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This thesis submitted in total fulfilment of the degree, which is not jointly awarded.
Declaration

This is to certify that

This thesis comprises the author’s original work,

Due acknowledgement has been made in text to other material used,

The thesis is less than 100,000 words in length.

Elizabeth Thomas
Abstract

This thesis examines the development of complex executive functions in primary school children as the ability to co-ordinate different processes, such as rule use, error monitoring and spatial memory, in order to obtain a behavioural goal in The Groton Maze Learning Task (GMLT). Four studies showed that spatial memory and error monitoring processes were independent in that they developed at different rates and were separable with experimental manipulations. GMLT measures showed different patterns of association with other neuropsychological tests of error-monitoring and spatial sequence learning. Results are discussed in relation to the development of executive functions.
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Thesis Presentation

This thesis is submitted as a series of two review and four empirical articles addressing a central theme, in accordance with The University of Melbourne, School of Graduate Research guidelines for submission of a Thesis with publication. These guidelines can be viewed at:


Three of the four articles presented in this thesis have been published in internationally refereed scientific journals. Co-authors acknowledge that 80-to-90 percent of the work on each publication was attributable to the first author (Elizabeth Thomas). In addition, the review of hidden pathway maze learning in chapter 2 was also published in a modified form not specific to the thesis topic. Published articles will appear in the thesis as they appear in print version. References in published papers are replicated in the final reference list. Thesis chapters are presented in format specified by the American Psychological Association (6th Edition).

Each of the chapters and article presented here are written to form separate parts of a cohesive thesis, and as stand-alone investigations. For this reason, in text references for each chapter will be cited as if each chapter was independent, and all references in unpublished chapters will be presented at the end of the thesis. For example, the first reference to (Pietrzak, Cohen & Snyder, 2007) in chapter 3 will be cited in subsequent references in chapter 3 as (Pietzak et al., 2007). The first reference to the same citation in chapter 4 will appear as (Pietrzak, Cohen & Snyder, 2007) and as (Pietzak et al., 2007) in subsequent references in chapter 4. This is to ease reading of each chapter. An introduction will be presented at the
beginning of each empirical chapter that are structured to allow the reader to understand the context in which each study was conducted and the inter-relationships between each article in relation to the theme of the thesis. Chapter 1 provides a brief overview of the theoretical background and methodological limitations of prior studies that inform the rationale for this thesis, and the methodological approaches designed to test hypotheses arising from this rationale. Chapter 2 reviews hidden pathway maze learning, as it is the main task used in the studies presented. Chapter 3 is a literature review of the study of executive functions in children as this is the main topic of the thesis. Chapter 3 presents arguments that defend the rationale for this thesis. Chapters 4-to-7 are empirical studies, and chapter 8 considers the conclusions derived from this thesis in a general discussion.
Chapter 1: The Research Problem

1.1 Introduction

Everyday problem solving requires the coordination of different means to reach goals. In his doctoral thesis, Case (1970) observed that young children had difficulty coordinating the different components of a maze learning task and this difficulty was most evident in ‘forgetting’ of one or more of the task requirements. He noted that each of the task requirements could be performed in isolation such as avoiding contact with the path perimeter, or maintaining the end-goal destination. Forgetting task components was interpreted as a function of the number of task elements to monitor. Therefore the difficulty in coordinating task requirements indicated a limitation in processing simultaneous information.

Difficulty coordinating the elements of a problem has been widely reported in adult neuropsychology (Duncan, 1995; Duncan, Emslie, Williams, Johnson, & Freer, 1996; Konow & Pribram, 1970; Sanderson & Albert, 1984) and in developmental psychology (Cepeda & Munakata, 2007; Manakuta, Morton, & Yerys, 2003; Towse, Lewis, & Knowles, 2007; Zelazo, Frye & Raptus, 1996; Zelazo, 2004). Cognitive co-ordination may be understood within the context of executive functions and working memory. Luria provided the first definition of executive function as: “…the essential apparatus for organizing intellectual activity as a whole, including the programming of the intellectual act and the checking of its performance” (1973, pp. 340). Theories of working memory posit a limit to the amount of information that can be processed concurrently, whether due to
attention, bias, or some other limiting factor (Cowan, 2010; Diamond, 2009; Halford, Baker, McCreddin & Bain, 2005; Happeney & Zelazo, 2003; Jarrold & Towse, 2006). Coordination difficulties may be understood as a limitation in the ability to prioritize and monitor component processes in achieving a goal. This characterization is consistent with definitions of executive function as a process of integrating, or coordinating multiple streams of information (Koechlin & Summerfield, 2007).

Although the coordination of cognitive processes has been widely studied in preschoolers (Henry & Bettenay, 2010), much less attention has been paid to the development of this ability in the early school years (Best, Miller, & Jones, 2009). Neuropsychological researchers have tended to focus on the development of component skills in isolation (e.g., working memory, inhibition, set shifting and updating: Lehto, Juujävvi, Kooistra, & Pulkkinen, 2003; Luciana & Nelson, 1998, 2002). Developmental theorists describe how conceptual structures emerge that can accommodate increasingly complex representations (Case, 1992; Marcovitch & Zelazo, 2009). Essential to a neuropsychological or development account of cognitive abilities is an understanding of how skills that develop on different time scales are coordinated toward a common goal. Approaches to studying multi-component aspects of complex cognition in neuropsychology have typically used dual task and conflict methodologies (e.g. inhibition tasks and switching tasks: Carlson, 2005), or multi-step planning tasks (e.g. Tower tasks and self-ordered planning or searching tasks: Luciana & Nelson, 2002; Welsh, Pennington, & Grossier, 1991). Characterizing the nature of cognitive coordination could be advanced by the use of tasks that do not rely on the resolution of conflict between competing goals, or strategic skills for forward planning. If component skills
necessity for a task must operate in co-operation then understanding how coordination fails would provide useful insights into the nature of executive functions.

Studying executive functions in the early school years poses challenges (Hughes & Graham, 2002). Of necessity, executive functions are exhibited within specific task domains (e.g., linguistic, numerical, or spatial). It is important to conduct research on executive functions in an area known to be developmentally intact. Preschool and young school-aged children’s ability to demonstrate complex problem solving skills also depend on motivational factors, and depth of task understanding (Reeve, Campione, & Brown, 1986). Consequently, many test batteries are suitable only for a restricted age range (e.g., Behavioral Assessment of the Dysexecutive Syndrome for Children [BADS-C]; Emslie, Wilson, Burden, Nimmo-Smith, & Wilson, 2003). This limits inferences that can be made about the development of a construct because different tasks must be used to measure the construct across age groups, in which the focal nature of the tasks may differ. Finally, many tests of executive function rely on the discovery of strategies for problem solving (e.g., The Wisconsin Card Sort, Tower of London and the CANTAB Spatial Working Memory Task: Anderson Northam, Hendy & Wrennall, 2001, pp93-98; see Best et al., 2009 and Best, Miller, & Jones, 2010 for reviews of executive function tasks). Once the optimal strategy is discovered, performance improves (Hughes & Graham, 2002). One consequence of this is that it reduces the test-retest reliability, even when parallel versions of the task are available. It also limits the amount of practice children can have on a task to become familiar with the task requirements. What is needed is an age-appropriate,
but complex EF task that can identify the sources of performance variability that can be interpreted within a child neuropsychological context.

Understanding the development of complex executive functions in school-aged children is optimal if tasks are selected that do not require language-based responses or depend on adherence to complex rules that are given linguistically and then only once (e.g. Reading Span: Daneman & Carpenter, 1980, Color-Word Stroop: Stroop, 1935, or N-Back: Kitchner, 1958). The ability to train children on a task therefore measures the ability to perform a task rather than the ability to learn the task requirements. There are at least two main issues for studying the development of cognitive coordination within an executive function framework. First, it must be possible to identify the elements that must be coordinated to solve the task. Second, it must be possible to manipulate/modify the task to examine factors that affect the coordination of the underlying components. Consideration of the nature of hidden pathway maze learning suggests that this paradigm has good potential for understanding the development of complex executive functions in young school-aged children.

The Groton Maze Learning Task (GMLT) was developed for use in adults but has been shown to be valid for assessing EF in children. The movement rules and goal of the GMLT are embedded in a simple game-like structure. Step-wise discovery of a pathway hidden beneath a field of tiles depends on the deployment of pre-trained rules and the use of error information after each move (Snyder, Maruff, Pietrzak, Cromer, & Snyder, 2008; Thomas, Reeve, Fredrickson, & Maruff, 2011). Children as young as 5-years-of age can acquire the task rules with minimal instruction and practice (Mayes, Snyder, Langlois, & Hunter, 2007; Schroder, Snyder, Sieski, & Mayes, 2004; Snyder et al., 2008b; Thomas et al.,
Importantly, studies have shown the independence of spatial memory and rule use measures of hidden pathway maze learning in clinical populations with disruption to the prefrontal cortex or the hippocampus (Milner, 1965; Milner, Corkin & Tueber, 1968; Pietrzak, Maruff, & Snyder, 2009a; Pietrzak, Snyder, Jackson, Olver, Norman, Piskulic, & Maruff, 2009b; Thomas et al., 2011). However conclusions about the independence of the spatial memory and rule use components of maze performance have been based on post-hoc analyses of adult clinical data. Investigating the independence of rule use and spatial memory processes in normally developing children is a preliminary step in understanding the nature of cognitive coordination development within this task. The rule structure, feedback and appearance of the GMLT can also be modified, thereby allowing analysis of the effect of manipulations of different task parameters to performance. Identifying factors that affect the coordination of intact underlying elements of problem solving would provide an important contribution to understanding the nature of executive functions in children.

