

Self-Explanation and Planning: A Microgenetic Study of Preschoolers' Strategy Use on  
the Tower of Hanoi

by

Michael Robert Miller

B.Sc., The Pennsylvania State University, 2003

M.Sc., University of Victoria, 2007

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of the Requirements for the Degree of

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in the Department of Psychology

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University of Victoria

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## **Supervisory Committee**

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Dr. Ulrich Müller, (Department of Psychology)

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Dr. Kimberly A. Kerns, (Department of Psychology)

**Departmental Member**

Dr. Wanda Boyer, (Department of Educational Psychology and Leadership Studies)

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## Abstract

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In early childhood, planning provides a basis for organizational skills that are useful for future school performance (Perez & Gauvain, 2009). However, research shows that preschoolers' planning abilities are limited because they often fail to consider task demands, are inefficient at self-monitoring, and are unlikely to use strategies to their advantage (Gardner & Rogoff, 1990). The present study examined whether preschoolers could improve their planning skills by consciously drawing connections between objects and events through the use of verbal self-explanations. A microgenetic design was used in order to repeatedly measure preschoolers' performance on the Tower of Hanoi (ToH) task over a period of 6 to 8 weeks. Forty-five children between the ages of 4 and 6 years were randomly assigned to 1 of 3 conditions: self-explanation, no self-explanation, and control. Each child was administered a pretest, 3 micro sessions based on condition, and a posttest. In addition to ToH performance, children also were measured on inhibitory control, working memory, short-term memory, and verbal ability at pretest, and on a novel planning task, the Box-ToH, at posttest. Multilevel models were used to analyze the data at the between- and within-person levels. Although no differences were found in ToH performance over time between conditions, preschoolers' use of self-explanations and strategies were independently related to individual improvements in ToH performance over time. Moreover, preschoolers' improvements in ToH performance were not reducible to age-related increases, inhibitory control demands, working

memory, short-term memory, or verbal ability. Lastly, findings did not support preschoolers' ability to transfer their knowledge of strategies on the ToH to the Box-ToH. Overall, the present study demonstrated that self-explanations and strategy use are both important predictors of understanding individual changes in planning performance during the preschool years. These findings have important implications in terms of improving preschoolers' executive function skills and preparing children for early academic success.

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To Amy, Matt, and Molly, who always make coming home that much better.

To The Paw, who kept me company during those late nights typing away at the kitchen table.

I could not have done it without you.

## Self-Explanation and Planning: A Microgenetic Study of Preschoolers' Strategy Use on the Tower of Hanoi

Planning is a component of children's executive function (EF), which refers to higher-mental, frontal-lobe processes that are involved in the conscious control of action and thought (Zelazo & Müller, 2010). During the preschool period, children undergo dramatic developmental changes in EF skills that are associated with adaptive functioning (Carlson, 2005; Garon, Bryson, & Smith, 2008). For instance, research has shown that EF is related to children's social understanding (Carlson & Moses, 2001), academic readiness, and school achievement (Müller, Liebermann, Frye, & Zelazo, 2008). In addition, impairments in EF are observed in different developmental disorders, such as Attention-Deficit Hyperactivity Disorder (Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005) and autism spectrum disorders (O'Hearn, Asato, Ordaz, & Luna, 2008). Currently, the compositional structure of EF in preschoolers is not clear, with some studies providing support for a unitary structure (e.g., Hughes, Ensor, Wilson, & Graham, 2010; Wiebe, Espy, & Charak, 2008; Wiebe, Sheffield, Nelson, Clark, Chevalier, & Espy, 2011), whereas other studies show that EF consists of two (e.g., Miller, Giesbrecht, Müller, McInerney, & Kerns, in press) or even more components (Hughes, 1998a). Moreover, recent factor analytic studies in children (e.g., Brocki & Bohlin, 2004; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003) and adults (e.g., Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000) suggest that EF is multidimensional in structure and consists of both basic and global processes. Basic EF processes include lower level cognitive skills, such as inhibitory control, working memory, and attentional flexibility. Global EF processes integrate the more basic EF processes and include, among others, planning and problem-solving skills.

Over the past two decades, the development of EF in preschool children has received considerable attention (Diamond, 2006). Less research, however, has specifically focused on preschoolers' development of planning (Shapiro & Hudson, 2004). Planning plays an important role in early childhood because it provides a basis for organizational skills that are useful for future school performance (Perez & Gauvain, 2009). In comparison to school-aged children, research shows that preschoolers' planning abilities are limited because they often fail to consider task demands, are less efficient at self-monitoring, and are less likely to use strategies to their advantage (Gardner & Rogoff, 1990; Hudson, Shapiro, & Sosa, 1995; Wellman, Fabricius, & Sophian, 1985). Preschoolers' difficulty with planning likely results from planning being a global EF process in which children have to simultaneously coordinate multiple basic EF processes, including inhibitory control, working memory, and attentional flexibility (Miyake et al., 2000; Shapiro & Hudson, 2004). One way that preschoolers may be able to better control the processes involved in planning is by consciously reflecting on situations through the use of language (Zelazo, 1999). Verbal self-explanations, in particular, may be useful for preschoolers' planning skills because they aid children in identifying problems, justifying actions, and drawing attention to errors (Keil, 2006). Moreover, research has shown that self-explanations help children create and use strategies that result in improved performance on problem-solving tasks (Lombrozo, 2006; Siegler & Lin, 2010). The goal of the present study was to examine how self-explanations aid preschoolers' development of planning.

In the first section of this paper, the role of speech and its relation to children's development of EF is discussed. In particular, the use of self-explanations is addressed

and presented as a tool for which children can readily generate planning strategies. The second section describes children's use of strategy in relation to planning. The third section outlines the advantages of capturing strategies and underlying processes related to children's development of planning through the use of the microgenetic method. Lastly, the present study is described, which used the microgenetic method in order to examine the role of self-explanations on preschoolers' strategy use and planning skills over time.

### **Speech and Executive Function**

According to Vygotsky (1934/1986), language (and in particular, speech) is the basis for children's cognitive growth because language provides purpose and intention so that behaviors can be better understood. For example, the purpose behind a child frantically searching his toy chest becomes clear once he cries, *I cannot find my teddy bear*. Vygotsky (1934/1986) indicated that in early childhood, language first follows children's actions, then it gradually shifts in time with action, until finally it is used to guide action in order to make plans. Essentially, language allows children to mentally step away (or to distance themselves) from their perceptual surroundings in order to plan ahead:

By creating through words a certain intention, the child achieves a much broader range of activity, applying tools not only to those objects which lie near at hand, but searching for and preparing such articles as can be useful in the solution of its task and planning its future operation. (Vygotsky & Luria, 1994, p. 110)

Vygotsky's view of language continues to influence contemporary theories of EF. For instance, Zelazo's (1999; 2004) Levels of Consciousness (LOC) model considers language to be an essential element of children's development of EF. The LOC model is

an information-processing model that explains age-related changes in EF in terms of the extent to which children can consciously reflect on a hierarchy of increasingly complex rules. Language, however, is the means by which children can move to a higher (or a more complex) level of consciousness. By labeling subjective experiences, children can treat these experiences as objects of consciousness, and then reflect on these objects at higher levels of awareness. Empirical support for the LOC model comes from a study by Jacques and Zelazo (2001) who showed 197 preschoolers pictures of three different items (e.g., a green shirt, a green cup, and a red cup). One picture (green cup) shared a common dimension (i.e., color or shape) with both other items. Children first were asked to select one matching pair (e.g., green shirt with green cup), and then they were asked to select a different matching pair (e.g., green cup with red cup). Four-year-olds were capable of matching the first pair, but they were poor at selecting the second matching pair. However, their performance significantly improved when they first were asked to label the two matching dimensions. According to the LOC model, labeling enabled the 4-year-olds to consciously distance themselves from the problem in order to reflect on the set of items at a higher level of awareness and, thereby, correctly select both matching pairs. Without labeling, the 4-year-olds were limited to a lower level of consciousness in which they could select only one matching pair.

In accordance with the LOC model, language continues to influence preschoolers' development of EF through private or self-directed speech. Self-directed speech tends to peak during the preschool years and then gradually becomes more internalized over the early elementary school years (Manfra & Winsler, 2006). Vygotsky (1934/1986) was the first to recognize the importance of children's self-directed speech for cognitive

development, noting that children use it as a tool to guide their thoughts and actions. Similarly, in the LOC model, while language (e.g., labeling) leads to the conscious control of thought and action, the model also suggests that children can consciously use language through self-directed speech in order to govern their thoughts and actions (Müller, Jacques, Brocki, & Zelazo, 2009). Research suggests that as self-directed speech develops over the preschool period, it begins to play an influential role in preschoolers' planning. For instance, in a sample of 46 children, Fernyhough and Fradley (2005) examined 5- to 6-year-olds' use of self-directed speech on the Tower of London, which is a planning task that requires children to reproduce a particular goal configuration by transferring three balls among three pegs. In the study, children's task-relevant, self-directed speech (e.g., self-guiding comments) was positively related to planning performance. Moreover, children's self-directed speech tended to increase up to moderate levels of task difficulty. In support of the LOC model, these findings suggest that children relied more on self-directed speech as the task became moderately complex, and thus, required higher levels of consciousness.

The benefits of self-directed speech on preschoolers' planning skills are likely to extend to other forms of speech as well, as long as the speech results in conscious control over thought and action. For instance, a recent study by Byrd, van der Veen, McNamara, and Berg (2004) found that a sample of 47 four- to five-year-olds performed better on the Tower of London task when they executed moves through spoken responses alone (i.e., the experimenter manually moved the materials in accordance to children's verbally stated moves) as opposed to manual responses alone or to combined spoken-manual responses. Byrd et al. (2004) interpreted their findings in terms of the LOC model, stating

that when responding through speech alone, children were able to consciously distance themselves from the task and inhibit impulsive moves. In addition, Byrd et al. (2004) suggested the possibility that manual responses and spoken responses affect different planning processes. Therefore, combining both responses may have made the task more difficult than a spoken response alone. Byrd et al. (2004) indicate that differences between manual and spoken responses on the Tower of London could have been further examined through the addition of control measures (e.g., working memory and inhibitory control tasks), which would have allowed them to test whether each type of response affected different planning processes. Moreover, by recording children's spoken responses only in terms of how a move should be executed, Byrd et al. (2004) had limited information from which to infer the reasoning behind children's planning. Providing children with the opportunity to explain their moves might have provided insight into the reasoning behind children's planning, resulting in children formulating better task plans. One way to address this possibility is through the use of self-explanations.

Self-explanations are self-generated conclusions based on reasoning that are constructed in order to draw connections between objects or events (Siegler & Lin, 2010). Through self-explanations, children can express their thought processes and create strategies for improved planning performance (Lombrozo, 2006). Like self-directed speech, self-explanations provide children with the opportunity to consciously control language in order to govern thought and action. However, unlike self-directed speech, self-explanations can be coherently addressed to other people for the purposes of judgment. Moreover, Keil (2006) indicates that self-explanations are advantageous because they provide opportunities to both reflect on and aid task performance by (a)

identifying the nature of a problem (e.g., *To solve this puzzle, I have to put these pieces in the right order*), (b) justifying and rationalizing actions (e.g., *These pieces must go together because they are the same color*), (c) drawing attention to errors (e.g., *This piece does not fit, so it must be in the wrong place*), and (d) predicting similar events in the future (e.g., *This puzzle is just like the one I did before*).

