CHILD DEVELOPMENT PERSPECTIVES

The Importance of Executive Function in Early Science Education

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ABSTRACT—*This article argues that executive function (EF) capacity plays a critical role in preschoolers' ability to test and revise hypotheses and, furthermore, that young children can engage in the process of testing hypotheses before they are able to revise or confirm them. Research supports the view that this ability depends on their EF capacity to represent, and reflect on, hierarchical rules relating actions to predicted or observed outcomes (i.e., differences between what they predicted and what they observed). The article concludes by discussing the ramifications of this perspective for early science education.*

KEYWORDS—*early science education; preschool; executive function; theory of mind; scientific reasoning; hypothesis testing; hypothesis revision; predictions*

On the basis of our experience with Foundations of Science Literacy, a comprehensive professional development program designed to help preschool teachers support young children's science development, we believe that early science education should include helping preschoolers develop basic scientific "habits of mind" or reasoning skills. Wilkening and Sodian (2005) define scientific reasoning as "the ability to generate, test, and revise theories and hypotheses, and to reflect on this process" (p. 137). Although the full complexities of explicit theory formation, experimental design, and evidence evaluation are beyond the grasp of preschoolers, basic forms of hypothesis testing and revision are not. By "hypothesis testing," we mean the ability to state predictions, test those predictions by manipulating objects, and accurately observe the outcome. By "hypothesis revision," we mean the ability to use hypothesis testing as a basis for confirming or revising predictions. We are particularly concerned with the ability of preschoolers to test hypotheses based on prior knowledge, which they must suppress in order for hypothesis revision to occur. Although we do not address the full range of preschoolers' abilities to evaluate patterns of evidence (see Koerber, Sodian, Thoermer, & Nett, 2005), we believe that our focus helps lay the foundation for science learning in school.

We argue that preschoolers' ability to test and revise hypotheses depends critically on their executive function (EF) capacity. Extensive research has established that EF is important to school readiness and school achievement in other domains (Blair & Razza, 2007; Espy et al., 2004; Gathercole & Alloway, 2008; McClelland et al., 2007; Müller, Liebermann, Frye, & Zelazo, 2008; Welsh, Nix, Blair, Bierman, & Nelson, 2010), but less research has directly targeted the role of EF in science learning at the preschool level. After situating scientific reasoning in a cognitive framework, we bring together a range of evidence to show that young children can engage in the process of testing hypotheses before they are able to revise or confirm them. Furthermore, we argue that preschoolers' ability to revise or confirm hypotheses depends on their EF capacity to represent, and reflect on, hierarchical rules relating actions to predicted or observed outcomes (i.e., differences between what they predicted and what they observed). We conclude by discussing the ramifications of our perspective for early science education.

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PROCESSING MODES, SCIENTIFIC REASONING, AND EF

An extensive body of research shows that humans reason using multiple modes, often dichotomized in terms of "experiential"

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versus "analytic" processing (Amsel et al., 2008; Carruthers, Stich, & Siegal, 2002; Evans, 2008; Kelso & Engstrom, 2006; Keren & Schul, 2009; Klaczynski & Cottrell, 2004; Kuhn, Katz, & Dean, 2004; Markovits & Barrouillet, 2004; Stanovich, 1999). Experiential processing is our default, heuristic mode: it is fast, automatic, minimally conscious, memory-based, and always engaged. In contrast, analytic processing is deliberate, controlled, conscious, and rule-based.

The interaction between experiential and analytic processing provides a useful framework for exploring scientific reasoning (Amsel et al., 2008; Hogan & Maglienti, 2001). Whereas scientific reasoning involves competence in both processing modes (Amsel et al., 2008; Evans, 2008; Klaczynski, 2004), the ability to think analytically is especially important when a response generated through analytic processing conflicts with one based on an experiential bias (Stanovich, 1999). From an evolutionary perspective, the very biases of heuristic processing that made it adaptive also mask the underlying properties of the physical and natural world (Barkow, Cosmides, & Tooby, 1992; Pinker, 1997). The scientific method, including hypothesis testing and revision, is an artifact of analytic processing that we invented specifically to circumvent these biases.