The thesis presents studies that demonstrate how task complexity, visual task support, and training affect children's memory and rule use/error feedback coordination in the GMLT. Chapter 2 reviews the HPMLT paradigm in neuropsychology. Although the test has long been considered a measure of adaptive behavior and prospective planning, contemporary accounts of the task have focused on clinical significance, than theoretical analysis. It is argued that interpretations of HPMLT performance have been limited by the use of single outcome measures. Only by considering the nature of different errors can inferences regarding the underlying cognitive processes be made. Chapter 3 presents a critical examination of empirical approaches to the study of executive
functions. It is argued that understanding the development of executive functions would be advanced by the use of tasks that measure the ability coordinate separate identifiable processes. This is important because previous work has focused on the emergence of individual control functions. However little is known about how young school-aged children manage complex information in executive function tasks. For example, it would be expected that more recently acquired skills would be more easily disrupted experimentally than older, more established skills (Kuhn, 2000; Reeve et al., 1986). Identifying the effect of task manipulations on cognitive functions sub-serving a task provides a method for investigating the developmental nature of cognitive coordination. The Chapter describes how the GMLT can be modified to investigate the development of cognitive co-ordination in children. Hypotheses are offered along with the design of empirical studies to test them. Four studies are reported.

1.2 Summary

In summary, the purpose of this thesis is threefold. The first aim of this thesis is to explore the effect of age and difficulty on children’s errors on the GMLT. Ceiling or floor effects would indicate the appropriate task difficulty level according to age. The second aim is to gain a better understanding of the nature of children’s problems coordinating task requirements by decomposing performance at the level of task difficult when performance deteriorates. By identifying the cognitive functions that contribute to performance deterioration, the third aim is to design studies that can support those functions and improve performance. Finally, it is intended to investigate the relationship between spatial memory and rule use/error use measures in children in order to characterize the developmental relationship between what are considered to be independent functions in adults.
Investigation of these questions would allow a more complete account of the development of executive functions with regard to the development and coordination of HPMLT sub-processes.
Chapter 2

Behavior at the choice-point: An historical review of theory, methods and design in the development of Hidden Pathway Maze Learning in Psychology.

“Much of our thinking goes beyond imagery and involves symbolization. Many of our ideas come as insight into complete relationship of things. Maze learning as an ideation process shows that insight may come gradually as the relationships are gradually grasped and coordinated in some symbolic manner by the mind.” (Chase, 1934, pp 438).

2.1 Introduction

The purpose of this chapter is to argue for the relevance and utility of hidden pathway maze learning paradigms for assessing executive functions and spatial memory in neuropsychological contexts, including children. The first proposition is that HPMLT have a long history in neuropsychology as a measure of delayed forward planning as evidence of the short-term formation of the representation of a spatial layout: Improving knowledge of a spatial plan with experience was associated with adaptive behaviour in discriminating turns toward a goal. It is argued that historical interpretations of HPMLT behavior are broadly consistent with contemporary concepts of executive function and spatial sequence learning. The second proposition is that HPMLT measures component processes of rule use and sequence memory that are partially independent. It is argued that investigating component processes in HPMLT is useful for understanding the development of complex spatial memory processes in children within the framework of cognitive coordination.
Hidden pathway maze learning tests (HPMLTs) require a participant to find the direction of a pathway hidden beneath a small-scale array of alleys, or stepping-stones across repeated trials. These tests differed in structure, requiring the use of a stylus to traverse peg-and-grove alleys, or finger/stylus responses to jump from tile-to-tile within a grid of locations. However, HPMLTs were commonly developed by American researchers in the early decades of the 20th century to investigate spatial reasoning and learning. The stepping-stone variant of the HPMLT paradigm has gained prominence in modern neuropsychology as a test of visuospatial learning and executive function (Bowden & Smith, 1994; Walsh, 1985). Hidden pathway maze learning has remained a useful model of cognitive function in neuropsychology because they are relatively brief to administer and are understood easily by healthy children and adults. Furthermore, children with reduced intellectual capacity due to brain damage or disorder have been able to perform HPMLTs because of the simplicity of their rule structure (Schroder, Snyder, Sielski, & Mayes, 2004). Despite the simplicity and brevity of the stepping-stone HPMLT, every move represents a discrete decision point and consequently a large volume of informative data can be obtained within a few minutes of task performance (e.g. the Groton Maze Learning Task (GMLT): Snyder, Bednar, Cromer, & Maruff, 2005). Computerized versions of such tasks have allowed for greater analytical scope than manual predecessors of the task because every move can be recorded, classified, and replayed. More importantly, when alternate pathways of the task are available, performance by healthy, or brain damaged participants shows no evidence of practice effects, which is an extremely rare quality in neuropsychological assessment. These factors make HPMLTs ideal for use in repeated measures research designs (e.g. Snyder, Jackson, Piskulic,
Olver, Norman, & Maruff, 2008a). These characteristics have allowed researchers to build brain-behavior models on the basis of general performance effectiveness (i.e. from analysis of total scores) and also by allowing analysis of the component cognitive processes as well as their integration (Pietrzak, Maruff, & Snyder, 2009a; Thomas, Reeve, Pietrzack, & Maruff, 2013). The HPMLT model has been a useful tool in neuropsychology because impairment and improvement in spatial reasoning and memory functions can be reliably measured over the course of normal development, and across a range of neuropsychological disorders and treatment interventions (Pietrzak, Cohen, & Snyder, 2007; Snyder et al., 2008a; Thomas, Reeve, Fredrickson, & Maruff, 2011).

While computerized HPMLTs are relatively new to neuropsychology, maze learning itself has been used to study adaptive goal-related behavior since the formalization of psychological science (Hamilton, 1911; Melrose, 1922; Ruckmick, 1921; Small, 1901). Current concepts of executive function (Lezak, 1982) and spatial memory (Kessels, deHaan, Kappelle, & Postma, 2001; O’Keefe & Nadel, 1978) were derived from maze learning methodologies designed to investigate behavior that was structured toward a physically remote, or future goal (Melrose, 1922; Ruckmick, 1921). It is argued that the historical investigations of motivation and learning are continuous with contemporary investigations of spatial memory and error monitoring. Analysis of the development of maze learning methodologies is important for understanding the theoretical relevance of HPMLT paradigms for neuropsychology. This review is also intended to show that the HPMLT paradigm is a potentially useful and defensible paradigm for investigating cognitive development in children. This theme will be explored in greater detail in
chapter 3 regarding approaches to studying the development of executive functions.

In the first section of this review we examine the historical considerations through which the stepping-stone variant of HPMLT was developed and analyzed. In the second half of the review, the modern uses of HPMLTs are considered, specifically focusing on use of versions of the stepping-stone maze in neuropsychology. It is argued that qualitative and quantitative analysis of performance is necessary for characterizing change, or difference in cognate abilities in clinically meaningful terms. Finally we discuss the implications of issues raised in this review and suggest directions for future research. This chapter was written for this thesis, but has also been published in a modified form: Thomas, E., Snyder, P. J., Pietrzak, R. H., & Maruff, P. (2014). Behavior at the choice point: Decision making in hidden pathway maze learning. Neuropsychology Review, 24, 514–536. doi:10.1007/s11065-014-9272-7

2.2 Hidden pathway maze learning: Historical considerations

In the introduction to the first edition of the Journal of Experimental Psychology, Trumball Ladd (1894) outlined the historical background to the objectives of the American Psychological Association (APA) by asking the question: “How shall we regard the science of mental life as related to the methods and conclusions of the most nearly allied physical sciences, to philosophy, and to human action and character?” (Trumball Ladd, pp 3). One of the aims of the APA at that time was to establish scientifically credible protocols and methods for investigating complex mental and behavioural processes in non-teleological and non-metaphysical terms (Hatfield, 2002; Trumball Ladd, 1894). For these reasons, maze learning paradigms were adopted early in psychological contexts because
they exploited rodent capacities to explore labyrinthine environments for ecologically salient rewards (Small, 1901) and allowed for the study of human behaviour within a controlled and modifiable paradigm. The HPMLT paradigm met the standards required of an objective factual science from which intelligent, problem-solving behaviour could be interpreted with regard to a cross-species ‘natural history of the mind’ (Small, 1901, p. 222).

From the beginning of comparative psychology (e.g. Darwin, 1871), the cognitive functions of animals and humans, especially children, in maze learning were considered sufficiently similar to regard common behaviours as reflecting a shared intellectual foundation (Hatfield, 2002; Lockard, 1971; Tolman, 1938; Small, 1901). Specifically, researchers in comparative psychology based their models on the assumption that animals and humans rely on common trial-and-error methods for problem-solving (Small, 1901, Hamilton, 1911). The trial-and-error exploration required by maze learning was therefore well-suited to the objectives of early psychological science for investigating selective processes underlying adaptive behaviour, on the basis that discrimination learning was the “basis of each and every act” (James, 1890 cited by Ruckmick, 1921, p. 3-5; Stephens, 1935). Tests of discrimination learning were also central to advancing theories that defined intelligence according to the ability to monitor performance on a complex task and adapt responses for the efficient pursuit of an end goal (Binet & Simon, 1909: cited in Peterson, 1922, pp 370; Porteus, 1918). Decisions made at each choice-point in a maze provided units of behaviour that could be analysed according to the ability to learn correct turns in the path from a blind alley (Brown & Buel, 1940; Hamilton, 1911; Miles, 1927; Peterson, 1920, 1922; Spence, 1932; Warden, 1924a, 1924b, 1925). The maze context was important because it allowed
for the study of behaviour when there is only partial knowledge of the
environment: It was not simply a method for studying the learning process, but
rather a method for measuring how an animal determines the nature of the
environment (Tolman, 1948). Researchers investigated how expectancies of a task
solution developed by the extent to which ineffective ‘habits’ of entry into blind
alleys were eliminated (Brownwell, 1939; Lashley, 1923; Muenzinger, 1927;
Pepper, 1934; Perry, 1918; Peterson, 1922; Tolman, Hall, & Bretnall, 1932). Thus,
in animal studies maze learning was considered an appropriate operational
definition for higher cognitive processes because it involved “the capacity to take
in a large situation, and by response to remote conditions to delay action and
inhibit motor tendencies aroused by immediate stimuli until they have been
coordinated with the larger circumstance” (Peterson, 1922, pp 387). Maze learning
was therefore regarded as a measure of intelligent learning in which the experience
of previously encountered elements of the maze was used to guide decisions
toward a future state of reward (Peterson, 1922), such as food in animals, or task
completion in humans. In general, maze learning was described as a complex
process of eliminating and integrating behavioral tendencies, or representational
elements of a cognitive map, in learning a maze pattern (Hull, 1932, 1934a, 1934b,

One important characteristic of the rodent maze learning paradigm was that it
could be applied largely unchanged to study problem solving in humans
(Hamilton, 1911; Miles, 1927; Warden, 1924a, 1924b; 1925). In humans, early
studies of maze learning were conducted using small-scale, table-top mazes with
subjects blindfolded and using their finger to process tactual cues (Chase, 1934;
Koch & Ufkess, 1926; Melrose, 1922; Scott, 1930; Warden, 1924b). Blindfolding
in humans was argued to allow for direct comparison of the cognitive processes involved in maze learning between animals and humans: deprivation of vision made maze learning dependent on motor cues, as seemed to be the case for rodents (Melrose, 1922; Warden, 1924b). According to Small (1901), tactual-motor experience was fundamental to spatial perception. It was generally argued that by blindfolding, the primitive basis of experience in kinaesthetic and motoric cues could be studied directly without the overlay of latter evolving visual and linguistic processes (Brownwell, 1939; Peters & McClean, 1935; Warden, 1924b).