A robust relation exists between self-explanation and improved learning (Lombrozo, 2006), and this relation has been found for children across a wide range of knowledge domains, including arithmetic, geometry, and Piagetian conservation tasks (Matthews & Rittle-Johnson, 2008). Although the majority of self-explanation research has focused on school-aged and adult populations (Lombrozo, 2006), a recent study by Rittle-Johnson, Saylor, and Swygert (2008) suggests that self-explanations can improve learning in children as young as 4 years of age. In a sample of 54 four- to five-year-olds, Rittle-Johnson et al. (2008) examined self-explanations on a series of classification tasks in which children completed patterns of differently colored toy bugs. After a pretest, children were assigned into one of three intervention conditions in which they were prompted to repeat correct answers aloud, to explain correct answers to themselves, or to explain correct answers to their mothers. In order to register an explanation, children needed to refer to the classification pattern in terms of speech or gestures (e.g., *Because blue bug, green bug, green bug*). At posttest, performance improved for children in both of the self-explanation conditions (self and mother), but not for children in the repetition condition. In addition, compared to children in the self and repetition conditions, children who provided self-explanations to their mothers were more likely to transfer their knowledge to two novel classification problems. Rittle-Johnson et al. (2008) suggested

that directing self-explanations to another person might require children to be more explicit in their explanations, resulting in greater generalization of task rules. In further support of this proposal, a previous study by Rittle-Johnson (2006) had found that self-explanations were related to school-aged children's transfer of mathematical equivalence knowledge. More important, results indicated that children's self-explanations aided in the generation of new strategies for correctly solving mathematical equivalence problems. In addition, children who were prompted to use self-explanations were more likely to apply these newly discovered strategies to novel problems than children who were not prompted to use self-explanations. Together, these findings suggest that children's use of self-explanations aid both in the development and in the generalization of strategies.

In summary, there is both theoretical and empirical support for the claim that speech is influential to children's development of EF. As explained by the LOC model, children can consciously use speech in order to reflect on their thoughts and actions at higher levels of consciousness. During the preschool years, children display difficulties with planning, but they also experience gains in self-directed speech that are related to planning. Furthermore, children's conscious control of self-explanations is related to improved learning and to the transfer of knowledge to novel tasks and situations. Recent research by Rittle-Johnson and colleagues (2006; 2008) suggests that self-explanations (a) are beneficial to learning in preschoolers, (b) aid in children's generation of strategies, and (c) are related to the transfer of children's knowledge and strategy use. Therefore, through self-explanations, preschoolers may be able to improve their limited planning skills by generating, using, and transferring beneficial planning strategies.

## Strategy Use and Planning

Strategies are “goal-directed operations used to aid task performance that are deliberately implemented, nonobligatory, and potentially available to consciousness” (Bjorklund, Hubertz, & Reubens, 2004, p. 347). Supported by a large body of empirical research (e.g., Bjorklund et al., 2004; Opfer & Siegler, 2007; Siegler, 1995; Siegler & Svetina, 2006), Siegler’s (1996) overlapping waves theory proposes that, at any one time, children generally know and use a number of different strategies for solving a particular problem. Over time, some strategies are used more often than others, some are used less often than others, some are frequently used, some are rarely used, new ones are generated, and old ones are discarded. These patterns result in individual variability in children’s strategy use, by which the same child may use different strategies on different problems, different strategies on the same problem on two different occasions, multiple strategies on a single problem, or the same strategy on different problems. An essential aspect of the overlapping waves theory is that in addition to describing quantitative changes in the frequency and effectiveness of children’s strategies, it also accounts for qualitative distinctions in children’s creation of novel strategies (Siegler & Lin, 2010). As such, the overlapping waves theory provides an integrative perspective for examining changes in preschoolers’ development of strategies on planning tasks.

An example of a complex EF task that often is used to measure children’s planning skills is the Tower of Hanoi (ToH; Simon, 1975). Traditionally, the ToH consists of two wooden apparatuses, both with three equally spaced pegs of the same length and a number of discs of graduated size (see Figure 1). One apparatus depicts the goal configuration, and the second apparatus depicts the original configuration.

Participants are required to reproduce the goal configuration on the first apparatus by transferring the discs between the pegs in the fewest moves possible on the second apparatus. In addition, participants must observe the following two rules: (a) only one disc can be moved at a time, and (b) larger discs cannot be placed on top of smaller discs. Task difficulty is increased as the task progresses by altering the original configuration of the discs so that more moves are required to reach the goal state, which is usually tower-ending (i.e., all discs on one peg) but also can be flat-ending (i.e., discs on all pegs). Due to the structure and rules of the task, performance is contingent on the ability to plan, execute, monitor, and revise moves (Bull, Espy, & Senn, 2004). Moves can be classified into optimal, non-optimal, erroneous, and other: An optimal move is a legal move that reduces the number of moves to the goal; a non-optimal move is a legal move that does not reduce the number of moves to the goal; an erroneous move is an illegal move that breaks one of the task rules; and a move that does not fit into the optimal, non-optimal, or erroneous categories (e.g., a stationary or an ambiguous move) is classified as other. An advantage of the ToH is that trials can be systematically varied in terms of the number of required moves and degree of difficulty. As such, an analysis of strategy use can be conducted by investigating the distribution of moves across different ToH trials (Fireman, 1996).

Studies monitoring children's performance on the ToH have shown that young children are likely to form different strategies as they gain experience with the task. For instance, Klahr and Robinson (1981) examined preschoolers' strategy use on a three-disc version of the ToH. Results indicated that preschoolers were likely to use basic principles involved in planning strategies observed in adults, such as moving a disc toward the goal

state, removing a disc that was blocking the goal state, and resorting to an easier, non-optimal move if the optimal move was too difficult. In comparison, Welsh (1991) examined 3- to 12-year-olds' performance on the ToH and found that younger children committed more errors on the ToH than older children, but that the most frequent errors for all children involved the first move. Specifically, the most common strategy was to first move a disc directly to the goal state even when this move was not optimal. Those children who successfully completed the more difficult ToH trials adopted the strategy of keeping the goal state clear.

The findings from Klahr and Robinson (1981) and Welsh (1991) are important because they show that preschoolers are capable of generating and using a variety of strategies on the ToH. However, in relation to the overlapping waves theory, it remains unclear how preschoolers' use of strategy on the ToH changes over time. In order to gain a better understanding of the development of preschoolers' planning strategies on the ToH, multiple observations need to be recorded over multiple periods of time. Developed within the framework of the overlapping waves theory, the microgenetic method is one approach that has been shown to be especially useful for observing changes in children's development of strategies (Siegler, 1996; 2006; Siegler & Crowley, 1991).

### **Microgenetic Method**

The microgenetic method is a repeated-measures observational approach that offers an efficient way to evaluate the development of a particular skill or ability (e.g., planning) over a relatively short span of time. Microgenetic methods have the following three main properties:

(a) Observations span the period of rapidly changing competence; (b) within this period, the density of observations is high, relative to the rate of change; and (c) observations are analyzed intensively, with the goal of inferring the representations and processes that gave rise to them. (Siegler, 2006, p. 469)

In other words, microgenetic studies are detailed, longitudinal studies that occur over a period of learning in order to discover strategies and processes leading to the development of a particular skill or ability. In regard to planning, dramatic developmental changes in children's EF skills take place during the preschool period (Carlson, 2005), which suggests that an appropriate time to observe children's planning abilities is over the preschool years. Through frequent and closely spaced spans of testing, microgenetic studies provide the opportunity to pinpoint the exact trial on which children use a new planning strategy or succeed on a particular planning task. One can then examine performance leading up to the successful trial, examine children's responses on the successful trial, and examine performance after the successful trial. As such, microgenetic studies not only allow one to see that development is occurring, but they also allow one to analyze the source (e.g., cause), path (e.g., sequence), rate (e.g., time and experience), breadth (e.g., generalizability), and variability (e.g., differences within and between individuals) of development (Siegler, 1996; 2006; Siegler & Crowley, 1991).

The ToH is well suited to the microgenetic method because it offers a wide-range of problems that can be systematically varied in terms of number of moves and degree of difficulty. At present, Fireman (1996) has conducted the only microgenetic study of children's ToH performance. In this study, a sample of 6- and 7-year-olds were given up

to 3 minutes to solve one seven-move, three-disc ToH trial. Results were then analyzed in terms of children's first moves, erroneous moves, and problem depth (i.e., number of moves still needed to reach the goal state). Fireman (1996) found that successful completion of the ToH trial was indicative of qualitative shifts in performance (i.e., focusing on the organization of moves) rather than quantitative processing-demands (i.e., focusing on the number of required moves). In particular, children who successfully completed the ToH trial were more likely to make non-optimal first moves, make more erroneous moves, and have a more irregular pattern of optimal moves compared to children who were unsuccessful. Therefore, children's success on the ToH was suggestive of trial-and-error performance. Fireman (1996) interpreted these findings as an indication that children's planning on the ToH depended more on creating and developing strategies rather than on choosing between already established strategies.

While the Fireman (1996) study provided insight into children's move-selection on the ToH, there were three noteworthy limitations to this microgenetic study. First, children who were successful on the ToH trial may have been so because they were able to make more moves over the 3-minute time limit compared to the unsuccessful children. More moves in general, therefore, may have resulted in more erroneous moves and a more irregular pattern of optimal moves. Second, children were tested on only one ToH trial. As a result, findings were based on a single level of difficulty rather than a range of levels of difficulty. Third, testing took place at only one point in time, which meant that Fireman's (1996) interpretation of strategy development was limited to the course of one 3-minute ToH trial. As Siegler (1996; 2006) notes, changes in strategy use are best captured with a high density of observations over a period of time in which learning is

taking place. Therefore, to better understand preschoolers' development of planning on the ToH, research is needed that repeatedly measures preschoolers' performance on a range of ToH trials and difficulty levels.

### **Present Study**

The present study used the microgenetic method to examine the relation between preschoolers' use of self-explanations and their development of planning strategies on the ToH over time. Through the aid of self-explanations, preschoolers were expected to be more aware of, make greater use of, and generalize potential planning strategies, which in turn were expected to lead to better ToH performance over time. This study aimed to build and expand on previous cross-sectional research by examining in more detail changes in preschoolers' strategy use and planning skills in terms of the variability, source, rate, path, and breadth of preschoolers' planning development (Siegler, 1996; 2006; Siegler & Crowley, 1991). In particular, the goals of the present study were to examine: (a) whether there is variability in preschoolers' ToH performance in regard to between-person differences in within-person change, (b) whether self-explanations contribute to preschoolers' planning performance and strategy use over time, (c) whether self-explanations lead to greater increases in strategy use and planning over time, (d) whether preschoolers' patterns of strategy use change over time, and (e) whether preschoolers' use of strategy on the ToH extends to their use of strategy on a novel planning task.

The present study also aimed to determine whether initial levels of cognitive ability moderate preschoolers' ToH performance both at the start of testing and over time. Recent research by Byrd et al. (2004) suggests that preschoolers' planning may involve

multiple cognitive processes. Moreover, other research has found that a number of basic EF processes (De Smedt, Taylor, Archibald, & Ansari, 2010; Hughes, 1998b; Huizinga, Dolan, & van der Molen, 2006) and verbal ability (Farrington-Flint, Vanuxem-Cotterill, & Stiller, 2009) underlie planning in school-aged children (see also Kaller, Rahm, Spreer, Mader, & Unterrainer, 2008; Senn, Espy, & Kaufmann, 2004). In order to gain a better understanding of the processes that underlie preschoolers' planning skills, the present study included measures of inhibitory control, working memory, short-term memory, and verbal ability.

