	24	24
Aspect + Topic Switch Conditions	Pearson Correlation	1	.743**
	Sig. (2-tailed)		.000
	N	24	24

\*\* . Correlation is significant at the 0.01 level (2-tailed).

\* . Correlation is significant at the 0.05 level (2-tailed).

Children were assigned post-hoc to the category of “flexible” or “inflexible” task-switching based upon their task-switch accuracy in switch trials. Flexible children were categorized as those for whom accuracy on switch trials was > 75 percent, while inflexible children had accuracy less than 75 percent. (It is notable in this task that children who never switched tasks—showing the classic “perseverative” pattern, typical of the Dimension Change Card Sort (DCCS) Task, would have 50 percent accuracy, due to the alternating rule structure). 41 percent of four year children were categorized as flexible (successful) switchers, and 59 percent were categorized as inflexible (poor) switchers. As expected, all 5-6 year old children performed flexibly. We performed a separate 2 (Flexibility [Flexible/Inflexible]) x 2 (Aspect [PROG/COMP]) x 2 (Topic [+TOP/-TOP]) x 2 (Last-Mention [First-Character/Second-Character]) ANOVA for 4-year-olds’ choice of pronoun reference. Flexibility mediated pronoun reference. There was an interaction of topic x aspect,  $F(1, 22) = 13.499, p < .001, \eta^2 =$

.380. There was an interaction of topic x flexibility,  $F(1, 22) = 7.804$ ,  $p < .001$ ,  $\eta^2 = .016$ . Flexible switchers performed like older children and adults: integrating topic switch information with aspect information. Inflexible (high task-switch error) children did not. Thus, flexibility appeared to predict which children could accurately integrate two cues in an adult-like manner.

Following Brown-Schmidt (2009), we also ran linear regressions to determine whether accuracy in the task-switch test predicted individual choices in the pronoun comprehension test. We ran separate regressions for cases where there was 1) a topic switch and completed aspect (+TOP/COMP) and 2) a topic switch and progressive aspect (+TOP/PROG). In the first case, information from topic switch alone should guide a shift in pronoun referent. Switching accuracy did not account for a significant percentage of the variance in the topic switch/completed aspect cases (+TOP/COMP). However, switching accounted for a significant (55%) percentage of the variance in cases with topic switch and progressive aspect (+TOP/PROG) ( $\beta = .755$ ;  $R^2_{\text{adjusted}} = 0.55$ ;  $p = 0.0001$ ). Age did not account for significantly more variance than flexibility.

### *Discussion*

We replicated the finding of Experiment 4a that older children (ages 4-6) use verb aspect as a cue to pronoun resolution. Children of all ages use the presence of progressive verb aspect to guide a pronoun switch more often than the presence of completed verb aspect. However, younger children (age 4), have difficulty using information from multiple two cues to guide a pronoun resolution. Older children appear to continuously update their initial choice of pronoun resolution—progressively updating their preferred resolution if given multiple cues. Young children (age 4) show large individual differences in their ability to integrate multiple cues. While they appear to use verb aspect as a cue in isolation, as a group they perform at

chance when asked to integrate multiple cues. This poor group performance may be mediated by large individual differences in cognitive flexibility at this age. A substantial minority of 4-year-old children do not update rules accurately in explicit measures of rule-switching flexibility. They often failed to switch rules, even after given instructions to change response behavior. Unlike flexible children, inflexible children appear to have difficulty integrating multiple cues to pronoun resolution. They do not revise their initial parsing (determined via the presence of a topic switch) when new information (e.g. verb aspect) suggests the need for revision.

## GENERAL DISCUSSION

Our results yielded interpretable data on three probabilistic cues important for the resolution of ambiguous pronouns—verb semantics and topic switches—from preschool age children. Notably, there has previously been conflicting work on when, and how, children can use cues to reliably guide revision of a pronoun referent. While limited evidence suggests that children can use some aspects of verb semantics to guide ambiguity resolution (Pyykkönen, 2009) to the authors' knowledge no work has explored whether and when children can use temporal cues suggested by verb aspects. Some evidence (e.g. Song & Fisher, 2005) suggests young children are sensitive to ongoing topic as a guide to pronoun referent, but this evidence is equivocal. Further, there is emerging evidence that children find the integration of multiple discourse cues to be difficult above and beyond single cues (Clackson, Felser, & Clahsen, 2011).