2.3 The development of the hidden pathway maze learning paradigm

Although the use of blindfolding was intended to make human and animal maze learning paradigms similar, the deprivation of vision and forced reliance on tactual-motor information was not a normal context for assessing learning and cognition in humans. For example, the participants in Jensen’s (1934) study required approximately 22 trials and made over 200 errors, with or without punishment by electric shock, to negotiate a blindfolded 30 choice point maze (e.g. see Figure 2.3.1).
Figure 2.3.1. Jensen, M. B. (1934). The effect of punishment by electric shock for errors on a raised finger maze. The blindfolded participant negotiates a maze with a stylus in the right hand. He receives shocks for errors via immersion of left-hand fingers in a salt-bath rheostat attached to an electric circuit.

The blindfolding method used in maze learning studies was observed to cause confusion in humans with regard to orienting to the maze for discovery of the pathway direction (Gould & Perin, 1916; Peterson, 1920). Errors arising from the disorientation in blindfolded maze learning were instead interpreted as frustration leading to ‘non-rational’ behaviour such as repeating mistakes and perseverating at points of disorientation (Barker 1931; Peterson, 1920). Consequently, apparatus emerged that were designed to reduce the artificiality of tactual maze learning tasks for humans and with restricted visual information without blindfolding, but which retained the focal construct of maze learning as a method for studying
‘rational behaviour’. For example mazes were developed that allowed indirect visual control such as a map, or ‘two-story duplicate’ maze (Miles, 1927- see Figure 2.3.2), or the use of hidden stops for hiding the path in a peg-groove stylus maze (Carr, 1921- see Figures 2.3.3 to 2.3.4).

In the Miles (1927) maze, the maze layout could be seen from the top. However, the top view maze was useful only for negotiating the bottom maze hidden from view if some form of visuo-tactile transformation could be used to bring the two mazes into alignment. In the Carr (1921) maze, the entire maze problem is revealed, but slotted grooves hold the stylus in place (Figure 2.3.3), and physical stops beneath the visible apparatus signal entry into blind alleys (Figure 2.3.4). In both examples, the maze layout could be seen, but required transformations such as image rotation (Miles, 1927), or memory for the location of blind alleys (Carr, 1921). The innovation of partial visual cues to the maze layout overcame the impedance of blindfolding to maze learning while preserving the complexity of the task as a spatial learning paradigm. In studies from the early decades of the 20th century, the role of visual guidance on acts of skill in a motor task were discussed in theoretical and practical terms (see also, Koch, & Ufkees, 1926; Warden, 1924a). Mainly, researchers were concerned with how symbolic knowledge of space, or ‘ideation’ is built from the interaction of sensory cues with intellectual processes (Carr, 1921; Chase, 1934; Cox, 1928; Perin & Gould, 1914; Sartian, 1940; Tilborg, 1936; Warden, 1924a, 1924b, 1925). Chase (1934) concluded that in ideational learning all senses are utilized in order to coordinate the central organization of ideas beyond language and imagery.
Figure 2.3.2. The two-storey duplicate maze (Miles, 1927). The participant must learn a pathway through a stylus maze on the lower section hidden from view. On the top panel, an identical maze may be used to guide tactual move selection. Note that lower maze is an inverse of the top maze.

Figure 2.3.3. Stylus grooves in the Carr maze (Carr, 1921). Slotted grooves are used to hold the stylus in place within the maze after entry, until exit at the end point.

Figure 2.3.4. The pathway of the Carr maze with the position of stops indicated by dashed lines across the pathway. A represents the entry, and B represents the end position. See Griffith (1931) for an electrical Carr maze.
The use of indirect visual guidance, as a practical concern in maze learning paradigms, presented another methodological problem for designing apparatus for use in humans that had not been so important in blindfolded mazes. For example, in a blindfolded maze, the number and length of turns at a choice point are not apparent from the outset of the task, as they are when the maze layout can be scanned visually. Only tactual and kinaesthetic exploration of the alleys one-at a time can reveal the spatial array, upon which future choice point selection can be made when a location is revisited in future trials (Cox, 1928). However, in mazes that are partially revealed, all alleys and turns are immediately present for visual selection at any given choice point. It was recognized that the length and number of turns, as well as the direction to the visible end-goal could influence the probability of selecting an alley. As focus turned from the number of errors or trials to task completion in maze learning to the probability of selecting particular turns (Tolman, 1938; Hill, 1939; Hull, 1932; 1934a, 1934b), consideration of the maze layout became more important (e.g. Jones & Yoshioka, 1938; Warden, 1921). Researchers consequently designed standardized maze apparatus in which every alley was of equal length and with the same number of blind alleys with a single correct alley available for selection at every choice-point (Griffith, 1931; Warden, 1924a). By standardizing the configural aspects of maze pathways, such as the number and direction of turns, and the length of the alleys, the task could be analysed as homogenous units with equal potential for selection (Warden, 1924a: see figure 2.3.5).
Figure 2.3.5. The standardization of maze alley length and number of blind alleys in a stylus maze used by Warden (1924a).

The introduction of electrically mediated visual and auditory feedback signals allowed development of maze learning paradigms in which blind alleys could be signalled symbolically, for example by activating a light or a buzzer when a blind alley was entered, rather than relying on physical stops to indicate dead ends (Barker, 1931; Faber & Berman, 1938; Gilbert, 1934; Gurnee, 1938; Razran, 1936, 1939). Furthermore, the ability to signal errors at every move made the need for physical alleys redundant. The maze could be represented by a field of locations, each of which could be selected one-at-a-time like stepping-stones, with immediate feedback for each step as correct or incorrect. Hence, movement along a series of stepping-stones could be equated with the forward movement or turns allowed by the alleys in a tactual maze. Contiguous points in the surrounding grid defined movement options spatially. Movements in the maze were therefore standardized because every step in the maze pathway gave rise to equal and identical response options for horizontal and vertical moves in a two-dimensional space. In electrical mazes, each location was connected to a contact plate, or screw head contacts wired into an electrical circuit. The circuit was designed so that true points in the
pathway gave different feedback to correct and incorrect locations with lights, buzzers, clickers, or shocks, but the pathway itself was not visually revealed (see Figure 2.3.6).

![Figure 2.3.6](image)

*Figure 2.3.6.* The underside-wiring diagram of the Barker (1931) maze. The bold line represents the pathway, and the fine lines signal errors with a buzzer.

Barker, (1931), Griffith (1931), Gurnee (1938) and Faber & Berman, (1938) describe similar electrical stepping-stone apparatus. In the Barker (1931) Stepping Stone Maze a 13 x 13” square grid with 169 equidistant screw points formed the homogeneous maze field (Figure 2.3.6). A 14-step pathway was connected to buzzer that was activated by a thimble stylus on contact. Rewiring the order of the screws could change the pathway. Adjacent incorrect locations were connected to a counter clicker to record and signal errors. Barker describes the possible uses and variations in the maze design, such as creating a 3 dimensional maze, but does not specify any rule structure, or a criterion for task completion, nor were these variants used experimentally.
Faber and Berman (1938) describe a variable electrical contact maze with 1025 screw head contacts in a 41 x 25 maze grid with a red, green and white light for signaling responses. Each screw was connected to a double throw switch that could change the valence of the feedback and thereby determine the form of the pathway. Although the apparatus was not used experimentally, errors were to be scored by the experimenter. Faber and Berman also describe a maze design developed by Razran (1936, 1939) consisting of a fixed pathway 20 x 20 bolthead maze with red and blue feedback signal lights. However Razran’s studies were concerned with salivation conditioning with light reinforcement in which the maze itself was treated as an unsolvable distracter task.

The advantage of the stylus grid maze over traditional alley-way maze paradigms was that by presenting the maze as a homogenous grid of stepping-stones, the pathway to be solved could not be mapped visually onto alleys. By restricting the field of visual attention to the immediate location in the pathway, the maze could only be discovered through individual trial and error movements at each choice point, rather than by forward visual exploration of alleys. In this way, a complex task was reduced to a series of simple decisions at standardized choice-points, revealed in manual choices based on the ability to develop and apply a mental representation of the task. Electrifying the feedback also removed the influence of the experimenter on performance and allowed for automatic recording of each move (see Ruckmick, 1927, for an electrified version of the Warden maze).

Gurnee (1938) and Mann & Jewell (1941) first described a rule structure to guide performance in the stepping-stone maze. A rule structure is useful in stepping-stone maze designs because moves are not physically restricted to contiguous alleys as they are in the alley stylus mazes: In stepping-stone mazes moves can be made anywhere
in the grid. Therefore to measure maze choice-point behavior consistent with a stylus
maze, rules must be imposed, for example, to limit possible choices to immediate
contiguous locations. Mann and Jewell used a 12 x 8 bolthead maze in which the
starting point was set in the top left corner, and the finish at the bottom right corner
(see Figure 2.3.7). Individuals were instructed to find the 35 step pathway by moving
only one position in any direction, and if the choice was incorrect, to return to the last
correct tile and from there make a new choice.

Figure 2.3.7. The Mann and Jewell bolt head maze (1941). Participants were to find a
pathway traversing the contra-lateral corners of the grid, one step at a time, returning
after errors before resuming a search.