### **Design and Analysis**

The present study used a quasi-experimental, untreated control group, repeated-measures design with dependent pretest and posttest samples. This design consisted of the following three groups of children: (a) an experimental group that was instructed to plan their actions and provide self-explanations during the ToH in order to promote strategy development over time, (b) a comparison group that was not instructed to plan or provide self-explanations during the ToH over time, and (c) a control group that was not exposed to the ToH over time.

To test for variability in individual ToH performance over time, multilevel modeling analysis was used over repeated-measures analysis of variance (RMANOVA). Whereas RMANOVA assumes that all individuals have the same mean change in slope over time, multilevel models are beneficial because they simultaneously account for change at both a within-person level and a between-person level (Singer & Willett, 2003). In other words, multilevel models are able to estimate the amount of change for each participant while evaluating the variation between individual intercepts and slopes

(Raudenbush & Bryk, 2002). Compared to RMANOVA, multilevel models also are advantageous due to greater flexibility regarding statistical assumptions of heterogeneity, sphericity, and missing data (Weinfurt, 2000).

## **Method**

### **Participants**

Fifty-one children between the ages of 4 and 6 years were recruited from two preschools and from two public elementary schools in a metropolitan area of southwestern Canada. Six children declined to participate and were dropped from the sample. The final sample consisted of 45 children (21 girls;  $M_{age} = 5;4$  years,  $SD_{age} = 0;7$  years, age range: 4;0–6;1 years). Each group was randomly assigned 7 girls and 8 boys for a total of 15 children: experimental group ( $M_{age} = 5;5$  years,  $SD_{age} = 0;7$  years, age range: 4;2–6;1 years), comparison group ( $M_{age} = 5;4$  years,  $SD_{age} = 0;7$  years, age range: 4;0–6;1 years), and control group ( $M_{age} = 5;4$  years,  $SD_{age} = 0;8$  years, age range: 4;1–6;0 years). Due to ethical restrictions of the public school board, direct measures of ethnicity and socioeconomic status were not obtained. However, the majority of the sample was Caucasian (about 85%) and came from families who were generally upper-middle class.

### **Procedure**

Three trained researchers tested children individually in a preschool or an elementary school setting. Over a period of 6 to 8 weeks ( $M = 48.63$  days,  $SD = 4.12$  days, range: 42–55 days), children were administered five separate test sessions: a pretest, three micro sessions based on group assignment, and a posttest. One researcher conducted the pretest and micro sessions, and two other researchers who were blind to group conditions conducted the posttest sessions. All researchers were trained to follow

the same task procedures. Test sessions were videotaped in order to record and code children's use of strategy on the planning tasks. Children received a sticker at the end of each test session for their participation.

### **Pretest**

All groups were administered the same pretest. The pretest measured children's inhibitory control, working memory, short-term memory, verbal ability, and initial ToH performance. The task order was fixed (i.e., inhibitory control, short-term memory, working memory, ToH, inhibitory control, short-term memory, working memory, and verbal ability) in order to facilitate comparisons between tasks and separate tasks of similar cognitive demand (for justification, see Carlson & Moses, 2001). For the ToH, children received two trials at the two- to six-move levels and four trials at the seven-move level for a possible total of 14 trials. In order to capture children's initial ToH performance, the pretest ToH was discontinued when children were unable to solve two consecutive trials of a given length.

### **Micro sessions**

Micro sessions began about 1 to 2 weeks after children's pretest sessions ( $M = 12.66$  days,  $SD = 1.65$  days, range: 9–15 days). Children were administered a total of three micro sessions each spaced about 1 to 2 weeks apart ( $M = 11.50$  days,  $SD = 1.05$  days, range: 8.5–14.0 days). Due to absences, 9 children (4 experimental, 4 comparison, and 1 control) were administered only two micro sessions, but no children received less than two micro sessions.

In order to test for a self-explanation effect, the procedures for the micro sessions differed by group. Children in the experimental and comparison groups were

administered the ToH. First, children in both groups were reminded of the rules and goal of the ToH, and then they were administered a one-move practice ToH trial. Each micro session consisted of two ToH trials at the two- to six-move levels for a total of 10 trials. Regardless of performance, children were administered all 10 trials so that both the experimental and comparison groups would be administered an equal number of ToH trials over time. The only procedural difference between the experimental and comparison groups was that children in the experimental group were asked to provide self-explanations before the start of each trial and for each move during the trial (see Appendix), whereas children in the comparison group were not asked to provide self-explanations at any time during the session. Finally, children in the control group were not administered the ToH, but instead were asked to draw a picture of their choice (e.g., favorite animal). The procedure was the same for all three micro sessions.

For the experimental group, if children did not provide a self-explanation either before or during a ToH trial, they were prompted to do so up to two times (e.g., *What are you doing now?*). If children still failed to provide a self-explanation after two prompts, they were allowed to move on with the ToH trial in order to maintain interest in the task. Self-explanations were recorded in terms of quantity rather than in terms of complexity or depth of response. In order to count as a self-explanation, children needed to refer both to a specific disc and to a specific location (e.g., *The small disc goes here; I am moving this one to that peg*). Self-explanations were tallied both for the experimental group and for the comparison group in order to make comparisons between the two groups.

### **Posttest**

All groups were administered the same posttest. Two children in the comparison group who were absent for their third micro sessions received the posttest 4 weeks after their second micro session. The remaining children were administered the posttest within 1 to 3 weeks of their third micro session ( $M = 13.07$  days,  $SD = 3.24$  days, range: 9–21 days). Due to a two-week spring break for public schools, there was a greater difference in time between children's third micro session and posttest, relative to other sessions. The posttest measured children's final ToH performance and their performance on a novel planning task. The task order was fixed (i.e., ToH and then the novel planning task) in order to facilitate comparisons between tasks (Carlson & Moses, 2001). For the ToH, children received two trials at the two- to six-move levels and four trials at the seven-move level for a possible total of 14 trials. In order to capture children's final ToH performance, the posttest ToH was discontinued when children were unable to solve two consecutive trials of a given length.

## **Measures**

### **Planning**

*Tower of Hanoi.* In the ToH (Simon, 1975), the three discs were introduced as monkeys (i.e., the large disc was the daddy monkey, the mid-sized disc was the mommy monkey, and the small disc was the baby monkey), and the pegs were introduced as trees (Welsh, 1991). Children were told that the goal of the task was to move all of the monkeys to the rightmost tree in the fewest moves possible so that the daddy monkey was on the bottom, the mommy monkey was in the middle, and the baby monkey was on the top. This goal configuration was always displayed on the experimenter's apparatus. Children were then informed of the following two rules: (a) only one monkey could be

moved at a time, and (b) bigger monkeys could not be placed on top of smaller monkeys because doing so would squash the smaller monkey. Next, using their own apparatus, children were administered the following three practice trials: two one-move trials and a three-move trial that involved an initial detour from the goal. During the practice trials, the experimenter provided assistance as needed and explicitly explained the purpose of the detour trial (e.g., *Sometimes monkeys first have to be moved away from the goal in order to free space for other monkeys to move*). The task began with two trials that could be solved in two moves and progressively increased in one-move increments up to a seven-move trial with at least two trials at each level. The maximum number of moves allowed for each trial was five moves plus the minimum number of moves required to solve the trial (e.g., a maximum of eight moves were allowed on a three-move trial). As long as children solved the trial within the maximum number of moves allowed, it was considered correct. If a child broke a rule (i.e., made an error) at any point in a trial, the experimenter stopped the child (e.g., took hold of the discs), reminded the child of the broken rule (e.g., *Remember, we can only move one monkey at a time*), and reset the task configuration to before the error was made.

For all test sessions, children's ToH performance was recorded in terms of number of trials administered, time in seconds for all trials administered, number of total moves for all trials administered, number of errors for all trials administered, number of optimal first moves for all trials administered, number of correct trials, and maximum level solved. A number of additional performance outcomes were then calculated. First, a ratio of time to total moves was calculated, which indicated the average time in seconds per move. A ratio of errors to total moves was then calculated, which indicated the

average number of errors made relative to total moves. Next, a ratio of total moves to total trials administered was calculated, which indicated the average number of moves per trial. Lastly, correct trials were assigned a point value that corresponded to the level of the particular trial (Bull et al., 2004). For example, a correct 3-move trial earned 3 points, whereas an incorrect 3-move trial earned zero points. The sum of all points provided an indication of the total level of difficulty of correctly solved trials. Table 1 provides a summary of all ToH performance outcomes.

***Box variation of the Tower of Hanoi (Box-ToH).*** The Box-ToH (McInerney, 2006) was administered as a novel measure of planning in the posttest in order to examine children's ability to transfer their knowledge of strategy use on the ToH. The Box-ToH was an isomorphic variation of the ToH in which the three discs were replaced with three clear, nested plastic boxes of increasing size (i.e., small, medium, and large), and the three pegs were replaced with three square mats of equal size. The boxes and mats were introduced as frogs and lily pads, respectively. Apart from the physical modification of the materials, the task rules for the Box-ToH were the same as the ToH, the procedure for the Box-ToH was identical to the posttest procedure for the ToH, and performance on the Box-ToH was measured with the same outcomes as the ToH.

***Strategy.*** Strategy use was measured on both the ToH and the Box-ToH in accordance to procedures for measuring strategic performance in preschoolers adapted from Klahr and Robinson (1981). Rather than measuring strategies in terms of sequences or patterns of moves, the present study observed and analyzed strategy use with children's independent move selections. In particular, children's use of strategy was framed in terms of sub-goals and obstructions. Sub-goals involved moving a disc/box to

the goal state, and obstructions involved moving a disc/box that impeded the goal state. Moves were categorized into optimal (i.e., best legal move, which reduces the number of moves to the goal), non-optimal (i.e., legal move that does not reduce the number of moves to the goal), erroneous (i.e., illegal move that breaks one of the task rules), and other (i.e., stationary move). Separate scores for sub-goal strategies and obstruction strategies then were calculated using the following scoring system: one point for each sub-goal or obstruction move, and (a) two additional points if the move was optimal, (b) one additional point if the move was non-optimal, or (c) no additional points if the move was erroneous or other.

### **Inhibitory control**

Inhibitory control was assessed with Luria's (1966) Tapping Task (adapted from Diamond & Taylor, 1996) and Luria's Hand Game (Luria, Pribram, & Homskaya, 1964; adapted from Hughes, 1996). In the Tapping Task, children first were administered the imitative phase in which they used a pencil to perform the same tapping action (i.e., tap once or tap twice on the table) as the experimenter. Tapping actions were presented in an intermingled order and continued until children had successfully imitated three one-tap actions and three two-tap actions. Children then were administered the conflict phase in which they were instructed to tap once when the experimenter tapped twice, and to tap twice when the experimenter tapped once. The conflict phase consisted of 16 trials, with each type of tapping action appearing 8 times and never more than three times in succession. Performance was measured with the number of correct tapping actions, and self-corrections were counted as incorrect.

In the Hand Game, children first were administered the imitative phase in which they performed the same hand gesture (i.e., make a fist or point index finger) as the experimenter. Gestures were presented in an intermingled order and continued until children had successfully imitated three fist gestures and three pointing gestures. Children then were administered the conflict phase in which they were instructed to make a fist when the experimenter pointed, and to point when the experimenter made a fist. The conflict phase consisted of 16 trials, with each type of gesture appearing 8 times and never more than three times in succession. Performance was measured with the number of correct gestures, and self-corrections were counted as incorrect.