Extensive research on conceptual development (Carey, 1985; Keil, 1989) and teaching for conceptual change (McDermott, 1984; Posner, Strike, Hewson, & Gertzog, 1982; Talsma, 2006) has shown that children naturally form intuitive theories based on experiential thinking, and furthermore, that stubborn misconceptions embedded in these theories persist into adulthood. In our own research, for example, when we ask preschool children to predict whether different sized objects will float or sink, many think that *smaller* objects are more likely to sink than larger ones. These children explain their predictions in terms of the "strength" of the objects, which suggests that they are responding heuristically on the basis of an intuitive biological theory (Smith, Carey, & Wiser, 1985). Older children and adults respond more analytically, consciously basing their predictions about floating and sinking on attributes such as the objects' weight or their density relative to the medium in which they are placed. How do children and adults advance beyond their intuitive ideas about floating and sinking?

One answer is that as we gain executive control over our thinking, we learn how to inhibit prepotent, experiential responses and focus our attention on analyzing a problem (Amsel et al., 2008; Zimmerman, 2007). Although EF is traditionally associated with inhibition, working memory, and shifting task set (Davidson, Amso, Cruess Anderson, & Diamond, 2006), researchers have recently treated EF capacity as the ability to represent and process *hierarchical* rule systems, where a rule relates a stimulus to a response, a situation to an action, or a means to an end (Zelazo, Müller, Frye, & Marcovitch, 2003). Using EF, we hold rules in working memory, inhibit some rules and activate others on the basis of our goals and context, and reflect on the consequences of our choices (Zelazo, Carlson, & Kesek, 2008). We assume that children's ability to test a hypothesis requires them to maintain a rule in mind relating an action to an outcome. In order to revise their hypothesis, children must have even more EF capacity—to reflect on the difference between what happened (i.e., a rule relating an action to the observed outcome) and what they *thought* would happen (a rule relating an action to the predicted outcome). By reflecting on the difference between these rules, coordinated in a hierarchy according to the epistemological status of the outcome (Kuhn, 2000), they can inhibit their previous prediction.

THE DEVELOPMENT OF HYPOTHESIS TESTING AND REVISION

Zelazo and his colleagues have recently explicated the development of EF capacity in the levels of consciousness (LOC) model. According to this model, young children's capacity to consciously control their thought increases by discrete levels in a developmental trajectory as they use rules of increasing complexity (Zelazo, 1999, 2004; Zelazo, Gao, & Todd, 2006; Zelazo & Jacques, 1996). Zelazo has furthermore argued that reflection is instrumental in building the capacity to consider hierarchical rules of increasing complexity (Marcovitch & Zelazo, 2009a, 2009b; Zelazo et al., 2003; but see Cooper, 2009). Between 3 and 4 years of age, children are typically at the level of reflective consciousness 1 (RC1): They can use a pair of *univalent* rules—that is, rules making a distinction within the same dimension (Zelazo et al., 2006). For example, on the Dimensional Change Card Sort (DCCS; Jacques, Zelazo, Kirkham, & Semcesen, 1999; Zelazo, 2006), in which children are asked to sort sets of bidimensional pictures (crosses between color [blue and red] and shape [a star and a truck]), 3-year-olds can sort the pictures according to one dimension (such as color). This ability requires the capacity to reflect on one rule ("blue things go here") in relation to a second rule ("red things go there"). These children cannot, however, switch dimensions in sorting the same set of cards (switching from sorting by color to sorting by shape), indicating that they cannot integrate incompatible pairs of rules into one system.