Our studies suggest that, while the youngest children (age 3) may struggle with these cues, older preschool children can and do integrate both verb aspect (Experiments 1 and 2) and topic switches (Experiment 4b) as salient discourse cues. Emerging evidence suggests that cognitive flexibility may play a role in how salient and available certain cues are across multiple

sentences. Little is known, however, about how cognitive flexibility relates to young children's language development (Deák, 2003; Jacques & Zelazo, 2005). We found that one type of flexible cognition—measured by accuracy on a task-switch paradigm—but not other types, such as inhibition or general processing speed—predicted an adult-like ability to revise an initial parsing in light of two cues presented within a discourse context.

These results were obtained from modified versions of cognitive flexibility paradigms used with adults and older children. This is important because current theories of the role of cognitive flexibility in language typically do not specify what types of cognitive flexibility may be important for language processing, or include measures of such flexibility in their developmental studies. While some recent literature suggests this to be a valid approach—as cognitive flexibility can be thought of as a unitary construct in childhood (Wiebe et. al, 2011)-- other research suggests at least three important subcomponents of what we traditionally think of as flexibility—switching, memory updating and cognitive control (Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Wu, Chan, Leung, Liu, Leung, & Ng, 2011).

Burgeoning evidence suggests that switching flexibility is uniquely important to multi-sentence discourse. Task-switch, for instance, mediates children's ability to ignore a phonologically similar but contextually inappropriate distractor in pragmatically odd discourse (i.e., when children are given a phonologically matching distractor, “Blow out the candle/candy”) (Creel & Tumlin, 2009).

In a linguistic version of a rule-switching task (Munakata, 2002b) children must flexibly attend either to a speaker's words themselves, or to emotional paralinguistic cues which may conflict (i.e. “my dog ran away from home” spoken in a happy tone of voice). While children at this age do not show perseverative errors on traditional rule-switching tasks (i.e. they can easily change from sorting a red bunny by its color to its shape), they continue to make asymmetric

catastrophic errors when making judgments on the paralinguage. This occurred despite the ability of children as young as 4 to use paralinguage in situations where cues were not conflicting. Morton & Munakata (2002a) propose that the specific difficulty and need for cognitive flexibility found in both this task and in our stories—in which multiple cues are present and at times can conflict—occur as a result of children’s comparatively weak memory representations. They suggest that with age, recurring connections become stronger in PFC, allowing children to more efficiently link the context and specific stimuli in working memory. As with the Expectancy Hypothesis, more efficient cues—those which are probabilistically more reliable-- help children more efficiently activate the relevant rule in working memory, which in turn helps to maintain activation of the relevant stimulus representation. Determining the impact of either a topic switch alone or the use of one form or another (or either paralinguage or syntax alone) may be sufficiently completed with only a weak representation of the knowledge involved, while integrating two sources of information requires stronger representations of the same information. Individual differences in linguistic behavior at this age are to be expected, given the differing strength of the knowledge involved in each (Munakata, 2001).

It is notable given this theory and the Expectancy Hypothesis, however, that we did not find errors only when cues of a graded nature were used. In Experiment 4a, we found that the youngest 3-year-old children made entirely unpredicted errors in ascribing gender (a 100% reliable cue when two characters differ in gender) disproportionately in cases where the last overtly named character differed in gender. If, as is implied by the Expectancy Hypothesis and by Morton & Munakata (2002a; 2002b), children learn a weighting of cues based upon their proportional reliability, then it is unclear why children may make these errors. Unfortunately, we did not have measures of switching (or other) flexibility in Experiment 4a. Future work in

the lab is looking directly at whether perseverative gender-assignment errors are correlated with catastrophic switching errors in young (aged 3- and 4- year old) children.