### **Working memory**

Working memory was assessed with the Backward Word Span and the Backward Digit Span (Davis & Pratt, 1995). Children were required to verbally repeat in reverse order (a) sequences of single-syllable, non-semantically related words, and (b) sequences of single-digit, non-sequential numbers. Both tasks began with a training phase adapted from Slade and Ruffman (2005) that assisted children in understanding how to say the sequences backwards. In the training phases, children were shown a picture of either three objects or of three numbers (respective for each task). Moving from left to right, the experimenter pointed to the picture while saying aloud each object or number depicted. The experimenter then told children that they had to say the objects or numbers backwards, prompting them by pointing to the picture and moving right to left. Once children understood the backward sequences, the picture was removed. Beginning with two words or two digits, both tasks progressively increased in either one-word or one-digit increments with two trials at each level. Each task was discontinued when children

made errors on both trials of a given length. Performance was measured with the number of correct trials.

### **Short-term memory**

Short-term memory was assessed with the Forward Word Span and the Forward Digit Span (Davis & Pratt, 1995). Children were required to verbally repeat (a) sequences of single-syllable, non-semantically related words, and (b) single-digit, non-sequential numbers. Similar to the working memory tasks, children began with a training phase adapted from Slade and Ruffman (2005) in which children were shown a picture of three objects or of three numbers, and they were asked to name each object or number moving left to right. Once children understood the task, the picture was removed. Beginning with two words or two digits, both tasks progressively increased in either one-word or one-digit increments with two trials at each level. Each task was discontinued when children made errors on both trials of a given length. Performance was measured with the number of correct trials.

### **Verbal ability**

Receptive vocabulary was assessed with the Peabody Picture Vocabulary Test, 3<sup>rd</sup> edition (PPVT-III; Dunn & Dunn, 1997). The experimenter stated a word, and children had to point to the corresponding picture out of four choices. The task ended when children made at least 8 errors on a set of 12 words. Performance was measured in terms of raw scores (i.e., ceiling item minus number of errors).

### **Statistical Procedure**

Planning performance and strategy use were assessed through the use of multilevel modeling equations specified at two levels. The Level 1 (Equation 1) model

specified ToH performance for child  $i$  on each test session  $j$  as a function of the child's ToH performance at pretest ( $\beta_{0i}$ ) and the child's rate of linear change in performance over days between test sessions ( $\beta_{1i}$ ). The equation also included an error term ( $\epsilon_{ij}$ ) that represented within-person residual variation unaccounted for by the model. Equation 1 estimated both fixed (i.e., mean individual intercept and slope values) and random (i.e., within-person variability in the mean values) effects.

$$\text{ToH}_{ij} = \beta_{0i} + \beta_{1i}(\text{Days}_{ij}) + \epsilon_{ij} \quad (1)$$

To allow for a meaningful baseline, time was centered at zero days to reflect children's performance at pretest. Therefore, the intercept values represented pretest performance. As such, each successive time point (i.e., test session) was classified as the number of days since pretest.

The Level 2 (Equations 2 and 3) model estimated between-person differences in the within-person parameters from the Level 1 model. Equation 2 estimated individual intercepts ( $\beta_{0i}$ ) computed from Equation 1 as a function of average ToH performance between children at pretest ( $\gamma_{00}$ ) and the associated between-person residual variance in initial levels of ToH performance ( $\mu_{0i}$ ). Equation 3 estimated individual rates of change in ToH performance across the five measurement occasions ( $\beta_{1i}$ ) predicted in Equation 1 as a function of children's average rate of change in ToH performance per additional day of testing ( $\gamma_{10}$ ) and the associated between-person differences in children's rates of ToH performance ( $\mu_{1i}$ ).

$$\beta_{0i} = \gamma_{00} + \mu_{0i} \quad (2)$$

$$\beta_{1i} = \gamma_{10} + \mu_{1i} \quad (3)$$

To test for group differences in ToH performance, groups were dummy coded into dichotomous variables (e.g., 0 = comparison group; 1 = experimental group) and entered into the Level 2 (Equations 4 and 5) model in three separate analyses (experimental vs. comparison, experimental vs. control, and comparison vs. control) with Equation 1 as the Level 1 model.

$$\beta_{0i} = \gamma_{00} + \gamma_{01}(\text{group}_i) + \mu_{0i} \quad (4)$$

$$\beta_{1i} = \gamma_{10} + \gamma_{11}(\text{group}_i) + \mu_{1i} \quad (5)$$

In addition to the parameters in Equations 2 and 3, individual intercepts ( $\beta_{0i}$ ) in Equation 4 were estimated as a function of the average difference in ToH performance between groups at pretest ( $\gamma_{01}$ ), and individual rates of change in ToH performance over time ( $\beta_{1i}$ ) in Equation 5 were estimated as a function of the average difference in rates of change in ToH performance between groups ( $\gamma_{11}$ ), respectively.

Similar to group differences, the influence of inhibitory control (IC), working memory (WM), short-term memory (STM), and verbal ability (VA) on ToH performance was examined by including these predictor variables in the Level 2 (Equations 6 and 7) model in order to determine if they constrained variance in the Level 1 intercepts and slopes.

$$\beta_{0i} = \gamma_{00} + \gamma_{01}(\text{IN}_i) + \gamma_{02}(\text{WM}_i) + \gamma_{03}(\text{STM}_i) + \gamma_{04}(\text{VA}_i) + \mu_{0i} \quad (6)$$

$$\beta_{1i} = \gamma_{10} + \gamma_{11}(\text{IN}_i) + \gamma_{12}(\text{WM}_i) + \gamma_{13}(\text{STM}_i) + \gamma_{14}(\text{VA}_i) + \mu_{1i} \quad (7)$$

The time-based Level 1 model described in Equation 1 was then expanded in order to explain additional sources of within-person variance. Self-explanations and strategy use were included in the Level 1 model both separately (Equations 8 and 9) and together (Equation 10) as additional time-varying covariates of ToH performance. As

such, change in ToH performance was evaluated as a function of time, self-explanations, and strategy use.

$$\text{ToH}_{ij} = \beta_{0i} + \beta_{1i}(\text{Days}_{ij}) + \beta_{2i}(\text{Self-Explanation}_{ij}) + \epsilon_{ij} \quad (8)$$

$$\text{ToH}_{ij} = \beta_{0i} + \beta_{1i}(\text{Days}_{ij}) + \beta_{2i}(\text{Strategy}_{ij}) + \epsilon_{ij} \quad (9)$$

$$\text{ToH}_{ij} = \beta_{0i} + \beta_{1i}(\text{Days}_{ij}) + \beta_{2i}(\text{Self-Explanation}_{ij}) + \beta_{3i}(\text{Strategy}_{ij}) + \epsilon_{ij} \quad (10)$$

The slope parameter for time ( $\beta_{1i}$ ) in Equations 8-10 assessed a child's rate of linear change in ToH performance over time independent of self-explanations and strategy use.

The slope parameter for self-explanations and strategy use ( $\beta_{2i}$ ) in Equations 8 and 9 assessed whether higher or lower self-explanations (or strategy use) at a specific test session was related to higher or lower ToH performance independent of linear changes in ToH performance over time. In Equation 10, the slope parameters for self-explanation ( $\beta_{2i}$ ) and strategy use ( $\beta_{3i}$ ) assessed whether higher or lower self-explanations (or strategy use) at a specific test session were related to higher or lower ToH performance independent of strategy use (or self-explanations) and linear changes in ToH performance over time. Self-explanations and strategy use were centered at zero to represent ToH performance in the absence of self-explanations and strategy use, respectively.

Lastly, the analysis addressed children's ability to transfer their strategy use on the ToH to a novel planning task, the Box-ToH. In place of ToH performance, strategy use on the ToH was specified in the Level 1 (Equation 11) model as a function of time. Strategy use on the Box-ToH was then included in the Level 2 (Equations 12 and 13) model to evaluate if it constrained variance in the Level 1 intercepts and slopes.

$$\text{ToH Strategy}_{ij} = \beta_{0i} + \beta_{1i}(\text{Time}_{ij}) + \epsilon_{ij} \quad (11)$$

$$\beta_{0i} = \gamma_{00} + \gamma_{01}(\text{Box-ToH strategy}_i) + \mu_{0i} \quad (12)$$

$$\beta_{1i} = \gamma_{10} + \gamma_{11}(\text{Box-ToH strategy}_i) + \mu_{1i} \quad (13)$$

In addition to the parameters in Equations 2 and 3, individual intercepts ( $\beta_{0i}$ ) in Equation 12 were estimated as a function of the average difference in both ToH strategy use and Box-ToH strategy use at pretest ( $\gamma_{01}$ ), and individual rates of change in ToH strategy use over time ( $\beta_{1i}$ ) in Equation 13 were estimated as a function of the average difference in rates of change in both ToH strategy use and Box-ToH strategy use ( $\gamma_{11}$ ), respectively.

## Results

### Data Preparation

All variables were screened for univariate and multivariate outliers, for skewness, and for kurtosis using the software package PASW Statistics 18.0. Two outliers were found for ToH Obstructions, and one outlier was found for ToH Explanations, the Tapping Task, and the Forward Digit Span, respectively. These outlier values were replaced with the highest/lowest remaining score plus/minus one under the assumption that children's true scores were extreme on these tasks. Mahalanobis distance did not reveal any multivariate outliers, and all variables were reasonably distributed with only minor departures from normality. In total, 1.85% of the data were missing and handled with full information maximum likelihood estimation in HLM 6.06 (Raudenbush, Bryk, & Congdon, 2004).

### Descriptive Statistics

For each group and the sample as a whole, Table 2 displays (a) mean levels of correct trials, self-explanations, sub-goal strategies, and obstruction strategies for the ToH at each measurement occasion, (b) mean levels for the inhibitory control, working memory, short-term memory, and verbal ability tasks at pretest, and (c) the mean level of

Box-ToH correct trials at posttest. Although there were no age or sex differences over time for any of the variables, older children performed better than younger children on the Backward Word Span, PPVT-III, Box-ToH, and the pretest and posttest ToH. In addition, males made more moves per trial and had more obstruction strategies on the pretest ToH compared to females, whereas females took more time per move on the pretest ToH and made more optimal first moves on the Box-ToH compared to males. Controlling for these age and sex differences did not affect the overall findings. Zero-order correlations among the measures of inhibitory control, working memory, short-term memory, and verbal ability are presented in Table 3. Due to significant moderate correlations between both measures of working memory and both measures of short-term memory, scores were summed to create aggregated working memory ( $M = 4.84$ ,  $SD = 1.91$ ) and short-term memory ( $M = 10.93$ ,  $SD = 2.08$ ) variables that were then used in the data analysis. By contrast, the measures of inhibitory control were not significantly correlated. Because the Hand Game showed greater variability, the Tapping Task was dropped from the further data analysis and the Hand Game was retained as the only measure of inhibitory control.

### **Multilevel Modeling Analysis**

The statistical program HLM 6.06 (Raudenbush et al., 2004) was used to analyze the data at both the individual (Level 1) level and the group (Level 2) level by estimating multilevel models with full information maximum likelihood. The results are presented in three sections in order to examine (a) group differences in children's ToH performance, (b) the contribution of self-explanations and strategies to children's ToH performance, and (c) children's transfer of strategy use on the ToH to strategy use on the Box-ToH.