We hypothesize that these limitations manifest themselves differently depending on whether the relevant rules are arbitrary or nonarbitrary. In tasks involving arbitrary pairs of rules, such as the DCCS, children fail to switch from one pair of rules (color) to the other pair of rules (shape). In the case of scientific inquiry involving nonarbitrary rules, such as their naïve belief underlying a prediction versus their observation of the actual event "in the world," children can switch from rules about prediction (such as small → sink) to rules about observation (such as heavy → sink), but they make no attempt to reconcile any inconsistencies between them. In fact, research on the representational change task (Gopnik & Astington, 1988; Zelazo & Boseovski, 2001) shows that 3-year-olds have difficulty reconciling an initial belief with a subsequent observation that falsifies it. The representational change task is one of several paradigms (including false belief and appearance–reality) that researchers have used for more than two decades to study children's theory of mind (Flavell, 1986; Gopnik & Astington, 1988; Wellman, Cross, & Watson, 2001; Wimmer & Perner, 1983). In one version of the task, for example, children are presented with a familiar container (a candy box), shown that it contains something unexpected (string), and asked, "What did you think was in the box before I opened it?" Three-year-olds answer, "string." That is, even though these children can "switch" to a new belief about what is in the box, they still cannot integrate the information in the two contexts.

One implication from research involving the DCCS and representational change task is that 3-year-olds may be able to make an accurate observation about a particular event without being able to reflect on the difference between the observation and their initial, incorrect prediction. In our research using the Preschool Assessment of Science (PAS; Gropen, Clark-Chiarelli, & Hoisington, 2010), we explore preschool children's ability to engage in hypothesis testing and revision by having them make a prediction, test their prediction, and then (potentially) revise their prediction using a new set of materials. Figure 1 illustrates a simplified version of a PAS prediction cycle, involving a bowl of blue-colored water and three yellow cubes—a small wooden cube, a medium steel cube, and a large wooden cube. Children are told that when these three blocks are placed in the water, two of them will float and one will sink. In this cycle, children (a) handle the cubes and predict which cube will sink, (b) perform and observe the action and indicate which cube actually sank, (c) reflect on any discrepancy between their prediction and their observation, and (d) confirm or revise their prediction with a new set of yellow objects—a small wooden cylinder, a medium steel cylinder, and a large wooden cylinder. As we noted in the previous section, in this situation children often predict that the smallest cube will sink. Furthermore, despite making an initially incorrect prediction in Step 1, many children are capable of making an accurate observation in Step 2 (Gropen, Clark-Chiarelli, Ehrlich, & Thieu, 2011).

An interesting question is whether children displaying this pattern of responses (hypothesis testing) will also engage in hypothesis revision, leading to a revised set of predictions involving the cylinders (Figure 1, Step 4). Our research indicates that children who lack EF capacity to integrate incompatible rules into one system (as measured by their failure to switch dimensions on the DCCS) are significantly less likely to revise their incorrect predictions on the PAS (Clark-Chiarelli & Gropen, 2010; Gropen et al., 2011). This research supports the view that young children can engage in the process of testing hypotheses before they have the EF capacity to revise or confirm them.

Not until children are at the level of reflective consciousness 2 (RC2), around the age of 4, can they revise or confirm hypotheses through hypothesis testing. At this level of consciousness, children gain the capacity to integrate *incompatible pairs of rules into a single system*; children can now switch dimensions on the DCCS from sorting based on color to sorting based on shape (Zelazo et al., 2006), indicating that they can coordinate EF subfunctions of working memory and inhibition to achieve a particular goal in the face of competing rules. We hypothesize that children at RC2 should be able to reflect on differences between their initial prediction and the actual outcome, and on that basis revise their predictions. Several lines of evidence support the claim that changes in EF capacity enable hypothesis revision.

One line of evidence suggests that when given the opportunity to reflect, preschoolers can revise their originally mistaken scientific beliefs. For example, in their study of predictions involving the relation of object volume and sinking speed, (Kloos and Somerville 2001; also see Kloos & Van Ordern, 2005) found that more children could revise their incorrect predictions if they were given the chance to reflect on their mistaken beliefs than if they were not. Interestingly, the procedure for reflection was a structured demonstration tailored to children's beliefs and involved the "juxtaposition between the mistaken belief and its contradiction" (Kloos & Van Ordern, 2005, p. 202), making it similar to the reflection procedure in the PAS (Figure 1, Step 3).