After each move a light indicted whether the chosen locations was correct and
individuals were instructed to move through these locations as accurately and rapidly
as possible. Early maze formats differed considerably in the point choice
requirements: Alley mazes required discrimination of 2, or 3 non-diagonal choice
point turns, and early stepping stone mazes allowed 7 choice point locations, that is,
they allowed diagonal moves, in addition to left or right turns, or straight ahead movements (e.g. Barker, 1931; Mann & Jewell, 1941). In this type of apparatus, the requirement to return to the last stepping-stone after any error (i.e. return to the last correct location) was equivalent to the requirement to exit blind alleys in stylus mazes.

The development of the stepping stone maze was a technological advance in the automation and standardization of apparatus in psychology. Most studies describe the stepping-stone maze in practical terms of attempts to control extraneous aspects of the task, such as biased expectation of turns, or frustration from disorientation in the maze (Barker, 1931: Faber & Berman, 1938). The development of theoretical models of maze learning measures appear as something of an after-thought raised to consider the consequences of the methodological manipulations of the task itself. However, this conferred a statistical advantage for analyzing the units of complex behavior, insomuch as the elements of cognition could be studied as individual decisions, and as a unified whole, such as goals, expectations and immediate behavioral determinants (Jones & Yoshioka, 1938). Theories of complex volitional learning behavior developed throughout the 20th century did not focus on the stepping stone maze (e.g. Tolman, 1939) because it was rarely used until the latter half of the 20th century. However the potential for use of HPMLT paradigm in theoretical inquiries of spatial reasoning is apparent from quantitative and qualitative analysis of maze performance in at least one study (Jones & Yoshioka, 1938).

2.4 Analysis of performance in early hidden pathway maze learning studies.

Animal and human performance in hidden maze pathway learning was usually expressed as a reduction in errors over trials also termed a learning curve (Gould &
Perin, 1916; Lambert & Ewart, 1932; Thurstone, 1933). However, researchers of both animal and human behavior were also interested in qualitative parameters of the learning processes, such as the rate of elimination of specific choice points in relation to the end goal (Hull, 1934a, 1934b; Jones & Yoshioka, 1938; Peterson, 1920). It was observed that some turns were harder to learn than others, therefore in accounting for maze behavior it was important to understand how habits and expectancies of a maze solution changed with experience (Brown & Buel, 1940; Hill, 1939; Hull, 1934, Jones & Yoshioka, 1938; Meunzinger, 1927; Meunzinger & Vine, 1941; Tolman, 1932, 1938; Voeks, 1948, but see Mann & Jewel, 1941). Rather than simply analyzing learning curves, it was increasingly common to analyze qualitatively distinct categories of errors that related to different types of behaviors, such as anticipation of turns, or avoiding correct turns that lay in the opposite direction to the end goal (Brown & Buel, 1940; Jones & Yoshioka, 1938). By analyzing how different errors changed with experience it was possible to describe how ‘schemes of control’ are built through experience that distinguish learning efficiency (Gould & Perin, 1916, pp 142) and to develop theories of complex behavior (Hull, 1934; Tolman, 1938). Theories of maze learning were concerned with anticipatory and avoidance behavior that could not be simply explained by association learning, but required considerations of goals or purpose through qualitative and quantitative analysis (Hull, 1934a; Pepper, 1934; Perrin, 1923; Tolman, 1932).

Although HPMLTs were used extensively in the first half of the 20th century, only a few studies used the stepping-stone maze before the 1960’s within the theoretical framework of expectancy and change in motivated behavior (e.g., Jones &
Yoshioka, 1941; Mann & Jewell, 1938: but see Gurnee, 1938; Razran, 1936, 1939 for quantitative studies of reinforcement learning in the stepping stone maze).

In one study, a comprehensive analysis of maze learning behavior in adolescent humans was based on rodent models of maze learning (Jones and Yoshioka, 1938). Jones and Yoshioka studied 159 adolescents from 11–15 years on a 5 x 5 stylus maze with 22 and 23 steps (see figures 2.4.1.-2.4.3) with (1) no feedback, (2) a buzzer, or (3) a light on the fourth and subsequent trials signaling errors.

Figure 2.4.1. Perspective view of the Jones and Yoshioka stylus maze (1938).

Figure 2.4.2. The underside wiring diagram of the Jones & Yoshioka (1938) maze. Feedback was given by circuits A (shaded), which activates a light, and B (unshaded),
which activates a buzzer. Stops in the pathway were created by the use of brass strips (C and D) that closed the circuit and activated a signal. A reward box for the exit of each circuit was controlled by binding posts M1-M4 and Mc.

Figure 2.4.3. Pathway patterns used in Jones and Yoshioka (1938) are shown in bold with the entry indicated at A.

Results of this study revealed that the nature of task feedback had no effect on the reduction in errors. In all conditions, the children achieved error free performance after 13 to 15 trials. Interestingly, the authors noted that many of the errors made by children were incorrect responses made in the general direction of the end point, where the path continued laterally or turned away from the goal. Other frequent errors were with regard to anticipating turns, and to avoid the periphery of the maze. Individual differences were shown in the tendency to retrace and repeat errors and tended to occur most frequently when the correct pathway turned away from the goal. Jones and Yoshioka (1938) described these errors as reflecting (a) goal impetus; (b) drift impetus of direction of the section of the current pathway; and (c) local forward momentum where continuous trajectory
is made until an error, where (a) and (b) give rise to anticipatory errors. This study is important because it was the first to characterize comprehensively the nature, frequency, and change in errors in hidden pathway electrical stylus maze learning (see Brown & Buel, 1940, for a discussion of the findings of Jones & Yoshioka, 1938).

Errors such as retracing or repeating the same error were often reported in early animal and human maze learning studies (e.g. Peterson, 1920; Hill, 1939). These errors were described as ‘perseveration’ and were considered to define confused and irrational behavior (Gould & Perin, 1916; Peterson, 1920, 1922). Precursors to modern neuropsychological interpretations of maladaptive behavior were evident from the time of Binet and Simon (1909), Hull (1934a, 1943b), Porteus (1958) and Tolman (1959), in so much as they considered variability in adaptation in the maze learning context. However, analyses of repeating errors in the stepping-stone maze were not conducted until decades later when it was considered an important measure of perseveration behaviour in neuropsychological studies (Karnath, Wallesch, & Zimmerman, 1991; Milner, 1965).

2.5 Modern neuropsychological approaches to hidden pathway maze learning

With the development of the formal discipline of neuropsychology (Luria, 1973) came the search for experimental paradigms of cognition that could be used to identify or differentiate the neural substrates of discrete cognitive processes that were disrupted by focal brain damage (Lashley, 1943; Orbach, 1955, 1959; Teuber, 1963; Van Orden, Pennington, & Stone, 2001). The study of impaired cognitive function in groups of patients with focal brain lesions, using analysis of cognitive task performance, rather than from classification of clinical symptoms, was regarded as an important method for understanding cognitive function from a
neuropsychological perspective (Teuber, 1966, 1972). Identifying tasks that were differentially affected by focal injuries in different brain regions was considered a fundamental precursor to understanding more complex behavior on tests of intelligence or reasoning. Teuber described this neuropsychological method as a potential biological alternative to the factorial analysis developed in the discipline of statistics (Teuber, 1963).

Maze learning tasks were considered useful for studies of cognition in patients with different focal brain lesions because of the extensive use of this paradigm in animal learning studies. Furthermore the processes involved in different spatial tasks were well established compared to other areas of neuropsychological research (Semmes, Weinstein, Ghent & Tueber, 1955). Non-verbal tasks, such as maze learning, were useful in neuropsychological experiments because they could be used to study patients with impairments in aspects of language that were a common presentation after focal cortical injury (Teuber, 1966). However, the relationship between brain function and aspects of spatial processing, such as taxon navigation, object-location learning, or topographical memory was not well understood (Kessels et al., 2001: Olton, 1985), and consequently the neuropsychological interpretations of impairments in hidden pathway maze learning have been speculative.

2.6. Maze learning and lesions of the frontal lobes.

The importance of the frontal lobes to cognitive models of problem-solving became evident very early in the history of neuropsychology (Bigelow, 1850). For example, Teuber (1963, 1966) speculated that lesions of the frontal lobes disrupted the coordination of cognitive processes that depended on other brain structures. Experimental paradigms used to describe the effects of lesions involving the frontal
lobes exploited dissociations between the ability to evaluate errors in performance and to utilize information from errors in planning future actions (Konow & Pribram, 1970). Another way of considering this was as the ability to structure behavioral sequences and monitor their outcomes (Luria, 1963, 1973). Impairment in this type of complex adaptive behavior was observed commonly in patients with frontal lobe lesions.

In order to study disturbances in adaptive behavior in patients with lesions involving the frontal lobes, maze tasks were utilized often because optimal performance on HPMLT required multi-step forward planning. Paper-and-pencil perceptual mazes that depended on visual analysis were used to study non-verbal executive functions, as ‘planning and monitoring’ tasks (e.g. Elithorn maze: Benton, Elithorn, Fogel, & Kerr, 1963; Elithorn, 1955; Porteus maze: Landis & Erlick, 1950; Porteus 1965). In general, the Porteus and Elithorn mazes measured the ability to plan the most efficient route through a visual array of alleys or dots that were connected through a series of grids that could be increased in size in order to increase the complexity of decision-making demands. Route finding efficiency in the Porteus maze was measured by the number of entries into blind alleys and by the number of dots traversed in the Elithorn maze (Benton et al., 1963; Landis & Erlick, 1950). Failure to follow the task rules was also an important measure of the ability to maintain task set or rules during maze performance (Benton et al., 1963; Landis & Erlick, 1950). Both tasks measured rule break errors, such as deviating from the pathway boundary and backtracking (Benton et al., 1963; Landis & Erlick, 1950). Neuropsychological studies indicated that performance on paper-and-pencil perceptual maze tasks was impaired in people with focal lesions involving the right/bilateral frontal lobe, as
well as the right parietal lobe, suggesting that both planning/monitoring and spatial processing functions were necessary for optimal performance on the task (Elithorn maze: Benton et al., 1963; Elithorn, 1955; Porteus maze: Landis & Erlick, 1950; Porteus & Kepner, 1944). Interestingly, the theoretical models of maze learning as a measure of adaptive behavior and motivation that had been developed in earlier decades (e.g. Tolman, 1959; Hull, 1934a) were mostly disregarded in neuropsychological studies. Instead, brain-based models of maze learning focused on the face-value construct that a task was designed to measure, such as learning or planning (e.g. Lashley, 1943; Teuber, 1966).