**Group differences in Tower of Hanoi performance.** The first set of analyses examined whether children's ToH performance differed over time (a) for the sample as a whole, and (b) among the experimental, comparison, and control groups. Children's ToH performance was examined in terms of correct trials, maximum level solved, points per level of correct trials, a ratio of total time in seconds to total moves, a ratio of total errors to total moves, a ratio of total moves to total trials administered, and optimal first moves (see Table 1). Using the same form as the general multilevel model (Equations 1-3), growth models were fit for each ToH outcome in order to first determine whether there was significant variability in ToH performance at pretest and over time for the sample as a whole.

The summary of all estimated growth models is presented in Table 4. Focusing first on the fixed effects (i.e., mean values), the tests of intercept ( $\gamma_{00}$ ) were significantly different from zero for all estimated models, which meant that children differed in their levels of ToH performance at pretest. With the exception of the moves-to-trials model, the tests of slope ( $\gamma_{10}$ ) for all estimated models indicated significant within-person change in the rate of ToH performance over time. For example, in terms of correct trials, children solved an average of 8.29 trials at pretest and then continued to solve 0.05 trials with each additional day. Relative to initial ToH performance, this represented an average increase of 0.5% ( $0.05/8.29$ ) in correct trials for each additional day since pretest. Therefore, over the course of the study, the average number of correct trials increased by about 27% ( $0.5\% \times 48.63$  days). Furthermore, children took an average of 5.34 seconds per move at pretest, but took an additional 0.03 fewer seconds per move on average for each day since pretest. This resulted in a 0.6% ( $-0.03/5.34$ ) decrease in seconds per move for each

additional day from pretest and approximately a 25% ( $0.6\% \times 48.63$ ) decrease in seconds per move over the course of the study.

In regard to the random effects (i.e., variability in the mean values), with the exception of the errors-to-moves and the moves-to-trials models, all estimated models in Table 4 had significant random effects of intercept ( $\mu_{0i}$ ), significant random effects of slope ( $\mu_{0i}$ ), and non-zero within-person random effects ( $\epsilon_{ij}$ ), indicating that reliable differences in ToH performance existed between children at pretest, between children over time, and within individuals, respectively. As indicated by Singer and Willett (2003), the proportion of total variance in ToH performance that was associated with between-person and within-person sources was calculated by dividing the between-person residual by the sum of the between- and within-person residuals [ $\mu/(\mu + \epsilon)$ ]. For example, in terms of correct trials, approximately 67% [ $4.60/(4.60 + 2.27)$ ] of the total variance in ToH performance at pretest was due to differences between children. Therefore, approximately 33% ( $100\% - 67\%$ ) of the total variance in correct trial performance was due to within-person variation.

Whereas a relatively large proportion of total variance in ToH performance at pretest was accounted for by between-person differences, the proportion of total variance in ToH performance accounted for by between-person differences over time averaged less than 1% for all ToH outcomes in Table 4. In other words, approximately 100% of the total variation in ToH performance over time was accounted for by within-person variation. Therefore, the likelihood of finding significant between-person differences in ToH performance over time was very small. The inferential tests of the fixed effects in Equations 4 and 5 assessed whether the experimental, comparison, and control groups

differed in ToH performance at pretest and over time, respectively. As displayed in Table 5, no average group differences in slope were found for five ToH outcomes that were selected on the basis of significant between-person random slope effects. However, average group differences in intercept were found for correct trials, points-per-level, and optimal-first-moves. In other words, the groups did not differ in ToH performance over time, but they did differ significantly in ToH performance at pretest. Specifically, the experimental group solved significantly more ToH trials at pretest and recorded significantly more optimal-first-moves at pretest compared to both the comparison and the control groups, and the experimental group also recorded more points-per-level at pretest compared to the comparison group.

Between-person differences in ToH performance were further addressed by the inferential tests of the fixed effects in Equations 6 and 7, which examined the contribution of inhibitory control, working memory, short-term memory, and verbal ability to ToH performance at pretest and over time (see Table 6). With the exception of points-per-level at pretest and time-per-moves over time, differences in children's average values of ToH performance were significant at pretest and over time, independent of all control measures. In addition, inhibitory control significantly contributed to children's pretest performance in terms of correct trials, maximum level, and points-per-level, whereas verbal ability contributed positively to points-per-level at pretest and negatively to time-per-moves at pretest. Overall, the addition of the control measures accounted for an additional 4.9% to 12.1% of between-person variance in pretest ToH performance.

In summary, children's performance on the ToH differed over time for the sample as a whole, independent of inhibitory control, working memory, short-term memory, and verbal ability processes. However, group differences in ToH performance over time were not found. Therefore, further analyses to examine group differences were not conducted.

**Self-explanations, strategy use, and Tower of Hanoi performance.** Having determined that a significant amount of the total variance in children's ToH performance was due to individual variation over time, additional analyses were conducted in order to further explain within-person variability over time. Specifically, the next set of analyses examined whether self-explanations and strategy use predicted changes in individual ToH performance. Separate multilevel models were fit that included additional time-varying predictors of self-explanation and strategy use. For these analyses, self-explanations were tallied for all children (regardless of group) at all five test sessions. First, the inferential tests of the fixed effects in Equation 8 and 9 (see Table 7) examined whether children's use of self-explanations, sub-goal strategies, and obstruction strategies each separately covaried with children's ToH performance over time. The results for self-explanations are presented in terms of optimal-first-moves because it was the only outcome that produced significant results. The results for strategy use are presented in terms of correct trials, but similar results were found for points-per-level and time-per-moves.

In terms of the self-explanation model, the slope coefficient for days ( $\gamma_{10} = 0.04$ ,  $p < .01$ ) was significant, indicating an increase in an individual's optimal-first-moves over time, independent of self-explanations. The slope parameter for self-explanations ( $\gamma_{10} = 0.02$ ,  $p < .01$ ) also was significant, which meant that relative to ToH performance at pretest, for every additional self-explanation, there was a small corresponding increase

(0.02/6.62) in optimal-first-moves independent of time-based increases in ToH performance. The effect of self-explanation on children's optimal-first-moves remained significant even when controlling for inhibitory control ( $\gamma_{10} = 0.04, p < .01$ ), but not for working memory, short-term memory, and verbal ability.

In terms of both the sub-goal strategies and the obstruction strategies models, the significant slope coefficient for days reflected a small increase in correct ToH trials ( $\gamma_{10} = 0.01 - 0.03, p < .01$ ) over time, independent of sub-goal or obstruction strategies. The findings also revealed significant slope parameters for sub-goal strategies ( $\gamma_{10} = 0.09, p < .01$ ) and for obstruction strategies ( $\gamma_{10} = 0.02, p < .01$ ). This meant that, relative to pretest ToH performance, for every one-point increase in sub-goal or obstruction strategies (e.g., difference between a non-optimal move and an optimal move), there were corresponding increases of 2.2% (0.09/3.82) and 2.5% (0.15/5.99) in correct ToH trials that were independent of time-based increases in ToH performance. While not depicted in Table 7, the slope coefficients for sub-goal ( $\gamma_{10} = 0.10, p < .01$ ) and obstruction goal ( $\gamma_{10} = 0.13, p < .01$ ) strategies remained significant even after controlling for inhibitory control, working memory, short-term memory, and verbal ability as Level 2 predictors of strategy.

Next, a multilevel model was fit in order to examine the simultaneous effects of self-explanations and strategy use on ToH performance over time. The inferential tests of the fixed effects in Equation 10 (see Table 8) examined whether a child's use of self-explanations and strategies together covaried with the child's ToH performance over time. Separate analyses were conducted for sub-goal strategies and obstruction strategies, and optimal-first-moves were used as the ToH outcome. For both models presented in

Table 8, the findings revealed significant slope coefficients for days, independent of strategy use and self-explanations. In addition, both models had significant slope values for self-explanations, which indicated that independent of time and strategy use, for every additional self-explanation, there were small corresponding increases (about 0.5%) in a child's optimal-first-moves. Similarly, the significant slope coefficient for sub-goals ( $\gamma_{10} = 0.03, p < .01$ ) reflected an increase of about 0.5% optimal-first-moves for every unit increase in sub-goals, independent of time and self-explanations. The slope coefficient for obstruction strategies was not significant, meaning that within-person changes in obstruction strategies did not affect ToH performance over and above self-explanations and changes in ToH performance across time.

In summary, children's use of self-explanations, sub-goal strategies, and obstruction strategies all showed increases in individual ToH performance over time, even after controlling for changes in ToH performance as a result of time. Furthermore, self-explanations and sub-goal strategies produced independent effects on individual ToH performance over time.

**Transfer of Tower of Hanoi strategies to the Box-Tower of Hanoi.** The final analysis examined whether children's knowledge of ToH performance and strategy use transferred to a novel planning task, the Box-ToH. The inferential tests of the fixed effects in Equation 12 and 13 examined whether children's performance on the Box-ToH predicted between-person differences in ToH performance at pretest and over time. As depicted in Table 9, children's performance on the Box-ToH was matched to eight identical indicators of their performance on the ToH, including self-explanations, sub-goal strategies, and obstruction strategies. For all eight performance outcomes, there were

no significant slope parameters, which meant that children's performance on the Box-ToH did not significantly reflect changes in children's ToH performance over time. However, with the exception of maximum levels and self-explanations, children's Box-ToH performance explained between-person differences in similar outcomes of ToH performance at pretest.

### **Discussion**

Over a period of 6 to 8 weeks, the present study repeatedly measured preschoolers' performance on a range of ToH trials in order to investigate whether self-explanations aided in preschoolers' development of planning across time. Specifically, the goals of the present study were to examine (a) variability in preschoolers' ToH performance over time in terms of between-person differences in within-person change, (b) the effects of preschoolers' use of self-explanations in terms of group differences in ToH performance over time, (c) how preschoolers' use of strategy affects their ToH performance over time, and (d) preschoolers' ability to transfer their strategy use from the ToH to a novel planning task, the Box-ToH.

Overall, the findings revealed that increases in preschoolers' ToH performance differed both between and within children over time, and that these increases were independent of inhibitory control demands, working memory, short-term memory, and verbal ability for most ToH outcomes. Group differences in preschoolers' use of self-explanations did not significantly affect ToH performance over time. However, preschoolers' self-explanations and strategy use both independently influenced individual ToH performance over the course of the study, even after controlling for age-related increases in ToH performance. Lastly, the present study found that preschoolers' use of

strategy on the ToH over time did not generalize to their performance on the Box-ToH. Rather, preschoolers' performance on the Box-ToH was representative of their performance on the ToH at pretest. The implications of these findings are discussed in turn.

### **Self-Explanations and Planning**

Although the present study found that preschoolers' performance on the ToH improved over time, there were no significant differences in performance between the experimental, comparison, and control groups over time. Therefore, over the course of the study, prompting preschoolers to explain their moves both before and during ToH trials did not provide an advantage over children who were not prompted to explain their moves or over children who were only administered the ToH at pre- and posttest. However, when children's performance was collapsed across groups, self-explanations were related to individual gains in ToH performance over time in terms of optimal first moves. Thus, to clarify, self-explanations did not lead to between-person differences in ToH performance over time, but they did lead to improved individual performance on the ToH in terms of children making optimal first moves on a given ToH trial. As both of these findings are important in their own right, each is separately addressed.