Conclusion: These results show that ability to use a previously untested probabilistic cue—English verb aspect—develops in early childhood. Ability to integrate information from this cue and from an additional, probabilistic cue (topic switch) was predicated on successful executive functioning in our youngest participants. These individual, as well as age-related, differences in task-switch in particular predicted adult-like choice of pronoun referent.

## ACKNOWLEDGMENTS

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# **Conclusion**

## **5.1 General Contributions**

The primary objective of this thesis was to contribute to our understanding of the development of cognitive flexibility. We mainly addressed this with experiments in children aged 3-7. Children in this age range show a transition from inflexible switching, marked by many errors, to flexible switching. Preschoolers are known for making perseverative errors following an overt and directly-cued (explicit) task-switch. They continue to sort by the initial rule in a two-rule sorting task even after a verbal change in rules (Zelazo, 1996). Multiple studies show that although children aged 5-6 years no longer make these perseverative errors on standardized tests like the DCCS, they continue to show high switch costs. These switch costs decline significantly in magnitude until early adolescence (Diamond & Kirkham, 2005). Much later, in the course of healthy aging, elderly adults show increased switch costs in some, but not all, task-switch paradigms (Wasylyshyn, Verhaeghen, & Sliwinski, 2011). These findings together suggest a U-shaped performance curve for task-switch costs across the lifespan, and this has been confirmed in at least one study (Cepeda, Kramer & Gonzalez de Sather, 2001).

The study of cognitive flexibility has been hampered by a lack of continuous measures usable with both preschoolers and flexible older children. Ceiling effects are seen in traditional card sort tests (such as the DCCS) in the majority of older children (Zelazo, Frye & Rapus, 1998). A minority of five year olds, however, continue to switch slowly and ineffectively like an average 3- year old child. One goal of this study was to develop measures of cognitive flexibility usable across these ages. Although cognitive flexibility is thought to be important in a wide range of activities--from constructing context-derived categories- e.g. “supplies for beach camping” (Barsalou, 1991) - to modifying objects for unusual uses (e.g. recognizing that a box can be a platform in addition to a container (Dietrich & Kanso, 2010)--we chose to



operationalize cognitive flexibility as a requirement to update (switch) representations in a modified task-switch paradigm. Latency costs on switch trials--so-called switch costs--are a robust parametric measure which differs within, as well as between, ages. More importantly, these individual differences in switch costs predict educational achievement (Bull & Scerif, 2001; van der Sluis, de Jong, & van der Leij, 2007). Thus, they are a tractable and predictive measure of cognitive flexibility.

The prefrontal cortex hypothesis (Miller & Cohen, 2001; Welsh, 2002; Diamond, 2002; Casey, Trottenham, Liston & Durston, 2005, Amso & Casey, 2006) suggests that late maturation of regions of PFC (especially inhibition) underlies the development of executive functions, and, by extension, cognitive flexibility. Inhibition (especially in Go/No-Go and Stop Signal tasks) has been found to involve right middle/inferior frontal gyrus, and these regions mature relatively late (Aron et. al, 2004; Simmonds, Pekar & Mostofsky, 2007). It is notable, however, that the largest gains in PFC maturation are actually seen later than the age of transition from perseverative to flexible behavior (Gogtay, Giedd, Lusk, Hayashi, Greenstein, Vaituzis, et. al, 2004). Perceptual-motor processing speed (processing speed) may moderate the impact of inhibition on task-switch (Huizinga & van der Molan, 2006) and can be differentiated from other executive functions using latent variable modeling (McAuley & White, 2010).

While executive functions-based accounts of flexibility are predominant in the developmental literature, emerging evidence from the adult literature (Logan & Bundesen, 2004; Schneider & Logan, 2005; Logan & Schneider, 2007) suggests it may be possible to explain the apparent behavioral disjunction in task-switch performance without the need to appeal to a parallel qualitative change in executive functions. Flexible switching may be as well or better explained by to children's ability to use cues to retrieve appropriate rules from working memory, especially under conflict conditions (Morton & Munakata, 2002a). Cue processing

differences predict switch costs in adult task-switch paradigms (Logan & Schneider, 2007). They have seldom been studied as possible explanation for children's task-switch errors. We presented a series of studies which tested whether executive functions (specifically inhibition and processing speed) and/or low-level association-activation differences (such as those in the Associational Activation Strength hypothesis and in cue-processing) predicted the development of task-switch flexibility.