While performance on perceptual mazes was disrupted by focal lesions of the frontal and parietal lobes, qualitative analyses of the errors made by these different patient groups were not conducted and so it is not possible to determine post-hoc whether the nature of performance impairment differed across clinical groups (Benton et al., 1963). This is perhaps because the errors made on perceptual mazes could not be understood easily in terms of prevailing neuropsychological models of that time (e.g. Landis & Erlick, 1950). For example, solving perceptual mazes required a co-coordinated series of steps that take into consideration the entire problem space, as well as evaluation of possible global solutions. Individual moves were inextricably tied to a multi-step plan of action. Moves that did not conform to the ideal solution could not be easily understood according to a theoretical account of the discrete behavioral processes of maze learning. As HPMLT's were designed to reduce each move to a local series of options within the problem space, each move could be analyzed with regard to behavior at every choice point (Jones & Yoshioka, 1938). In this way, maze learning could be regarded as a series of conceptually similar choice-point sub-problems. Each
move constituted a discrete decision unit in a local problem for finding the next step, and which was guided by the overall goal of learning the pathway (Griffith, 1931). The HPMLTs retained the focal construct of multi-step forward planning, and spatial learning, but allowed for analysis of each move in each sub-problem in theoretical terms. In contrast to perceptual mazes, HPMLTs were amenable to qualitative and quantitative error analysis, which could be used to guide clinical interpretations of focal brain injuries (Milner, 1965). The HPMLTs were also useful because patient groups with different cortical lesions were often impaired in both memory and executive functions but it was difficult to identify the contribution of these different impairments to poor performance on a single neuropsychological task. Milner (1965) was the first to argue that the effects of different cortical injuries on problem solving and learning could be dissociated using analysis of error types on the stepping-stone version of HPMLT.

2.7. Maze learning and lesions of the temporal lobes.

The importance of hippocampal and medial temporal lobe brain structures to memory encoding and retrieval was exemplified in patient H.M., who displayed severe verbal and spatial anterograde amnesia following bilateral mesial temporal lobectomy (Milner, Corkin, & Tueber, 1968). Despite this dense amnesia, H.M.’s short term-spatial memory capacity, as measured by Corsi Block span, was within the normal range (Milner, 1971). H.M. and other patients with focal damage to the right medial temporal lobe appeared to have difficulties learning new information that was beyond the span of immediate memory (Milner, 1965, 1971; Milner, Corkin, & Tueber, 1968). To investigate the extent to which focal hippocampal lesions disrupted learning in the spatial domain, Milner needed a task with a temporal, or sequential ordering component that was beyond the span of immediate
spatial memory and therefore required cumulative learning (Milner 1965). Milner used a HPMLT that was similar in design to the Mann & Jewel (1941) maze. The Milner maze and later-developed Oxford HPMLT were simpler than the Porteus or Elithorn perceptual mazes because they did not require any development or evaluation of potential global solutions for problem-solving. They were also simpler than human scale mazes that were navigable by the use of maps for orienting in a landscape (Milner, 1965; Semmes et al., 1955). The Semmes et al., (1955) maze required the translation of a 2-dimensional paper map to the location and orientation within a physical landscape. Furthermore, the rule structures of HPMLTs were simple and could be understood easily even by patients with specific disturbances of language (e.g. arising from focal lesions of Broca’s area). For example, Milner (1965) showed that patients with Broca’s aphasia could perform the HPMLT within normal limits (Milner, 1965).

In Milner’s HPMLT, individuals were required to locate a 29-step pathway with 11 turns hidden within a 10 x 10 matrix of stepping stones, or locations to complete a single learning trial. The individual had to find the path traversing contra-lateral corners of the grid using move rules for the selection of each contiguous location using a stylus pen (see Figure 2.7.1). The rules of the Milner HPMLT included: go back to the preceding bolthead location when an error is signaled (by an auditory ‘click’); do not retrace sections of the correct pathway (or do not backtrack on the pathway); and do not move diagonally (Milner, 1965).
Milner's criterion for task completion was the individual obtaining three successive error free trials, or to complete a total of 25 trials in two blocks given daily, or until criterion was reached. On the Milner HPMLT, the patient H.M. was unable to learn the maze within any single session and also unable to reduce the number of errors made learning the same pathway even after 215 trials across days. The inability to learn the pathway on the Milner maze was unrelated to any perceptual or intellectual disability arising from his brain injury (Milner et al., 1968). Subsequent studies interpreted the deficits in performance on the Milner maze observed in patients with right retro-Rolandic cerebral damage as topographical amnesia that was independent of spatial perception or general

*Figure 2.7.1. The pathway of the Milner HPMLT (Milner, 1965).*

The use of HPMLTs to study the effect of lesions or impairment to the hippocampus in humans was well established by the mid 1970’s, mostly using The Oxford Stylus Maze, or the Stylus Maze Test (Newcombe et al., 1987; Newcombe & Russell, 1969; Ratcliff & Newcombe, 1973), or HPMLTs that used similar designs (Talland, Hagen, & James, 1967; Talland & McGuire, 1967). The Oxford HPMLT was similar in design to peg and groove mazes like the Jones & Joshioka (1938) and the Sartian (1940) HPMLTs. The Oxford Stylus HPMLT consisted of an 8 x 8 grid of raised blocks where individuals traced a path in an alley between locations from a start point to a finish point with auditory and visual feedback signals given when the path was traced onto an incorrect location. When errors were signaled the individual returned to the last choice point before moving again. Task A was a 6 choice point path in which the examiner demonstrated the path and the participant was required to relocate the pathway to a criterion of 3 error free trials, or 26 trials. This was used to allow training and practice trial to ensure task understanding (Newcombe & Russell, 1969). Task B had 10 choice points and the pathway was not demonstrated, therefore it had to be discovered by trial and error (see figure 2.7.2).
The Oxford HPMLT was developed as part of a project to study the long-term cognitive effects of focal brain injuries, including those affecting the medial temporal lobes and posterior parietal cortex (Newcombe & Russell, 1969). The structural similarities between the Milner and Oxford HPMLT are unlikely to have been accidental, given the reported communication between the Montreal and Oxford groups regarding common research interests (Newcombe & Russell, 1969). The Oxford HPMLT contained 10 steps with 6 turns. Milner et al., (1968) reported that H.M. showed some evidence of slow memory acquisition and retention on a modified version of the Milner HPMLT that included 8 steps with 3 turns, but was unable to learn a HPMLT with 10 steps and 4 turns (Milner et al., 1968). H.M.’s ability to learn the smaller HPMLT was likely due to the capacity to encode the pathway within working memory, which was intact. Although it is common to examine the effect of increasing task difficulty on aspects of performance in neuropsychological tests (e.g.
De Luca et al., 2003; Luciana & Nelson, 1998, 2002; Welsh, Pennington & Grossier, 1991), only two studies to date have examined the effect of increasing task difficulty, such as grid size and pathway length on a stepping-stone HPMLT (Mathewson, Dywan, Snyder, Tays, & Segalowitz, 2008; Thomas et al., 2011). Both studies found that manipulation of HPMLT pathway length/grid size was associated with qualitative changes in performance in children (Thomas et al., 2011), as well as neurological differences between older and younger adults (Mathewson et al., 2008). The results of these studies are discussed later in this review (see Section 3.3.)

Using the Oxford HPMLT, Newcombe and Russell (1969) found evidence of dissociation between visual perception that was impaired in patients with occipital lesions, and maze learning that was specifically impaired in groups with temporoparietal lesions, but not in patients with occipital lesions. In accordance with Milner (1965), Newcome and Russell (1969) argued that performance of the different lesion groups on the HPMLT could be dissociated such that impairment due to right hemisphere lesions could be interpreted as a spatial cartographic problem in posterior parietal groups, and an mnestic disturbance in patients with right temporal hippocampal excision.

Milner recognized that her HPMLT was sensitive to injuries of the frontal lobe but that this sensitivity depended on analysis of the nature of errors made by patients during pathway learning. For example patients with focal injuries involving the frontal lobe made more errors than controls or patients with aphasia (arising from lesions of Broca’s area), in that they revisited locations signaled as incorrect more often, back-tracked along the pathway or jumped to non-contiguous locations (Milner, 1965). Despite the higher rate of these rule break errors, patients with brain injures involving the frontal lobes could report that they knew their errors were in violation
of the task rules. Subsequent studies have similarly found that failing to return, and within search (often termed perseverative errors) are more common than other rule break error types in HPMLTs (Karnath et al., 1991; Matson, Berk and Lucas, 1997; Milner, 1965; Pietrzak et al., 2007; Snyder et al., 2005a; Snyder Maruff, Pietrzak, Cromer, and Snyder, 2008; Steinberg, Chaikelson, and Schwatzman, 1983; Thomas, Snyder, Pietrzak, Jackson, Bednar and, Maruff, 2008).

While the Milner HPMLT had been developed for study of cognitive impairment in patients with lesions involving the hippocampus, it was applied more broadly to understand cognitive impairment in patients with neuropsychiatric conditions associated with deficits in executive functions, such as schizophrenia, obsessive compulsive disorder, as well as in patients with frontal lobe lesions (Behar, Rappoport, Berg, Denkla, Mann, Cox et al., 1984; Canavan, 1983 [Oxford HPMLT]; Head, Bolton, & Hymas, 1989; Karnath et al., 1991 [modified HPMLT]; Matson et al., 1997 [Austin HPMLT]; Rettew, Cheslow, Rappoport, Leonard, & Lenine, 1991; Steinberg et al., 1983; Wallesh, Karnath, Papagno, Zimmerman, Deuschl, and Lucking, 1990 [modified HPMLT]). In most studies using the Milner HPMLT and its variants, qualitative and quantitative analysis of errors were used to guide interpretation of impaired performance in the clinical group under investigation. For example, following Milner (1965) it was common in the studies cited above to compare the rate of specific errors in HPMLT made by different patient groups, such as repeating errors, breaking rules and to differentiate these from errors that comply with the rules, but probably reflect difficulty learning the pathway over trials. Typically errors were classified as qualitatively different forms of behavior that reflected rule-following, or rule-breaking and were interpreted as distinct disturbances in brain areas associated with error evaluation, and spatial learning and memory.
Unfortunately, most studies using the Milner HPMLT that have reported separate measures of rule break and spatial memory errors have not included performance from any of the control groups they also studied (for exceptions see: Head et al., 1989; Hymas, Lees, Bolton, Epps, & Head, 1991; Rettew et al., 1991). Consequently, no guidelines had been developed to classify normal from impaired performance for the different types of errors on the HPMLT (Bowden & Smith, 1994). Subsequently, researchers using HPMLT have shown the sensitivity to detect change or difference in cognition according to analyses of error types reflecting the spatial learning and rule breaking aspects of performance in terms of effect sizes (Pietrzak et al., 2009a; Pietrzak et al, 2009b; Thomas et al., 2008).