The null finding for group differences in ToH performance in the present study was unexpected and contrasts with previous studies that found that children who were prompted to explain their solutions to problems performed better on subsequent cognitive tasks than children who were not prompted to provide explanations (Rittle-Johnson, 2006; Rittle-Johnson et al., 2008). One difference between these previous studies and the present study was the point in time at which children were prompted to provide self-

explanations. In previous studies, children always were asked to provide self-explanations at the end of the task. However, in the present study, children were prompted to provide self-explanations before and during ToH trials with the expectation that they would formulate a plan for how to solve the task, either ahead of time or as they progressed through the trial. It may be the case that the effects of self-explanations are sensitive to differences in the timing of prompting, and that prompting for self-explanations at the end of a task is more conducive to learning than prompting for self-explanations at the start of a task. Having children first work through a problem before asking them to evaluate their performance may provide them with insight into more efficient ways to solve the task as opposed to first asking children to analyze how they intend to solve a potentially unknown problem. Future research is needed in order to examine this possibility.

It is also possible that group differences in the present study were not found as a result of the age of the children sampled or of the specific way in which children were asked to provide self-explanations. In terms of age, most studies that have found significant effects of self-explanations on improved learning have been with school-aged children and adults (Lombrozo, 2006; see also Matthews & Rittle-Johnson, 2008). However, Rittle-Johnson et al. (2008) found that self-explanations were related to between-group differences in learning and in the transfer of knowledge in children as young as 4 years of age (Rittle-Johnson et al., 2008). In the present study and the study by Rittle-Johnson et al. (2008), preschoolers were asked to explain the procedures behind how to solve a planning task and a classification problem, respectively. However, neither study asked children to explain the reasoning behind why they chose a particular plan or

solution. It is possible that the effects of procedural self-explanations in preschoolers fluctuate between different knowledge domains. This possibility could be further explored by examining differences in procedural and conceptual self-explanations in preschoolers across different knowledge domains.

Another reason for why group differences in ToH performance over time were not found in the present study may be due to initial differences between groups at pretest. As shown in Table 5, children in the experimental group performed significantly better than children in the comparison and control groups on three different ToH outcomes at pretest despite random assignment to groups. Therefore, having started at a higher level of ToH performance relative to the other groups may have lessened the impact of self-explanations on ToH performance for children in the experimental group. Moreover, whereas children in the experimental group provided significantly more self-explanations during the micro sessions compared to children in the comparison group, children in the comparison group provided spontaneous self-explanations during all five test sessions (see Table 2); this may have diminished the effect of the self-explanation manipulation. In fact, all three groups spontaneously provided self-explanations during the pre- and posttest, which suggests that preschoolers are inclined to use self-explanations while planning even when they are not directly prompted to do so.

Preschoolers' spontaneous production of self-explanations is one likely source of why, in the present study, self-explanations were found to contribute to improvements in individual ToH performance over time, even after controlling for age-related improvements in ToH performance and strategy use. In accordance with the LOC model (Zelazo, 1999; 2004), preschoolers' production of self-explanations may have provided

them with the opportunity to mentally distance themselves from the immediate situation in order to reflect on a given ToH trial at a higher level of awareness, leading to improved ToH performance over time. In the present study, self-explanations were related to children's production of optimal first moves on the ToH over time; this suggests that children were most likely to aid in mental reflection through self-explanation at the start of a given ToH trial, which is essentially when planning is most likely to take place (i.e., before the action). As noted by Vygotsky (1934/1986), language follows children's actions at first, but during early childhood a shift gradually occurs, and children begin to use language in order to guide their actions. In the present study, children who provided self-explanations before their first move would often catch errors that they likely would have made had they not formulated a plan before taking action. During ToH trials, children's self-explanations tended to be purely descriptive and would often take place with children's movement of a disc, rather than before the move was made. This may be why self-explanations only had an effect on children's first moves and not on the other ToH outcomes. Future research could explore this claim by experimentally manipulating children's use of self-explanations before, during, and after different ToH trials in order to see if performance between groups differs over time.

### **Strategy Use and Planning**

In addition to self-explanations, the present study found that preschoolers' use of sub-goal and obstruction strategies (in terms of independent move selections) predicted improvements in ToH performance over time. Furthermore, the effects of sub-goal and obstruction strategies on ToH performance were not reducible to age-related influences, inhibitory control demands, working memory, short-term memory, or verbal ability.

These findings are consistent with previous research that found that preschoolers were capable of generating different strategies on the ToH that were related to overall performance (Klahr & Robinson, 1981; Welsh, 1991).

On average, preschoolers' use of strategy increased over the course of the study, which in turn was related to increases in ToH performance (see Figures 2a and 2b). However, as depicted in Figures 3a and 3b, a great deal of individual variation existed both for sub-goal strategies and for obstruction strategies over the course of the study. In accordance to the overlapping waves theory (Siegler, 1996), the patterns of strategy use in Figures 3a and 3b show that on a given measurement occasion, children were likely to use more sub-goal strategies than on a previous occasion, or use less obstruction strategies than on another occasion. Moreover, children were more efficient (e.g., made optimal moves) in their use of obstruction strategies on some days, but then less efficient (e.g., made error moves) in their use of obstructions 2 weeks later. Overall, children's greater use of sub-goal strategies relative to obstruction strategies (see Table 2) was likely due to the design of the ToH. In any correct 4-move (or 4 + n move) trial, children needed to make at least three sub-goals, whereas there might have been no need for them to use an obstruction strategy. Regardless, the present study was concerned with how children's use of different strategies affected their ToH performance rather than comparing children's relative use of sub-goal and obstruction strategies on the ToH.

### **Preschoolers' Transfer of Planning Knowledge**

Whereas previous studies involving children's use of self-explanation have found that children were capable of transferring learned knowledge to novel situations (Rittle-Johnson, 2006; Rittle-Johnson et al., 2008), the results of the present study did not

support preschoolers' transfer of planning knowledge. In particular, the findings revealed that children's overall performance, use of self-explanations, and use of strategies on the ToH over time did not generalize to their performance on the Box-ToH at posttest. Instead, children's performance on the Box-ToH was related to their ToH performance at pretest, meaning that children performed similarly on initial presentations of both planning tasks. Moreover, although children made individual gains in ToH performance over time, these gains in planning knowledge did not transfer to their performance on the Box-ToH task, despite the similarities between the two planning tasks in terms of rules and procedures.

One reason for why transfer effects were not found in the present study may be related to the fact that a self-explanation effect was not found between groups. In recent studies by Rittle-Johnson and colleagues (2006; 2008), transfer effects were found only for children who had been instructed to provide self-explanations. These findings suggest that self-explanations are a driving force behind children's ability to transfer their learned knowledge to novel situations. In the present study, because there were no significant differences in ToH performance between children as a result of self-explanations, differences between children in their ability to transfer their knowledge of the ToH to the Box-ToH were unlikely. In fact, children's use of self-explanations during the Box-ToH was one of two performance outcomes (the other being maximum level) that were not related to children's ToH performance at pretest. On average, children were actually less likely to use self-explanations on the Box-ToH ( $M = 0.49$ ,  $SD = 1.47$ ) than they were on the pretest ToH ( $M = 4.31$ ,  $SD = 6.77$ ). One reason for this discrepancy may be due to the fact that the Box-ToH was always administered after the ToH at posttest in order to

facilitate comparisons between tasks. Therefore, task fatigue could have influenced children's performance on the Box-ToH, resulting in less self-explanations.

Counterbalancing the task order may have produced different results, and future research should examine this possibility.

### **Conclusion**

The present study demonstrated that self-explanations and strategy use are both important predictors of understanding individual changes in planning performance during the preschool years. These findings are in support of a growing body of literature that shows that children's use of self-explanations are beneficial to learning and aid in the generation of strategies (Keil, 2006; Lombrozo, 2006; Rittle-Johnson, 2006). As a global process of EF, planning requires children to recruit organizational skills that are useful for future school performance (Perez & Gauvain, 2009). Therefore, the development and promotion of self-explanations and strategies has important implications in terms of improving preschoolers' EF skills and preparing children for early academic success (Müller et al., 2008).

Some limitations of the present study need to be taken into consideration. First, children were recruited from the public school system in order to maintain generalizability of the results to the general population. However, the collection of demographic data was restricted, so direct measures of ethnicity and socioeconomic status could not be obtained. Even so, it should be noted that the children who participated in this study lived in an area that was generally upper-middle class and, therefore, results may not generalize to other populations. Second, the present study was designed in order to take advantage of the strengths that the microgenetic method offers,

including multiple measurement occasions over a relatively short span of time. The analysis also was conducted in order to take advantage of the strengths that multilevel modeling provides over RMANOVA, including the ability to simultaneously account for between-person differences in within-person change. Despite these strengths in design and analysis, however, there were also limitations to both. In regard to design, repeated measures over a short period of time could have resulted in practice effects that may have unevenly influenced the results in favor of children in the experimental and comparison groups who had more experience with the ToH task than children in the control group. However, due to the fact that group differences were not found, it is unlikely that practice effects had any influence on the findings. In regard to analysis, the time-varying covariates (self-explanation and strategy use) were simultaneously measured, and this potentially creates a problem of reciprocal causation in which gains in ToH performance may be responsible for gains in self-explanation and strategy use. Comparing children's current ToH performance to prior estimates of self-explanation and strategy use over time is one way to address this concern.

Future research needs to examine procedural differences in regard to measuring the influence of self-explanations on children's development of planning. It is possible that prompting children to explain their performance after the task leads to greater improvements in planning compared to asking children to explain their performance ahead of time or during the task. In addition, what is asked of children in their self-explanations may be of importance in regard to observing a self-explanation effect for planning. For instance, there may be distinct differences in the effects of self-explanations depending on whether children are asked *how* to procedurally solve a

problem versus being asked to conceptually explain *why* they solved a problem in a specific way (Rittle-Johnson, 2006). Moreover, it is possible that, rather than from the actual act of explaining, improvements in learning are the result of underlying cognitive processes that are tied to self-explanations. For example, aspects of EF and self-regulation may be important in terms of children distancing themselves from the immediate situation in order to better explain the solution to a particular problem (Byrd et al., 2004; Giesbrecht, Müller, & Miller, 2010).

In summary, the present study showed that preschoolers' use of self-explanations and strategy on the ToH were related to individual gains in planning performance over time. These findings have important implications in terms of improving preschoolers' EF and future academic skills. Future research should explore how procedural distinctions in self-explanation differentially affect improvements in preschoolers' planning over time.