Morton & Munakata (2002a) proposed the Associational Activation Strength hypothesis to explain children's performance in the DCCS. Rules that are less familiar are harder to activate in working memory (Munakata, 2001). Children (Towse, Lewis, & Knowles, 2007; Marcovitch, Boseovski & Knapp, 2007; 2010) and older adults (de Jong, 2001) both show deficits maintaining rules (goals) in working memory. Children who make perseverative errors in the DCCS also show weaker representations of these goals (rules), even when those rules are tested in no-conflict, non-switching tasks (Cepeda & Munakata, 2007; Blackwell, Cepeda & Munakata, 2009). Appropriate verbal cues help children to activate appropriate rules even when conflict in the stimulus itself does not provide conclusive evidence for one response pattern.

We hypothesized that young children's semantic cue-processing difficulties might extend as far as to the direct appropriate verbal cues used in the DCCS. Deák (2000, 2003) found efficiency differences in semantic cues to word meanings even when all cues were explicit descriptions of one specific feature of a multi-featured object. Progressively more abstract and indirect cues would elicit similar kinds of switch-costs in progressively older children, thus accounting for apparent "perseverative" errors still seen in older children in more complex card-sorting tasks--without a need to appeal to executive functions or the capacity to represent more complex rule-contingencies (c.f. Zelazo, 2006).

Cue-processing accounts predict that rules which give less direct evidence for S-R rules should hinder performance. However, one possible exception to this concerns transition cues. Transition cues do not directly cue S-R rules, but instead cue switch contingencies (e.g. a circle means “switch rules” but does not directly indicate which is the new rule). Rule cues, by contrast, directly cue appropriate low-level S-R rules. Thus, the two cues activate different kinds of memory representations by which children can select their current response, but neither are arbitrary. We predicted that children would not show the typical cue-related decrements in performance with transition cues in switch trials. Instead, they might provide a selective benefit to children in the hardest (incongruent) switching conditions. Jamadar, Michie & Karayandis, 2010, suggest children have may difficulty relating current response options to prior actions and may, consequently, over-rely on cues which signal such switch contingencies (though they did not test this prediction with children). Similar effects are seen in the aging literature (Rendell, McDaniel, Forbes & Einstein, 2007).

This thesis presents a series of studies which systematically varied the semantic information content of cues in a novel task-switch paradigm. We find evidence that children have difficulty using cues to retrieve appropriate memory activations. For younger children, this may extend even to the semantically direct rule cues used in, e.g., the DCCS. For older children, this manifests as a selective benefit in incongruent switch trials when transition cues are used.

We also used separate 1D matching tests which replicated the perceptual-motor and cue requirements from the task-switch test, without having switch trials or conflict stimuli. Cue-processing difficulties in the 1D matching test (which does not require switching and has no incongruent stimuli), further disconfirms a (pure) inhibition-based account, and may tie in to accounts of working memory access in children’s flexibility.

## **5.2 Summary of Findings**

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

We hypothesized that the youngest children (aged 3 and 4 years) would show cue-processing difficulties even with direct cues such as those used in the DCCS. These cue-processing difficulties might explain perseverative switch errors without the need to appeal to dramatic age-related changes in executive functions. Children, may, in effect, recognize a need to switch (i.e. not truly be perseverative), but not be able to use cues to guide their behavior appropriately. There is some precedence for this in the literature. Perner & Lang (2002) reported that children produced the standard pattern of perseveration in only one of four switching tests, and only when it was first (when children presumably had the least semantic experience with the cue types). It is difficult to distinguish this hypothesis from executive functions-based theories using standard card-sorting tasks. However, we directly tested this hypothesis by carefully controlling the demands of cue-processing—in both switch trials and stay trials in a task-switch tests—and in low-level matching tests divorced from switch demands.

Children were tested in a computerized task-switch test in which most trials were preceded by an audio-visual cue that specified either a demand to switch sorting rules, or a demand to continue using the same sorting rule. Interspersed control trials were identical to the other trials, but used no cue. We hypothesized that because cues no longer uniquely specified switching, we should see attenuated differences between switch and stay trials (at least in incongruent cases).