The Austin HPMLT (see figure 2.7.3) a version of the HPMLT Milner maze was designed for use in clinical neuropsychological settings as a test of cognitive functions that depended on the frontal lobes (Darby & Walsh, 2005; Walsh, 1985). The popularity of the test in neuropsychology was because it had proved to be a sensitive test to dysfunction of cognition following frontal lobe injuries (Bowden & Smith, 1994), at a time when there were few if any tests that were specific to a single brain region, especially the frontal lobes (Burgess et al., 2006).
Darby and Walsh (2005) describe several case studies that highlight the sensitivity of the Austin HPMLT to injuries involving the frontal lobes. In these cases patients with lesions or injury involving the frontal lobes typically made persistent errors on the HPMLT showing that like H.M., they were unable to learn the maze pathway. However H.M. and other patients with unilateral or bilateral hippocampal, temporal, or parietal injuries made almost no repeated errors that broke the task rules. H.M.’s inability to learn the pathway was not due to a failure to follow the task rules, but was attributed to a disturbance of sequential behavior that prevented the acquisition of the pathway in memory (Milner, 1965). Unlike H.M., the inability to learn the pathway in patients with frontal lesions was due to their inability to adjust their behavior on the basis of the errors made, whether due to disinterest in avoiding errors, or some other dysfunction (Milner, 1965). This inability was considered by Walsh to indicate some disability to regulate purposive behavior (Darby & Walsh,
2005, pp 141, 149). This inability to change behavior on the basis of errors, or repeating the same error continually despite negative feedback, was observed in patients who had suffered traumatic head injury and in adults with chronic alcoholism (Darby & Walsh, 2005). Walsh was careful to emphasize that these deficits reflected a problem of error utilization, rather than error evaluation, because all of their patients demonstrated that they knew their errors were occurring but despite this did not modify their behavior in accord with this knowledge (Darby & Walsh, 2005, pp 168). Hence, this impairment was framed as a difficulty in implementing behavioral plans, not an impairment in awareness or in the assessment of the significance of the errors that broke the task rules. On the HPMLT this failure to learn from errors was observed as a rapid reduction in errors across the initial learning trials with the persistence of a small number of errors across the remainder of trials with performance never becoming error-free (i.e. defined by Walsh as 3 errorless trials) despite individuals being allowed to continue learning the maze indefinitely. It appears that this criterion of error-free performance within 20-30 trials (Walsh, 1985) was selected because Walsh (1960) also reported that patients who had undergone frontal leucotomy also made rule break errors similar to those that had been observed by Milner (1965). However, Walsh found that the rate of rule break errors in patients with frontal lobe leucotomy was not significantly greater than controls (Darby & Walsh, 2005 pp, 149, 167). Studies have consistently shown that the rate of rule break errors is typically much lower than the rate of pathway memory errors (Behar et al., 1984; Canavan, 1983; Milner, 1965; Rettew et al., 1991; Steinberg et al., 1983). Inter-individual differences in HPMLT errors can be shown using metrics that consider the relative rate and variability of differences within and between groups (i.e.
effect sizes), than the raw rate of different errors (Snyder, et al, 2005a; Snyder et al., 2005b).

Bowden and Smith (1994) criticized the use of a criterion requiring stable error-free performance to define difficulties of error utilization in HPMLTs, from both a statistical and theoretical perspective. First, stable error-free performance could be achieved in patients with injuries involving the prefrontal cortex albeit after many more trials than required by healthy controls (Milner, 1965). Second, in some healthy adults error-free performance required as many as 50 trials (Bowden et al., 1992), and therefore failure to reach criterion in 20 or 30 trials (Walsh, 1985) could not be considered a reliable measure of cognitive impairment. Finally, Bowden and Smith (1994) showed that the rate of learning (i.e. reduction in errors) over the initial 10 trials on the Austin HPMLT was highly predictive of the number of errors on subsequent trials made by both healthy adults and patients with heterogeneous brain lesions (Bowden & Smith, 1994). Although it was traditional to examine maze performance in terms of trials to a criterion of error free completion, after the studies of Bowden, it became increasingly common to examine errors over a pre-specified number of trials (e.g. Barker, Greenwood, Jackson, & Crowe, 2005; Morrison & Gates, 1988; Osterberg, Karlson, & Hansen, 2009). The consequence of this was that it made the time for testing briefer than when trials to error-free performance was used and it also provided a statistically defensible basis for standardized task administration.

In the late 1980’s, the Austin HPMLT was used by some researchers to study impairments in spatial mapping in clinical conditions proposed to be associated with disruption to the hippocampus, such as alcohol dependence (Bowden, 1988, 1989; Bowden & McCarter, 1993; O’Brian, Bowden, Bardenhagen, & Cook, 2003). The
rapid encoding and recall of object-locations has consistently been shown to depend on the right mesial temporal region (Saling, 2009). However, the neurological impact of long-term chronic alcohol use on brain structures associated with executive functions has not, to our knowledge, been assessed using error analysis in the Austin HPMLT. The Austin HPMLT was used extensively in clinical neuropsychological studies, including normative and validation studies in healthy adults (e.g. Bowden & Smith, 1994; Bowden et al., 1992; Crowe et al., 1999; Morrison & Gates, 1988; Tucker, Kinsella, Gawith, & Harrison, 1987). Studies that administered the Austin HPMLT in neurologically impaired populations in which executive functions would likely be affected, typically define impairment in terms of the total errors, total trials, and total time to reach some criterion (Darby & Walsh, 2005; Österberg et al., 2009; Österberg, Österberg, Ørbæk, & Karlson, 2002; Ørbæk, Karlson, Bergendorf, & Seger, 2000; Barker et al., 2005; Kinsella et al., 1995). Despite the extensive use of the Austin HPMLT, it is difficult to integrate data across studies because no standard method for administration and scoring of the task has been developed or validated. For example, studies using the Austin HPMLT differ in the criterion for task completion (10 trials: Barker et al., 2005; Bowden et al., 1997; O’Brian et al., 2003; Österberg et al., 2009; Walton & Bowden, 1997; two, or three error free trials: Kilpatrick et al., 1997; Kinsella, et al., 1995; Kinsella et al., 1997; Mathais & Kent, 1998; Morrison & Gates, 1988). More importantly, although the task rules have been described by Bowden and by Milner (Bowden, 1988, 1989; Milner, 1965), studies using the Austin HPMLT have been inconsistent in reporting which, or if any rules were given to participants prior to assessment (Barker et al., 2005; Matias & Kent, 1998; Matson, Berk & Lucas, 1997; Österberg, et al., 2009; Österberg, Ørbæk, & Karlson, 2002; Österberg, Ørbæk, Karlson, Bergendorf, & Seger, 2000).
Searching the same location, or within-search errors were regarded by Milner (1965) as errors common to patients with frontal lobe injuries and interpreted as ‘perseveration’, but they are not included as rules as reported by any studies published using the Austin or Milner HPMLT. The definitions of rule break errors have also been inconsistent, when they have been recorded in the Milner HPMLT. There were at least 5 studies before the mid 1990’s that indicated the rates of rule break errors in different clinical groups was sufficiently high to warrant analyses as a separate measure to other error categories (Behar et al., 1984; Canavan, 1983; Milner, 1965; Rettew et al., 1991; Steinberg et al., 1983). However, subsequent studies using the Austin HPMLT have not considered the quantitative and qualitative nature of errors. By comparison, studies that included healthy controls showed that rule break errors were infrequent in this group and ranged from approximately 1-to 5 errors in trials to criterion (17 trials: Milner, 1965; 20 trials: Steinberg et al., 1983: 10 trials: Rettew et al., 1991). As described earlier, Bowden & Smith (1994) described the wide variance in trials to criterion across control and clinical groups in the Austin HPMLT. Furthermore, trials to criterion and errors to criterion are also highly correlated in healthy adults (r = .73-.91: Tucker et al. 1987). Bowden has also shown that test-retest reliability on alternative pathways of the Austin HPMLT is generally low (errors to criterion: r = .77, trials to criterion: r = .64: Bowden, 1989). The rules of the Austin maze are given verbally and task administration does not contain training, or pre-trial practice. This raises the possibility that improved performance on the second administered pathway (e.g., Bowden, 1989) reflected acquisition of the task rules in the first administration that were consolidated by the second administration.

Although the Austin HPMLT has been used widely in clinical neuropsychological contexts, this review suggests that it still remains more of an
experimental than clinical neuropsychological test. Researchers have sought to characterize variability in the rate of pathway learning in order to understand the metric properties of the task, as much as to investigate cognition in different groups. Furthermore the construction of the Austin HPMLT as a commercial manual task without alternate pathways limited the administration of the task to verbal instructions without practice or task familiarization. In order to use HPMLTs for the study of cognitive functions, as opposed to being a tool for understanding the nature of maze learning, recent computerized adaptations of the HPMLT paradigm have become more standardized, with rules to guide performance and criteria for classification of errors specified. Two examples of such adaptations are discussed below.