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## Appendix

### Protocol for the Experimental Group Micro Sessions

At the start of each ToH trial, the experimenter says to the child, “*Before you start, I want you to take a second to think about how you are going to get all of the monkeys to the home tree so that the daddy is on the bottom, the mommy is next in the middle, and the baby is last on the top. Now, before you move any of the monkeys, can you tell me how you are going to do this?*” If the child does not respond, the experimenter provides the following prompt, “*Can you tell me how you are going to move each monkey so that the daddy ends up on the bottom, the mommy is in the middle, and the baby is on top?*” If the child still does not respond, the experimenter says, “*Tell me which monkey you are going to move first. Then which monkey will you move?*”

After the child explains how he/she plans to move, the experimenter says, “*Okay, now you can start. Move your monkeys so that they look just like my monkeys (points to experimenter’s ToH apparatus), and as you move, tell me out loud how you are moving each monkey.*” If the child does not respond, the experimenter provides the following prompt up to two times, “*Which monkey are you moving now?*”

If the child gives up before completing a trial, the experimenter says, “*Okay, how were you trying to move the monkeys? Why did this not work? Let’s try another one.*” If the child does not respond, the experimenter provides the following prompt up to two times, “*We wanted the monkeys to look like this (points to experimenter’s ToH apparatus), right? Why did this not work? Let’s try another one.*”

Table 1

*Descriptions of Performance Outcomes for the Tower of Hanoi*

Performance outcome	Description
Correct Trials	Total number of correctly solved trials
Maximum Level	Greatest level of trial difficulty that was correctly solved
Points-Level	Total level of difficulty of correctly solved trials
Time/Moves	Average time in seconds per move
Errors/Moves	Average number of errors made relative to total moves made
Moves/Trials	Average number of moves made per trials administered
Optimal-First-Moves	Total number of optimal first moves for trials administered

Table 2

*Descriptive Statistics by Group and the Whole Sample for Tower of Hanoi Time-Varying Variables, Control Tasks, and the Box-Tower of Hanoi*

Variable	Range	Experimental ( <i>n</i> = 15)	Comparison ( <i>n</i> = 15)	Control ( <i>n</i> = 15)	Total ( <i>N</i> = 45)
		<i>M</i> ( <i>SD</i> )	<i>M</i> ( <i>SD</i> )	<i>M</i> ( <i>SD</i> )	<i>M</i> ( <i>SD</i> )
<i>ToH Correct</i>					
Pretest	3-14	10.20 (2.65)	8.33 (2.61)	7.60 (3.20)	8.71 (2.98)
Micro 1	2-10	9.69 (0.63)	8.07 (2.16)		8.86 (1.79)
Micro 2	2-10	9.50 (0.94)	8.79 (2.12)		9.14 (1.65)
Micro 3	6-10	9.67 (0.90)	9.31 (1.25)		9.50 (1.07)
Posttest	4-14	12.07 (2.69)	11.47 (2.45)	9.80 (3.86)	11.11 (3.14)
<i>ToH Explain</i>					
Pretest	0-23	4.73 (7.91)	4.13 (6.01)	4.07 (6.72)	4.31 (6.77)
Micro 1	0-46	31.15 (11.95)	3.64 (8.71)		16.89 (17.32)
Micro 2	0-53	30.21 (15.89)	2.07 (7.19)		16.14 (18.76)
Micro 3	0-57	38.93 (15.48)	3.46 (11.61)		22.46 (22.56)
Posttest	0-58	4.73 (14.94)	3.60 (13.40)	2.33 (3.66)	3.56 (11.55)
<i>ToH Sub-goals</i>					
Pretest	28-130	94.80 (28.80)	75.87 (29.99)	67.27 (31.20)	79.31 (31.54)
Micro 1	18-89	79.23 (4.32)	65.71 (18.42)		72.22 (15.02)
Micro 2	18-85	77.57 (2.98)	72.21 (16.85)		74.89 (12.18)
Micro 3	42-87	78.47 (4.32)	73.85 (11.71)		76.32 (8.73)
Posttest	29-134	112.53 (23.92)	105.13 (26.03)	88.13 (37.27)	101.93 (30.76)
<i>ToH Obstruct.</i>					
Pretest	4-41	23.73 (9.31)	19.27 (10.85)	16.60 (11.93)	19.87 (10.92)
Micro 1	0-23	14.23 (3.68)	11.79 (5.38)		12.96 (4.72)
Micro 2	0-32	15.07 (6.15)	13.36 (5.12)		14.21 (5.62)
Micro 3	6-28	14.27 (4.65)	12.31 (2.93)		13.36 (4.00)
Posttest	3-40	28.47 (8.25)	25.40 (9.77)	21.07 (10.91)	24.98 (9.96)
Tapping Task	6-16	14.53 (1.36)	12.67 (3.37)	14.33 (1.63)	13.84 (2.40)
Hand Game	3-16	9.00 (2.78)	9.20 (3.51)	9.60 (3.48)	9.27 (3.21)
BW Word Span	0-5	2.73 (1.22)	2.33 (1.45)	2.80 (1.26)	2.62 (1.30)
BW Digit Span	0-4	2.00 (0.76)	2.20 (0.94)	2.47 (1.06)	2.22 (0.93)
FW Word Span	3-8	5.47 (1.13)	5.00 (1.13)	5.60 (1.18)	5.36 (1.15)
FW Digit Span	3-9	5.67 (1.23)	5.47 (1.36)	5.60 (1.12)	5.58 (1.22)
PPVT-III	49-120	84.93 (15.48)	81.67 (15.49)	90.40 (17.57)	85.67 (16.25)
Box-ToH	4-14	11.13 (3.14)	10.53 (3.31)	9.47 (3.27)	10.38 (3.24)

*Note.* Box-ToH statistics are in terms of correct trials. ToH = Tower of Hanoi; Explain = self-explanations; BW = backward; FW = forward; PPVT-III = Peabody Picture Vocabulary Test, 3<sup>rd</sup> edition.

Table 3

*Zero-Order Correlations Among Measures of Inhibitory Control, Working Memory, Short-Term Memory, and Verbal Ability (N = 45)*

Variable	1	2	3	4	5	6	7
1. Tapping Task	-						
2. Hand Game	.27	-					
3. BW Word Span	.16	.46**	-				
4. BW Digit Span	.22	.39**	.45**	-			
5. FW Word Span	.09	.09	.24	.24	-		
6. FW Digit Span	.00	.22	.23	.35*	.55**	-	
7. PPVT-III	.25	.35*	.47**	.33*	.29	.23	-

*Note.* BW = backward; FW = forward; PPVT = Peabody Picture Vocabulary Test, 3<sup>rd</sup> edition.

\* $p \leq .05$ . \*\*  $p \leq .01$ .

Table 4

*Fixed and Random Effects of Tower of Hanoi Performance as a Function of Time*

Parameter	Fixed effects				Random effects	
	Coefficient	SE	t-ratio	df	Variance component	$\chi^2$
<i>Correct Trials</i>						
Intercept ( $\gamma_{00}$ )	8.2926	0.3734	22.21**	44	4.5950	172.76**
Days slope ( $\gamma_{10}$ )	0.0466	0.0097	4.78**	44	0.0026	114.40**
Level 1 residual ( $\epsilon$ )					2.2704	
<i>Max Level</i>						
Intercept ( $\gamma_{00}$ )	5.5325	0.1726	32.05**	44	0.9958	180.61**
Days slope ( $\gamma_{10}$ )	0.0127	0.0043	2.98**	44	0.0005	106.17**
Level 1 residual ( $\epsilon$ )					0.4670	
<i>Points-Level</i>						
Intercept ( $\gamma_{00}$ )	31.8540	2.1017	15.16**	44	127.3547	129.47**
Days slope ( $\gamma_{10}$ )	0.2791	0.0575	4.85**	44	0.0771	92.62**
Level 1 residual ( $\epsilon$ )					96.9746	
<i>Time/Moves</i>						
Intercept ( $\gamma_{00}$ )	5.3416	0.3787	14.11**	44	5.0255	212.94**
Days slope ( $\gamma_{10}$ )	-0.0273	0.0071	-3.84**	44	0.0009	70.65**
Level 1 residual ( $\epsilon$ )					1.9247	
<i>Errors/Moves</i>						
Intercept ( $\gamma_{00}$ )	0.0698	0.0087	8.14**	44	0.0023	140.56**
Days slope ( $\gamma_{10}$ )	-0.0011	0.0002	-6.00**	44	0.0000	55.01
Level 1 residual ( $\epsilon$ )					0.0015	
<i>Moves/Trials</i>						
Intercept ( $\gamma_{00}$ )	4.7209	0.1552	30.41**	44	0.5790	92.03**
Days slope ( $\gamma_{10}$ )	0.0048	0.0034	1.41	44	0.0000	29.60
Level 1 residual ( $\epsilon$ )					0.6944	
<i>Optimal-First-Moves</i>						
Intercept ( $\gamma_{00}$ )	6.7843	0.3037	22.34**	44	3.3256	232.13**
Days slope ( $\gamma_{10}$ )	0.0366	0.0080	4.58**	44	0.0021	157.31**
Level 1 residual ( $\epsilon$ )					1.1100	

*Note.* Performance outcomes are italicized. Fixed and random effects correspond to Equations 1-3.

\*\*  $p \leq .01$ .

Table 5

*Fixed Effects for Group Differences in Tower of Hanoi Performance*

Parameter	Experimental vs. Comparison		Experimental vs. Control		Comparison vs. Control	
	<i>t</i> -ratio	<i>df</i>	<i>t</i> -ratio	<i>df</i>	<i>t</i> -ratio	<i>df</i>
<i>Correct Trials</i>						
Intercept ( $\gamma_{00}$ )	2.38*	28	2.08*	28	0.10	28
Slope ( $\gamma_{10}$ )	-1.30	28	-0.55	28	0.80	28
<i>Max Level</i>						
Intercept ( $\gamma_{00}$ )	1.47	28	2.02	28	0.62	28
Slope ( $\gamma_{10}$ )	-0.93	28	-0.61	28	0.32	28
<i>Points-Level</i>						
Intercept ( $\gamma_{00}$ )	2.50*	28	1.68	28	-0.27	28
Slope ( $\gamma_{10}$ )	-1.25	28	-0.50	28	0.82	28
<i>Time/Moves</i>						
Intercept ( $\gamma_{00}$ )	-0.69	28	-1.23	28	-0.24	28
Slope ( $\gamma_{10}$ )	0.59	28	-1.45	28	-1.69	28
<i>Optimal-First-Moves</i>						
Intercept ( $\gamma_{00}$ )	2.52*	28	3.35**	28	0.99	28
Slope ( $\gamma_{10}$ )	-1.60	28	-0.97	28	0.81	28

*Note.* Performance outcomes are italicized. Inferential tests correspond to Equations 1, 4, and 5.

\* $p \leq .05$ . \*\*  $p \leq .01$ .

Table 6

*T-Ratios of Differences Between Tower of Hanoi Performance Outcomes and Control**Measures*

Parameter	Correct Trials	Max Level	Points-Level	Time/Moves	Optimal-First-Moves
Intercept ( $\gamma_{00}$ )	4.16**	8.01**	1.87	7.67**	4.73**
IN ( $\gamma_{01}$ )	2.58*	2.67*	2.78**	-1.83	1.44
WM ( $\gamma_{02}$ )	-0.32	0.41	-0.21	0.40	0.14
STM ( $\gamma_{03}$ )	0.56	-0.35	0.26	-0.53	0.19
VA ( $\gamma_{04}$ )	2.50	1.28	2.46*	-2.39*	1.75
Days ( $\gamma_{10}$ )	2.26*	2.37*	2.73**	-1.70	3.32**
IN ( $\gamma_{11}$ )	-2.05	-1.83	-1.65	1.47	-1.47
WM ( $\gamma_{12}$ )	0.66	0.02	0.54	-2.00	0.08
STM ( $\gamma_{13}$ )	-0.64	0.55	-0.33	0.14	-0.74
VA ( $\gamma_{14}$ )	-0.79	-0.89	-0.68	1.61	-0.81
$\Delta\mu_{0i}$	12.1%	9%	-	7.5%	4.9%

*Note.* For all *t*-ratios, *df* = 40. IN = inhibitory control; WM = working memory; STM = short-term memory; VA = verbal ability. Inferential tests correspond to Equations 1, 6, and 7.

\**p* ≤ .05. \*\* *p* ≤ .01.