As predicted, 3- and 4-year olds who made errors made as many errors on cued “stay” trials as on cued “switch” trials, and were significantly more accurate in un-cued stay trials. Notably, very few of these children showed a classic perseverative pattern--continuing to sort by the same rule for the entirety of the block. The majority made at least one cue-directed switch throughout the task. Thus, they did not appear to become “stuck” on well-rehearsed

associations between the initially relevant perceptual features and motor responses. This casts initial doubt on the predictive value of inhibition.

We also hypothesized that children would show memory activation differences even in cue-based matching tests which had no stimulus uncertainty (incongruity) or switch trials. The results showed that RT differences to sort animals and colors were the best predictors of task-switch accuracy. This account fits evidence from studies of adults' task-switch, which suggest that "true" task-switch costs are small or non-existent relative to simple cue-processing effects (Arrington, et. al 2007). Additional variance was predicted by simple measures of processing speed, but no additional variance was predicted by inhibition. This fits with other evidence that there is a modest role for processing speed in predicting task-switch, above and beyond working memory differences (Cepeda, Kramer & Gonzalez de Sather, 2001).

Two outstanding concerns remained after Experiment 2a with 3- and 4-year-olds. First, it was unclear how differences in cue-processing would predict task-switch in children who have mastered the semantic demands of a directly cued task-switch task. Can cue-processing effects explain the transition to flexible behavior, or are they only important when a task is at the cusp of a child's ability? Second, the 1D matching test shows more construct overlap with the task-switch test than do the other inhibition or processing speed tests. This similarity, rather than cue-processing, may simply account for previous correlation between 1D matching and switching. To address this (and to make sure that our 1D-matching test measured true cue-processing, not just another measure of processing speed), we created a new processing speed measure which used the same stimuli as the 1D matching test, but was uncued.

We replicated the design of Experiment 2a with a group of older children. Switch costs in older children were still predicted by speed in the cued unidimensional matching test. Thus,

as in adults who make few errors (Arrington, et. al, 2007), cue-processing predicted switching even for children with low overall error rates.

### **5.2.2 Children’s Task-Switching: A Role for Cue Integration**

Chevalier & Blaye (2009) suggested that children’s poor performance in some measures of cognitive flexibility (e.g., Shape School and the Advanced DCCS, Espy, 1997; Smidts, Jacobs & Anderson, 2004; Zelazo, 2006) was because of the indirect nature of the cue—cues shared no semantic overlap with the associated rule. When they instead used semantically related cues in the Advanced DCCS (a rainbow for “color game” instead of a black border) children showed marked improvement.

Cues which are not arbitrary, but which do not cue rules may also be beneficial for children. Jamadar, Michie & Karayandis (2010) suggest that children may particularly fail to activate (or neglect) switch goals. Transition cues, then, provide direct environmental support for when a switch is appropriate. Thus, children should selectively benefit on switch trials. This is an important prediction, because, *a priori*, transition cues might be expected to hinder children in all cases, and provide an additive \*decrement\* in switch trials. Children must remember what response they made on the previous trial, for instance, which they do not have to do with rule trials. Transition cues provide conclusive evidence for the need for a switch contingency, which may instead help children to activate what would otherwise be a sub-threshold contingency within working memory.

We tested whether cue processing, EFs, or both, predicted 4- to 6-year-old children’s switch costs in computerized task-switch tests and 1D matching tests (which had no switch or incongruent trials). We systematically manipulated the semantic content of two verbal cues. Rule cues indicated the appropriate sorting rule (i.e., color or shape). Transition cues (i.e. the

same vs. the other game) indicated whether a shift in response set was appropriate. Cues indicated different kinds of memory representations by which children can select their current response. While children showed overall slower response latencies with transition cues, such cues were selectively helpful in the most difficult switching conditions: incongruent switch trials. Notably, no other common executive functions-based hypothesis predicts this facilitation. This provides even stronger evidence that cue-processing accounts can explain children's task-switch behavior: Cuing some, but not other, contingencies directly improved performance, while inhibitory demands did not change between with transition vs. rule cued-task-switch tests.