2.8. Computerized versions of HPMLT.

Computerization of the maze format from the late 1980’s had several advantages for administering and analyzing performance on HPMLTs (Morrison & Gates, 1988). First, computerization allowed greater flexibility of HPMLT design and administration. Second, computerization makes it possible to record and classify automatically every move, as well as every move sequence with respect to prior moves or to the maze layout. Functional neuroimaging studies using HPMLT have shown changes from frontal to temporoparietal activity over practiced trials, consistent with a shift from trial-and-error searching when the pathway is unknown, to navigation from memory (Van Horn et al., 1998). This analysis is also consistent with the interpretation of HPMLTs as a spatial learning paradigm within the context of executive functions (Milner, 1965). At least two versions of this HPMLT were designed in the first decade of 2000 for use in clinical research, and imaging environments respectively. The Groton Maze Learning Task (Schroder et al., 2004) preceded the development of the Integneuro maze (Paul et al., 2005). However, in
order to critically examine common limitations of HPMLT studies in general, the Integneuro maze will be examined before consideration of studies using the Groton Maze Learning Task.

2.9. The Integneuro Maze.

The IntegNeuro battery from the Brain Resource Company has been used mostly for investigating the brain correlates of cognitive deficits associated with heterogeneous brain disorders (Lipton et al., 2009; Paul et al., 2009; Tate et al., 2010). The Integneuro maze is an 8 x 8 HPMLT presented on a touch screen. Moves are made using a 4-directional control panel (with arrows) set on the screen below the maze. Feedback is given by auditory and visual responses below the maze (not on each selected tile). Diagonal and jump moves are not possible.

The Integneuro maze task runs until two error-free trials, or a timeout of anywhere between 7 minutes (Clark et al., 2006; Mathersul et al., 2009; Schofield et al., 2009) and 10 minutes (Gunstad et al., 2007; Paul et al., 2005: Paul et al., 2006; Paul et al., 2009; Silverstein et al., 2007). The computer software records the number of trials, errors, and time to completion (Clark et al., 2006). Overruns are also recorded, where participants continue to search locations in a linear trajectory when the pathway turns. The reason for inclusion of this measure and its theoretical significance has not been made explicit in any study that has used the Integneuro maze. Overruns have been reported previously and described as pattern factors of the maze that generalize to a local forward drift momentum, or orientation direction in choosing pathway locations (Jones & Yoshioka, 1938). In other words, if the pathway is unknown, participants tend to continue searching in the same goal-ward direction until an error is indicated. The pathway consists of 24 steps (Integneuro
User Manual Version 2007v3: available from www.brainclinics.com), however, the
number of turns included in these steps has not been reported and there is no evidence
as to whether different pathways are used. The Integneuro maze is described as a test
of executive functions based on the Austin HPMLT, and there is extensive normative
data from 6-years to- 70+ in 1007 participants (Clark et al., 2006), and one validation
study (Paul et al., 2005). However this validation study did not use any other form of
maze task for comparison (for example the Austin maze on which the task was
purportedly based: Paul et al., 2005).

The Integneuro maze appears to be based on the Morrison and Gates (1988)
computerized version of the Austin maze in that moves are executed via a 4-
directional keypad made remotely from the maze grid, not within the grid itself. The
move restrictions of this format are similar to the physical ‘alleys and stops’ of the
Oxford maze and its predecessors in which diagonal or jump moves cannot be made
(Jones & Joshioka, 1938). However because move decisions are executed remotely to
the maze environment, it is possible that move sequences could be coded
linguistically according to application of a sequence of commands restricted to ‘up,
down, left, right’. Because these commands can be applied and evaluated without
visual inspection of the maze layout it is possible that the Integneuro maze task could
be completed efficiently from verbal memory alone, or that any visual decision
making could be supported or enhanced by linguistic processing. Therefore
differences in the rule structure and administration of the Integneuro maze limits
comparison to models of HPMLT maze learning based on performance on the Austin
and Milner HPMLT as measures of either executive functions or spatial mapping.

In one study, the correlation between Integneuro maze completion time and the
Rey Complex Figure Test-delay (RCFT-d) was taken as a validation of the Integneuro
maze (Paul et al., 2005). However the selection for the RCFT measure in the delayed form as a validating task is unclear. While the authors assert that the Integneuro maze is a measure of executive functions, the delayed trial of the RCFT is considered to be a task of visual memory (Caffara, Vezzadini, Dieci, Zonato, & Venneri, 2002). The use of the RCFT as a test of executive function depends on the analysis of error patterns, and organization abilities (Meyers & Meyers, 1995; Meyers & Volbrecht, 1998). The common operations required by the Integneuro maze and the RTDFT-d were not discussed. Divergent validity was established by the lack of correlation between Integneuro maze measures and the California Verbal Learning Test-Research (short delay). However at least 30 measures were recorded from 12 tests administered in the experiment, but an inter-correlation matrix of measures in the battery was not reported. The veracity of the claim of validation of the Integneuro maze cannot be assessed without a more complete report of the convergent and divergent relationships with other tests of cognitive functions administered in the experiment. No such data has as yet been published for this version of the HPMLT.

The Integneuro maze has been used extensively in imaging and tractography studies as a task of executive function within the context of spatial learning (Lipton et al., 2009; Schofield et al., 2009; Seckfort et al., 2008; Tate et al., 2010). However imaging studies using the Integneuro maze have used summary measures over trials, not behavioral trial by trial data in relation to stability or changes in brain functions over trials. The contribution of studies using the Integneuro maze for understanding HPMLT performance is limited, because the maze has not been validated as a HPMLT, and the theoretical significance of the measures it records, such as overruns are not well understood.

The Groton Maze Learning Test (GMLT) is a touch screen HPMLT, based on the Austin and Milner HPMLT (see Figure 2.10.1). The GMLT was developed by P.J. Snyder and colleagues for use in neuropharmacological studies at the former main campus for research and development of Pfizer Inc. (Boulanger, Snyder, & Cohen, 2006; Castner et al., 2004; Pietrzak, Cohen, & Snyder, 2007). Maze pathways begin at the top left-hand corner and end at the bottom right-hand corner (see Figure 2.10.1). The pathway remains hidden and only the most recently selected square is illuminated. When a correct square is touched, it turns white with a green tick, accompanied by an auditory tone. When an incorrect tile is touched, it turns white with a red cross, and no tone is emitted. Move feedback appears for 250 ms, following which, the square changes color to blue. If two successive errors are made, the last correct location (referred to as the “head of path”) flashes 10 times with a tick. Correct and error-move feedback provides pathway information (Pietrzak et al., 2009a; Pietrzak et al., 2009b). For the GMLT, the grid size, pathway length/number of turns, and rules are the same as for the Milner HPMLT.
Figure 2.10.1. The GMLT. The grid shows the current location (blue tile) and the end goal (red target). The pathway begins in the top left corner and finishes in the bottom right corner.

Because the GMLT was specifically designed for clinical trials, there was emphasis placed on the ability to generate alternative forms that were resistant to practice effects (Maruff et al., 2006; Pietrzak et al., 2009b; Snyder et al., 2005a; Snyder et al., 2005b; Snyder, et al., 2008a). Hence, there are 20 alternate-form maze pathways in the GMLT, and these are all equivalent with respect to the number of correct moves, turns, and individual choice or decision points, within the 10 x 10 grid (Fig. 2.10.1). Each time an individual starts the test, a form is selected in pseudo-random order to ensure that no individual subject will see the same alternate form within three successive test sessions. When a subject attempts to discover the hidden maze on the first trial, or to make effective use of his or her internal spatial map for the hidden maze on successive learning trials, any presses on tiles that are allowed by the task rules for finding the hidden pathway are categorized by the GMLT software as exploratory errors. Moves that violate the task rules are classified as rule break errors (see Table 2.10.1 for a description of error categories, and Figure 2.10.2 for an example of errors). Researchers using
the GMLT were the first to systematically codify error categories in HPMLT, as well as the first to report analysis of different errors as a standard output feature (e.g. Maruff et al., 2006; Snyder et al., 2005a; Snyder et al., 2005b). Each step in the pathway must be located in sequence, according to the rules in order to complete a trial.

Table 2.10.1.

**Definition of Errors on the Groton Maze Learning Task. All Measures are recorded as Counts on Each Trial (Five Trials in Total).**

<table>
<thead>
<tr>
<th>Error type</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exploratory</td>
<td>Moves in accordance with task rules.</td>
</tr>
<tr>
<td>Failure to</td>
<td>Failing to return to the last correct location after an incorrect move.</td>
</tr>
<tr>
<td>return</td>
<td></td>
</tr>
<tr>
<td>Perseverative</td>
<td>The same error repeated after returning to the head of path.</td>
</tr>
<tr>
<td>Back</td>
<td>Moving backwards on the pathway.</td>
</tr>
<tr>
<td>Jump</td>
<td>Moving more than one tile from the current correct location.</td>
</tr>
</tbody>
</table>
Diagonal  Moving to locations diagonal to the current correct location.

Double tap  Tapping the same incorrect location twice.

Same tile tap  Tapping the correct location twice.

Between  Moves between tiles.

Out  Moves out of grid.

Re-searching locations allowed by the task rules that have been identified as the incorrect location for the next step in the pathway.

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Figure 2.10.2. Example of errors and moves in the GMLT. The pathway is highlighted in green, and each move is numbered in sequence. Step 5) legal error, step 13,14 and 15) failing to return, step 17) within search error, step 34) double tap, step 37) back on the pathway.
From any location in the GMLT, it is possible to move to any location within the grid. For the GMLT software to respond with appropriate feedback to every move, it is necessary that all moves can be classified according to the task rules and according to the nature of the move (i.e. see Table 2.10.1 for error classifications). A consequence of this is that the GMLT output can be rendered to provide raw data for each move and each response time, as well as trial-by-trial summaries of different errors and responses. Because the GMLT records and classifies every move, there are more categories of ‘erroneous’ moves than are reported by other HPMLT (double tapping tiles, moves between tiles). Correctly returning to the head of path after errors are signaled can also provide a measure of error feedback use, although this measure has not been previously reported. Most reports using the GMLT include incorrect moves that comply with the task rules (legal errors); errors that do not comply with the task rules (rule break errors); and repeating the same error in succession (perseverative errors). These error categories are typically summed over the five learning trials and expressed as an effect size of difference from control, or change from pre-treatment baseline score (Pietrzak et al., 2008a; Snyder et al., 2005a; Snyder et al., 2008a; Thomas et al., 2008). Practice trials are an essential component of the GMLT, as it is important to ensure that participants fully understand the rules of the task and can demonstrate stable baseline performance prior to administering the task in research or clinical applications. Other studies have reported a summary measure of learning efficiency, or a ratio of total moves over trials to task completion (Collie, Maruff, Snyder, Darekar, & Huggins, 2006; Maruff, et al., 2006; Pietrzak et al., 2007; Pietrzak et al., 2009a; Pietrzak, Sprague, & Snyder, 2008b; Snyder et al., 2005a). There is ample evidence in the references above suggesting the sensitivity of
GMLT measures to detect clinically significant change or difference using standard outcome measures of error and efficiency. However, these along with other GMLT measures can be used to address a variety of theoretical questions related to the specificity and qualitative nature of cognitive performance on a complex task.