Second, extensive research on a variety of theory-of-mind tasks demonstrates that children undergo a genuine conceptual change around the age of 4: They gain the capacity to think about beliefs as distinct from reality (see the meta-analysis of 178 studies in Liu, Wellman, Tardif, & Sabbagh, 2008; Wellman et al., 2001). According to Kuhn and Pearsall (2000), the capacity to think about beliefs as distinct from reality is a "milestone of foundational status in the development of scientific thinking" (p. 119); in particular, it underlies the core scientific ability to use evidence to falsify hypotheses. The relation of theory of mind to scientific hypothesis revision is particularly transparent in the case of the representational change task. Children around the age of 4 become able to reconcile an initial belief with a subsequent observation that falsifies it (Gopnik & Astington, 1988).

We argue that changes in EF capacity underlie both these particular changes in theory of mind and hypothesis revision. The finding that individual children gain competence in a number of theory-of-mind tasks at the same time (Astington & Gopnik, 1991) is consistent with the idea that some underlying developmental change is driving the change in performance. Following Zelazo and his colleagues (Zelazo et al., 2006; Zelazo et al., 2008), we suggest that this underlying developmental change is growth in EF capacity and, in particular, the child's capacity at RC2 to integrate alternative representations of reality in a hierarchical rule system. This conclusion also finds support in the findings that both EF and thinking about mental states activate the prefrontal cortex, that deficits in both are implicated in autism, and that individual differences in EF not only are correlated with concurrent performance on false belief tasks but also predict later developing performance on these tasks (Zelazo et al., 2008).

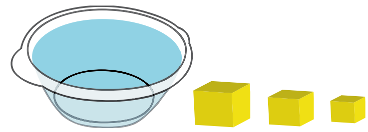
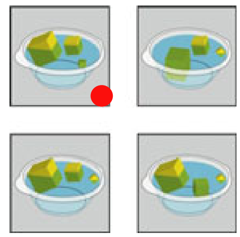
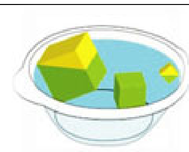
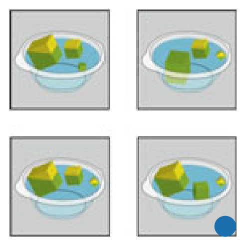
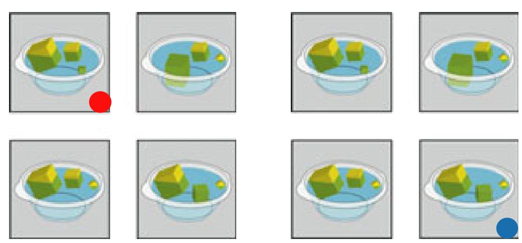
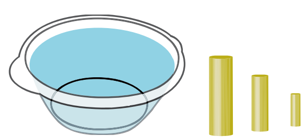
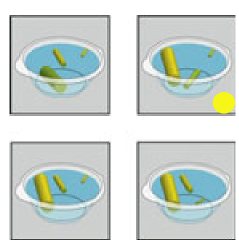
1) Prediction:	
"If we put these three blocks in the water, two of them will float and one of them will sink. Which one will sink?"	
"Ok. Take a look at each of these pictures… Point to the picture that shows which block will sink... All right, help me put a **red** sticker on that picture."	
2) Observation:	
"Let's see what happens. Put all the blocks in the water… OK, now watch me put all the blocks in the water."	
"OK. Take a look at each of these pictures… Point to the picture that shows what happened... All right, help me put a **blue** sticker on that picture."	
3) Reflection:	
"Is that what you thought would happen?... That's right… That's not what you thought would happen… (pull out both sets of pictures)."	
4) Confirmation / Revision:	
"If we put these three cylinders in the water, two of them would float and one of them would sink. Which one would sink?"	
"Ok. Take a look at each of these pictures… Point to the picture that shows which cylinder would sink... All right, help me put a **yellow** sticker on that picture."	

Figure 1. Prediction task from Preschool Assessment of Science.