As in Chapter 2, children also completed no-conflict, non-switch tests in which transition or rule cues preceded unidimensional matching trials. Crucially, 1D matching trials in Chapter 3 differed in whether they used transition or rule cues. We predicted that, although no cue whatsoever was needed for this simple task, cue effects would still be present. Again, no inhibitory demands are present in these trials. Children showed cue-driven differences in speed to match animals and colors. These differences predicted switch costs. Most variance was predicted by children's time to match with rule cues. Unique additional variance was predicted by their speed to match with transition cues.

Again, additional variance was predicted by an unrelated measure of processing speed. As in Chapter 2, stimulus factors were controlled between the 1D matching test, processing speed and the task-switch test. Measures of inhibition and processing speed used the same stimuli as the task-switch test. Additionally, confirmatory factor analysis (cognitive flexibilityA) was used to differentiate processing speed, inhibition and cue effects. Thus, factors of inhibition, perceptual-motor processing speed and cue-processing were separable, and the predictive power of low-level cue-processing cannot be dismissed as merely an effect of construct variance.

Children improve in task-switch with repeated exposure (Cartwright, 2002; Karbach & Kray, 2009). We found that individual differences in 1D matching predicted the largest proportion of variance in children's improvement in switch costs one week later. This adds an important theoretical extension to accounts of cue-processing. Evidence from Perner & Lang suggested that cue effects might be large when children have relatively little exposure to tasks (e.g. when the DCCS is presented first). However, children might also relatively quickly learn the appropriate cue-rule contingencies. Thus, cue processing might explain children's initial task-switch performance—but not the educationally relevant, stable, and individual differences in task-switch that persist even with repeated exposure. We found instead that cue-processing drives children's performance gains, at least as they continue to improve at the test. (However, it did not predict performance when children did not clearly show improvement).

### **5.2.3 Children's Resolution of Inter-Sentential Pronouns: A Role for Cognitive Flexibility**

Keeping track of a pronoun's referent across multiple sentences requires cue-based updating of understanding representations of events and relations, during the course of discourse processing. Cragg & Nation (2010) suggested that discourse comprehension is a critical real-world test case for the role of cognitive flexibility in language. Cognitive flexibility might underpin children's mastery of probabilistic discourse cues. Alternately, cognitive flexibility might be required when children must update linguistic information given multiple cues. We tested if and how cognitive flexibility constrains children's interpretations of cues which bias some kinds of representations (and thus, some potential actors over others). We tested the role of cognitive flexibility with cues in isolation, when children are just developing sensitivity, and when multiple cues are used together. We used cues that only probabilistically suggest (not require) contextual updating of representations. These cues included verb aspect, topic switch and last-mention.



In Experiment 4a, we confirmed that children use verb aspect as a probabilistic cue to guide representations—and thus appropriate referents—for action (Matlock, 2010). In Experiment 4a, 3- to 5-year olds heard brief stories in which a final ambiguous third-person pronoun could refer to one of two same-gender characters. Two variables were manipulated across vignettes: last character mentioned, and verb aspect (modality: Progressive/Completed). Young children showed developing sensitivity to verb aspect. The youngest children also showed a tendency to overuse information from last-mention, even when new and stronger cues should suggest a revision.

In Experiment 4b, 4- to 6-year-old children completed an expanded pronoun test (manipulating Aspect, Topic and Last mention), a timed task-switch test, and additional tests of executive functions and receptive language. Here, we could test directly whether cognitive flexibility constrained children's use of verb aspect or topic switch—which in and of themselves cue representation switches. We could also test whether cognitive flexibility constrains children's ability to use two of these cues together to follow an evolving discourse over multiple sentences. As in Experiment 4a, children ages 4-6 used verb aspect to guide their choice of referent. Cognitive flexibility constrained 4-year-old children's ability to integrate multiple discourse cues. Task-switch accuracy predicted children's reference choices, with flexible children choosing more like adults. Thus, cognitive flexibility appears to constrain the integration of multiple, ongoing cues (though not children's mastery of isolated, albeit probabilistic, cues) during real-world discourse.