Table 7

*Fixed and Random Effects of Tower of Hanoi Performance as a Function of Self-Explanations, Sub-Goals, and Obstructions*

Parameter	Fixed effects				Random effects	
	Coefficient	SE	t-ratio	df	Variance component	$\chi^2$
<i>Optimal-First-Moves</i>						
Intercept ( $\gamma_{00}$ )	6.6174	0.3216	20.57**	44	3.7121	101.55**
Days slope ( $\gamma_{10}$ )	0.0366	0.0079	4.62**	44	0.0020	103.93**
Self-Explanation slope ( $\gamma_{20}$ )	0.0194	0.0064	3.02**	44	0.0004	42.19**
Level 1 residual ( $\epsilon$ )					1.0429	
<i>Correct Trials</i>						
Intercept ( $\gamma_{00}$ )	3.8160	0.2252	16.95**	44	1.1113	57.64**
Days slope ( $\gamma_{10}$ )	0.0098	0.0034	2.89**	44	0.0012	58.03**
Sub-goal slope ( $\gamma_{20}$ )	0.0852	0.0032	26.86**	44	0.0002	56.14**
Level 1 residual ( $\epsilon$ )					0.3696	
<i>Correct Trials</i>						
Intercept ( $\gamma_{00}$ )	5.9940	0.3517	17.05**	44	3.1596	76.48**
Days slope ( $\gamma_{10}$ )	0.0316	0.0082	3.85**	44	0.0022	114.68**
Obstruction slope ( $\gamma_{20}$ )	0.1512	0.0155	9.77**	44	0.0036	52.31**
Level 1 residual ( $\epsilon$ )					0.9472	

Note. Performance outcomes are italicized. Fixed and random effects correspond to Equations 2-3 and 8-9.

\*\*  $p \leq .01$ .

Table 8

*Fixed and Random Effects of Optimal-First-Moves on the Tower of Hanoi as a Function of Time, Self-Explanations, and Strategy Use*

Parameter	Fixed effects				Random effects	
	Coefficient	SE	t-ratio	df	Variance component	$\chi^2$
<i>Optimal-First-Moves</i>						
Intercept ( $\gamma_{00}$ )	4.9430	0.4738	10.43**	44	5.6522	36.45**
Days slope ( $\gamma_{10}$ )	0.0225	0.0058	3.89**	44	0.0006	39.25**
Self-Explanation slope ( $\gamma_{20}$ )	0.0279	0.0072	3.90**	44	0.0004	26.37*
Sub-goal slope ( $\gamma_{30}$ )	0.0323	0.0053	6.04**	44	0.0005	20.37
Level 1 residual ( $\epsilon$ )					0.9208	
<i>Optimal-First-Moves</i>						
Intercept ( $\gamma_{00}$ )	6.1584	0.4744	12.98**	44	6.6157	37.07*
Days slope ( $\gamma_{10}$ )	0.0365	0.0081	4.53**	44	0.0021	66.15**
Self-Explanation slope ( $\gamma_{20}$ )	0.0284	0.0086	3.32**	44	0.0015	25.93
Obstruction slope ( $\gamma_{30}$ )	0.0297	0.0158	1.88 <sup>†</sup>	44	0.0039	23.70
Level 1 residual ( $\epsilon$ )					0.8105	

*Note.* Performance outcomes are italicized. Fixed and random effects correspond to Equations 2, 3, and 10.

<sup>†</sup> $p \leq .10$ . \* $p \leq .05$ . \*\*  $p \leq .01$ .

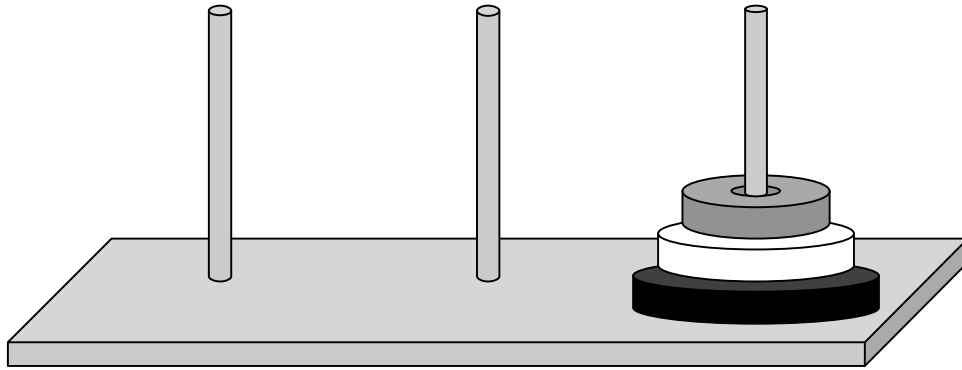
Table 9

*Fixed and Random Effects of Tower of Hanoi Performance as a Function of Box-Tower of Hanoi Performance*

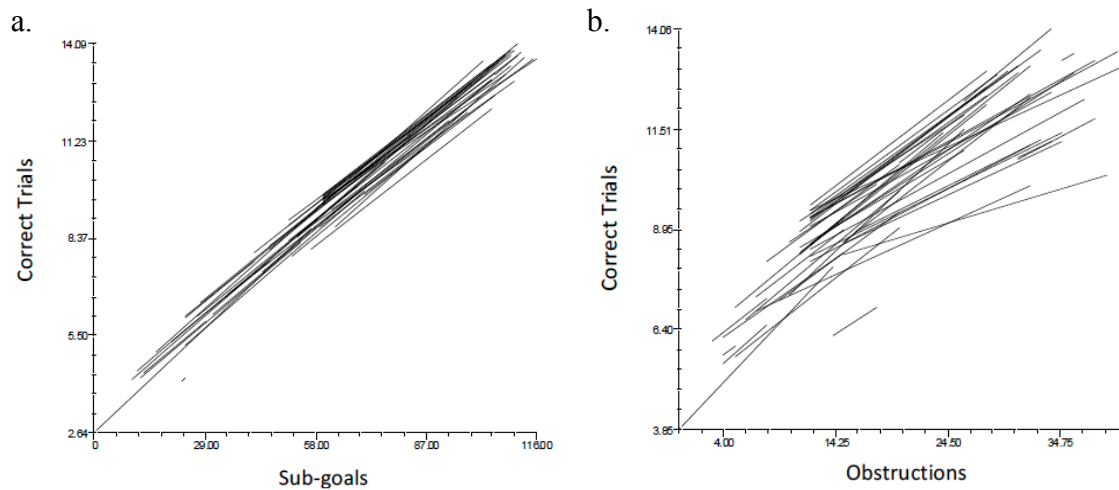
Parameter	Fixed effects				Random effects	
	Coefficient	SE	t-ratio	df	Variance component	$\chi^2$
<i>Correct Trials</i>						
Intercept ( $\gamma_{01}$ )	0.3115	0.1079	2.89**	43	3.3949	141.36**
Slope ( $\gamma_{11}$ )	0.0037	0.0035	1.05	43	0.0024	106.84**
Level 1 residual ( $\epsilon$ )					2.3446	
<i>Max Level</i>						
Intercept ( $\gamma_{01}$ )	0.1944	0.1250	1.55	43	0.8922	165.80**
Slope ( $\gamma_{11}$ )	0.0039	0.0031	1.25	43	0.0004	100.07**
Level 1 residual ( $\epsilon$ )					0.4792	
<i>Points-Level</i>						
Intercept ( $\gamma_{01}$ )	0.2790	0.0971	2.87**	43	87.8307	105.69**
Slope ( $\gamma_{11}$ )	0.0037	0.0029	1.29	43	0.0684	85.14**
Level 1 residual ( $\epsilon$ )					101.3002	
<i>Time/Moves</i>						
Intercept ( $\gamma_{01}$ )	0.6211	0.1158	5.37**	43	2.4079	117.63**
Slope ( $\gamma_{11}$ )	0.0017	0.0027	0.65	43	0.0008	68.45**
Level 1 residual ( $\epsilon$ )					1.9650	
<i>Optimal-First-Moves</i>						
Intercept ( $\gamma_{01}$ )	0.3440	0.1102	3.12**	43	2.4920	191.00**
Slope ( $\gamma_{11}$ )	0.0036	0.0032	1.12	43	0.0020	149.58**
Level 1 residual ( $\epsilon$ )					1.1347	
<i>Self-Explanations</i>						
Intercept ( $\gamma_{01}$ )	0.3632	1.4307	0.25	43	55.8537	41.61
Slope ( $\gamma_{11}$ )	0.0653	0.0386	1.69	43	0.0053	18.20
Level1 residual ( $\epsilon$ )					174.4840	
<i>Sub-goals</i>						
Intercept ( $\gamma_{01}$ )	0.3061	0.0967	3.17**	43	160.8624	74.87**
Slope ( $\gamma_{11}$ )	0.0016	0.0027	0.59	43	0.0575	51.54
Level 1 residual ( $\epsilon$ )					412.4144	
<i>Obstructions</i>						
Intercept ( $\gamma_{01}$ )	0.2400	0.1016	2.36*	43	14.0783	56.56
Slope ( $\gamma_{11}$ )	0.0012	0.0028	0.42	43	0.0009	28.70
Level 1 residual ( $\epsilon$ )					68.3543	

Note. Performance outcomes are italicized. Fixed and random effects correspond to Equations 11-13.

\*  $p \leq .05$ . \*\*  $p \leq .01$ .

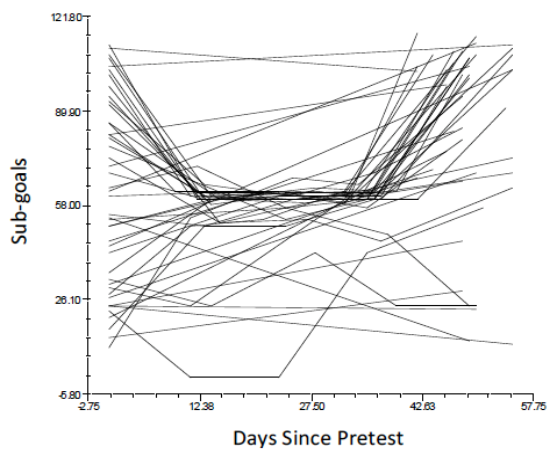


*Figure 1.* Illustration of the Tower of Hanoi.



*Figure 2.* Average sub-goal strategy trajectories (a) and average obstruction strategy trajectories (b) on the Tower of Hanoi as a function of days since pretest.

a.



b.

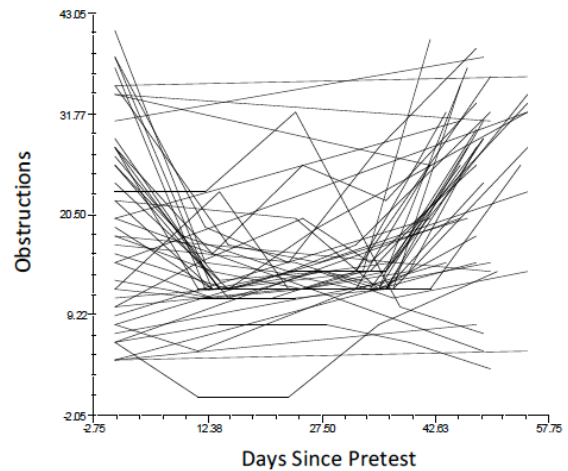


Figure 3. Individual sub-goal strategy trajectories over time (a) and individual obstruction strategy trajectories over time (b).