IMPLICATIONS FOR EARLY SCIENCE EDUCATION

We have argued that EF capacity plays a critical role in preschoolers' ability to test and revise hypotheses, and furthermore, that young children can test hypotheses before they have the EF capacity to revise or confirm them. In this final section, we explore the ramifications of this argument for early science education.

Although EF capacity is age related and based on the maturation of prefrontal cortex (Zelazo et al., 2003; Zelazo et al., 2008), preschoolers can benefit from pedagogy designed to help them *apply* their EF capacity to learning in specific science domains. Learners of all ages need help applying their EF capacity in order to learn new knowledge and skills. Children, in particular, may "revert" to a lower level of executive control, depending on their lack of familiarity with particular science content. In these cases, children's limited attention may be taxed by demands on working memory and they may have little capacity left over for inhibitory control or for coordinating these processes (see Espy & Bull, 2005).

Furthermore, evidence suggests that it is possible to strengthen EF capacity through training (Diamond, Barnett, Thomas, & Munro, 2007; Dowsett & Livesey, 2000; Kloo & Perner, 2003; Landry, Miller-Loncar, Smith, & Swank, 2002; Thorell, Lindqvist, Nutley, Bohlin, & Klingberg, 2009). This has important ramifications for the approach to early science education, for it belies a common argument: that it is pointless to challenge preschoolers' misconceptions about science on the grounds that adults have difficulty inhibiting some of the same misconceptions. On the contrary, the potential for strengthening EF capacity raises the possibility that learners can develop into critical thinkers—that is, those individuals (including scientists) who have more cognitive control than others (Klaczynski & Cottrell, 2004; Stanovich, 1999; Stanovich & West, 2000). Ultimately, the ability to think scientifically depends on forming habits of mind that promote cognitive control in the context of scientific inquiry.

We believe that there is no better time to start than in preschool. The cycle of hypothesis testing and revision, as we defined it here, is pedagogically relevant. It presents teachers with "actionable" information about what children know and tells them how to use that information to expand children's scientific understanding. We have three specific recommendations for improving early science education, informed by the research we reviewed above and warranted by our extensive experience in Foundations of Science Literacy.

First, because preschool is a period of rapid growth in children's ability to test and revise hypotheses, preschoolers can benefit from programs that explore these capacities. In particular, science learning during preschool can take place at various LOC, each involving the application and strengthening of EF capacity. At the level of RC1, teachers might help children not only apply their EF capacity by helping them make focused predictions and accurate observations in a new science domain but also engage in a process of reflection that is truly functional in terms of building EF capacity. At the level of RC2, the question is not only whether preschoolers can learn to use their EF capacity to reject misconceptions but also whether they can extend their capacity to explain *why* they have revised their predictions in a particular way.

Second, preschoolers would benefit from programs that support their ability to reflect on their science investigations. Although more research is needed on how best to support children's reflection, successful classroom strategies may include juxtaposing students' memory of what they predicted with what they observed (such as using verbal prompts or students' drawings; Gropen et al., 2011; Kloos & Van Ordern, 2005), pointing out the dimension relevant to the correct prediction (Kloos & Van Ordern, 2005), and collaborative learning, in which children learn by noticing differences between their beliefs and those of others (Gopnik & Astington, 1988).

Third, preschoolers would benefit from programs that integrate sufficient science content knowledge into their science learning activities. People often ask, "How much content does an early childhood teacher need to know?" The answer, we believe, depends on the EF capacity of students. At RC1, content knowledge is indispensible for planning investigations that support specific predictions, require accurate observations, and challenge children's misconceptions. At RC2, additional content knowledge enables teachers to engage children in extended conversations about scientific phenomena, respond flexibly to their questions, and introduce relevant scientific vocabulary. At this level, language is a useful vehicle for helping students make their implicit ideas *explicit* (Karmiloff-Smith, 1996; Zelazo et al., 2006). Educational research supports the view that explanation and reflection, when appropriately scaffolded, are powerful tools for helping children express their ideas, see new connections, and expand their grasp of scientific knowledge on their own (Bowman, Donovan, & Burns, 2001; Epstein, 2003; Landry & Forman, 1999).

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