### **5.3 Limitations and Context**

This thesis controlled for common limitations of developmental studies in cognitive science. We made effort, for instance, to control for test-specific construct variance. We made some effort to mitigate the potential effect of children's educational and SES background

(especially in Chapter 3 and Chapter 4) by recruiting both from suburban schools and, whenever possible, also from schools in lower SES areas. However, we did not recruit a truly representative regional sample of children, and we did not investigate demographic and educational factors as predictors of cognitive flexibility. This is an important limitation of our study, as children from extremely low SES (i.e. from families making well under the poverty line) show qualitative differences in executive functions relative to more affluent children (Fernald, 2008). These differences might result in a different task-switch performance pattern for some subgroups of “typically” developing children. Also, receptive vocabulary (PPVT) scores were high in some studies (most notably Chapter Two, Experiment 2). Thus, results might better generalize to slightly older children.

There were other, quantitative, differences between our results and other published studies of child task-switch. We did not find asymmetric switch costs, which are increased switch costs when switching to an easier rule (e.g., from naming colored ink to reading color words in the Stroop task). Asymmetric switch costs have been reported in adults (Allport & Wylie, 2000; Yeung & Monsell, 2003a) and recently with children (Ellefsen, Shapiro & Chater, 2006). It is unclear what expectations cue-processing and/or memory activation accounts (such as that of Morton & Munakata, 2002a) make regarding the presence of asymmetric switch costs. On the one hand, we might expect to see asymmetric switch costs because we did find rule differences in our 1D-matching tasks. Children typically were slower to match animals than colors. This might suggest that it would be harder to switch to sorting colors in the task-switch test because the animal rule was the “harder” rule in isolation. However, rule asymmetries in our 1D matching tests were relatively small compared to the baseline rule differences in typical asymmetric switch paradigms. There is much less difference in rule strength between sorting animals vs. sorting colors, for instance, than between the two rules in the Stroop test. Several

labs (Monsell, Yeung, & Azuma, 2000; Yeung & Monsell, 2003b; Hubner, Kluwe, Luna-Rodriguez, & Peters, 2004) have decreased or even reversed switch asymmetries by equalizing the degree of difficulty between the tasks, something which is similar already in our studies. We might expect to find asymmetric switch costs if we used task-switch tests with two highly unequal low-level S-R rules or non-bivalent stimuli. It would be an interesting application of this research to address how cue-processing predicts individual differences in children's asymmetric switch costs—that is, when they are present.

Our results fit conceptually with one finding from preschool goal neglect. Older children (aged 4 and 5) who still make perseverative errors are less likely to do so when they receive reminders before each trial (Marcovitch, Boseovski & Knapp, 2007; 2010). Marcovitch et. al. also found that children were more likely to perseverate when there were many congruent trials (trials which were sorted the same way under both sorting rules). They proposed that the preponderance of congruent trials tacitly encouraged children not to maintain goals in working memory. Thus, children might be showing a different qualitative pattern of performance in tasks with congruent trials than tasks with only incongruent trials. We used far fewer congruent trials than incongruent trials, so it is unlikely that children were showing cue-processing difficulties (e.g., in Chapter 2) simply because they were lulled into ignoring appropriate rules in our studies. Also, our results generalized to flexible older children, who were not as susceptible to this artificial task-specific limitation. However, anytime congruent as well as incongruent trials are used, it is possible that children show more of this “encouraged” goal neglect than in measures (like the DCCS) that use only incongruent trials. Again, this is something we could manipulate (by, for instance, changing the proportion of congruent trials) in future studies.

A final important limitation of our study concerns our characterization of working memory. We addressed the facilitative role of cues in retrieving rules from working memory,

and used control measures of WMS. We did not separately test a factor of working memory manipulation. This was partly because previous latent variable studies in children have found that separating working memory into distinct memory manipulation and memory capacity adds little predictive values to subdivisions of neuropsychological tasks (McAuley & White, 2010). It was also because the current literature did not provide a theory-driven means of designing tasks to measure memory manipulation uniquely, and the specificity of existing measures was in doubt. Fruitful future work could further address the behavioral manifestations of working memory manipulation with new child-friendly tests.

Verbal transition cues help children to retrieve the appropriate associations (rules, or goals) from working memory, especially with stimulus conflict. Older adults, too, rely on this facilitative effect (De Jong, 2001). However, young children's performance is impaired when cue-processing demands are increased in the task-switch test (by the introduction of stay cues). Importantly, it is not simply the presence of more cues in total that made our cued-stay trials difficult for children, but the fact that these cues signaled different possible responses, and children had to actively process the semantic content of each cue to respond appropriately. Kirkham, Creuss & Diamond (2003) found that repeating (unique) cue words in post-switch trials decreased the percentage of 3-year-olds who perseverated.

An account of developing flexibility based largely upon the semantic role of cues makes a further prediction that specific training with the instructional format (or "game") of the DCCS may cause children to improve. Perner & Lang (2002) provides a possible proof of concept of such an approach. They reported that children produced the standard pattern of perseveration only in the DCCS, and specifically only when the DCCS was the first of several switching tests administered. We suggest that children fail at the DCCS in this instance because it has the most pragmatically odd discourse structure. Completing other tests first mitigates this

by providing practice with discourse cues. We found in Chapter Three that baseline differences in cue integration predicted switch costs one week later. We have not, yet, introduced any formal training or interventions for task-switch, however such studies could provide future directions.

In Chapter Four, we provide evidence that learning the demands of discourse—specifically, integrating multiple discourse cues may depend upon cognitive flexibility. Another apparent limitation in preschool children’s representational flexibility-- appearance-reality errors--might also reflect difficulty integrating demands in a structured discourse format (Deák, 2006). Preschoolers often appear functionally fixated on one item description. For instance, they initially describe that an apple-shaped eraser looks like an eraser. However, many appear to become “stuck” on this description. They also endorse the idea that the eraser “really is” an apple. Previous work (Deák & Enright, 2006) suggests children may make these errors because they have difficulty mastering the odd discourse-pragmatic demands of the task-which consists of a series of successive forced-choice questions. Whenever children are asked several successive questions about a topic, with the same two answer-choices, many 3- and 4- year-olds repeat their choices, even when repeating their previous (yes/no) answer means affirming pragmatically odd responses. (I.e. they will affirm that dogs fly when they would not they otherwise do so) (Deák & Enright, 2006). Although the studies in Chapter Four used real-world discourse cues (and were thus more “naturalistic” in this regard than many studies of cognitive flexibility), there is still more to be done to design paradigms which more closely mimic the demands of everyday speech-cue processing that are imposed on young children. However, cognitive flexibility might constrain how children integrate information from complementary linguistic sources (e.g. gesture, prosody or emotional paralanguage) to alleviate ambiguity.

Some evidence (e.g. Morton & Munakata, 2002b) suggests these differences are also constrained by cognitive flexibility and could be further tested.

While there is important additional work to be done, this thesis has provided an initial categorization of children's developing cognitive flexibility in terms of cue processing differences. Our account relies upon evidence that processing the semantic content from a cue imposes a cost which can differ by cue, but is never entirely eliminated. Young children may have difficulty integrating even direct semantic information from cues to guide flexibility. Older children have mastered the pragmatic demands of explicit cues; however their switch costs are facilitated by direct cues which specifically indicate switch contingencies. Neither of these effects are predicted by classic executive functions-based accounts of developing flexibility. Our cue manipulations do not change the requirement to inhibit previous rules on switch—but not stay—trials, and inhibitory demands do not change between transition and rule cue conditions. A pure working memory maintenance account, in which children cannot maintain appropriate memory rules, would predict that introducing stay cues should facilitate performance. Instead, we see it imposes a cost for young children. Further, transition cues, which have a higher memory load, would be expected to hinder performance. Instead, they facilitate performance. While we did find a modest role for processing speed in developing cognitive flexibility, individual differences in cue processing uniformly provided the best prediction of both traditional task-switching differences and children's ability to integrate multiple cues in a “real-world” test of flexibility: keeping track of a pronoun's referent.

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