In neuropsychological research and practice, it is important that the choice of outcome measures is suitable for specific experimental and clinical questions. For example, summary outcome measures may be preferred to multiple, “process-based” measures when a test is included as part of a large test battery, or when non-specific brain disease or disorders would likely be associated with diffuse cognitive impairments, such as in schizophrenia (Pietrzak et al., 2009b). Alternatively, researchers may be interested in the component operations underlying task performance in which multiple measures are useful (e.g. Alderman, Burgess, Knight, & Henman, 2003). As the GMLT is a learning task, it is also possible to examine the learning process through the change in different parameters of performance over trials, although few studies have examined individual trial data in the GMLT (Pietrzak, et al., 2009a; Thomas et al., 2013).

One of the most consistent findings in studies using the GMLT is the differential effect of clinical status on measures of rule break, and legal or exploratory errors. Although there is vast amount of evidence from early studies confirming that HPMLTs measure some aspects of executive functions in addition to spatial mapping and learning functions, these processes can be differentiated on the GMLT. For example, exploratory and rule break errors can be independently affected in clinical groups, as well as with pharmacological manipulation of neurotransmitter systems. Although memory and executive function deficits often co-occur in cases of diffuse brain disorders, several studies have shown the dissociation of rule use and spatial
memory processes in hidden pathway maze learning (Canavan, 1983; Thomas et al., 2008; Snyder et al., 2005a; Snyder et al., 2008b). Rule-break errors are rare in healthy adults, but common in populations with executive function deficits due to anatomical, chemical, or age-related disruption to the prefrontal cortex (Pietrzak et al., 2008a; Snyder et al., 2008a; Snyder et al., 2008b; Thomas et al., 2008). In these studies, spatial memory in the GMLT is generally far less affected than executive functions (e.g. Snyder et al., 2008a; 2008b; Thomas et al., 2008). By contrast, patients with focal lesions of the hippocampus, reduced performance on HPMLTs is predominantly driven by reductions in spatial learning and memory, with little or no disruption to rule use ability (Milner, 1965; Milner et al., 1968). Importantly, the ability to understand the relative contribution of cognitive systems to performance can inform neuropsychological models of hidden pathway maze learning. For example, Snyder et al. (2008b) found that children with attention deficit hyperactivity disorder (ADHD) make more rule break errors than age-matched controls, but not more exploratory errors. Administration of stimulant medication in children with ADHD led to a greater reduction in legal than perseverative errors, suggesting that stimulant medication improves both learning/memory to a greater extent than executive processes in children with ADHD. Together, these findings are theoretically and clinically important because they suggest that it is possible to isolate and compare different task components of HPMLTs that allows for greater interpretive scope in analyzing performance variability.

Because every move in HPMLTs represents a discrete decision, behavioral analysis of move-by-move performance can be coupled with neuroimaging data. Although HPMLTs other than the Integneuro maze have not been widely used in imaging studies, they show great potential for coupling simple responses with brain
activity and cognitive behavior in a complex task. For example, by examining the brain responses to individual moves, such as returning after errors as opposed to failing to return after errors, it is possible to make theoretical claims regarding the brain-behavior relationship in error monitoring. Mathewson et al. (2007) investigated error-feedback processing in aging by examining the event related potentials to error feedback in older and younger adults performing three levels of maze difficulty. Fifteen younger females (18-26 years), and 15 older females (65-87 years) completed 8 4 x 4 maze (1 learn, 2 test trials), 4 6 x 6 mazes (1 learn, 3 test trials), and 2 8 x 8 mazes (1 learn, 5 test trials). The main finding was that in younger adults, electroencephalogram (EEG) feedback related negativity was sensitive to errors at all levels of difficulty in both learn and test trials (it should be noted that Mathewson et al., did not differentiate error types). The maxima of EEG activity was evident in medial brain areas, including the anterior cingulate cortex (ACC), with an anterior shift evident in more difficult learn trials, and posterior shift evident in practice trials. For older adults, there was no specific response differentiation in the medial prefrontal cortex; neural responses to correct moves and errors were associated with more diffuse brain activity. Behavioral data also showed that there were no differences in errors on learning trials at each level of difficulty, but that older adults were less efficient in learning the mazes. Processing speed (Trails A) did not account for the variance in error rates, suggesting that performance was dependent on higher-order learning and executive processes. Older adults also produced smaller feedback-related-negativity (FRN’s) associated with error feedback in all conditions, suggesting that older adults may have recruited brain regions less reliant on dopaminergic activity (i.e. than the ACC). For both groups, the P3 was sensitive to feedback valence. The differentiation between event-related-potentials (ERP) and P3
sensitivity to error feedback (correct and incorrect moves) with age also support the inference that these two systems may rely on different neurotransmitter systems. One confounding factor in this study was that neural responses were not analyzed separately for qualitatively different error types (rule break and exploratory). Based on developmental studies of maze performance, it would be expected that rule breaking errors would be more frequent in older adults than in younger adults. Analysis of qualitatively different errors could provide information regarding the brain-behavior relationship between internally-generated errors (rule breaking), feedback errors (failing to return, within search), and correct error discrimination (returning after an error). Because neural processes are likely to be different for each of these error types, frequent rule breaking errors, when aggregated with all other errors would appear as more diffuse activity and might account for the results observed in the older adult sample. This interpretation underscores the importance of assessing different error responses in making inferences regarding putative brain bases of error monitoring processes.

As noted earlier in this review, Walsh (1985) hypothesized that the main difficulty underlying rule break errors in clinical populations with injuries to the prefrontal cortex was an inability to use error information to plan and execute moves, or error utilization. Rule break errors can occur as a failure to follow rules, such as ‘jumps,’ diagonals, or backtracking, or as a failure to use prior task information to select the next move, such as failing to return after error signals are given, or repeatedly searching the same location within a trial. Error analysis of these different types of errors could be used to identify the nature of rule use difficulties in normal development, as well as in clinical samples. Such an analysis would thus provide useful information regarding the theoretical basis of variability in maze learning.
An example of componential analysis can be seen in one study in which the GMLT was administered to children from 5-to-9-years of age (Thomas et al., 2011). Error analysis in this study showed an age-related trend in the profile of different error categories (Thomas et al., 2011). Compared to older children, younger children made more errors related to the ability to use error information (i.e., failing to return and within search errors), than failing to follow the rules (i.e., making ‘jumps’ and diagonal moves). This finding is consistent with the early development of rule use, but the relatively latter development of error monitoring in childhood (Bunge & Crone, 2009; Marchovitch & Zelazo, 2009). It is also consistent with Walsh’s (1985) hypothesis that error utilization is the main difficulty demonstrated by individuals with executive function deficits.

2.11. Summary and research agenda.

Maze learning was a central methodology for studying fundamental aspects of cognition and behavior throughout the 20th century. HPMLTs were designed to overcome the limitations of other maze formats in humans, and to improve the psychometric properties of such tests in order to augment interpretation of performance. With the advent of brain-based approaches to adult neuropsychology in the 1950’s, maze learning became a useful diagnostic measure of mid-temporal lobe and frontal lobe function according to the profile of different errors made by patient groups. Theoretical accounts of what HPMLTs measured during the 1980’s and 1990’s were restricted by the use of summary outcome measures, such as total errors or trials to a criterion of task completion. The use of global measures and lack of task standardization have consequently prevented comprehensive analysis of brain-based, or cognitive systems that could account for performance variability both within, and across studies. However, on the weight
of evidence, modern HPMLTs are able to assess various cognitive abilities subserved by functionally separate neural systems for spatial learning/memory, and goal-directed error monitoring and rule use. The ability to measure different aspects of performance, as well as the potential to modify the task makes the HPMLT paradigm a powerful tool for investigating how different cognitive functions change, or remain stable as a function of age, clinical status, or task demands. Importantly, HPMLT tasks, when analyzed with appropriate measures, are appropriate for studying executive functions in which component operations on a complex task can be identified and quantified. The flexibility of the HPMLT, in terms of the range of outcome measures derived from a move-by move, and trial-by-trial basis allows for a comprehensive approach to characterizing performance parameters reflecting component aspects of visuospatial learning and executive function. As such, HPMLTs provide an ideal methodology for investigating the development of executive functions in children, as well as changes in visuospatial learning and executive function in neuropsychology, clinical trials, and other clinical applications. Future studies will be needed to further identify relationships between brain, behavioral and pharmacological models of HPMLTs.
Chapter 3

The development of executive functions in childhood.

3.1 Introduction

Hidden Pathway Maze Learning Tasks (HPMLTs) have mostly been used to study abnormal adult cognition in clinical neuropsychology, and occasionally in child clinical groups. However HPMLT are useful for studying childhood cognitive development because of its simplicity, brevity and repeatability. Furthermore, multiple measures can be extracted from performance data allowing for fine-grained analysis of the components of performance. In this section it is argued that HPMLT overcome the limitations of other approaches to the study of children’s ability to process complex, or multi-dimensional information. Limitations of tests for the assessment of executive functions in children are discussed. This section concludes with a rationale for the use of HPMLT to test complex cognition in children. It is argued that a theoretically robust account of the development of children’s spatial abilities in HPMLT requires both internal task manipulations, and external validation with comparison tasks selected to reflect hypothesized underlying constructs. Chapter three provides a description of studies designed to test how the cognitive functions required by HPMLT are organized in children.

3.2 Executive functions: theoretical and methodological considerations

Executive functions (EF) describe a cognitive system for the regulation of behavior in novel situations (Burgess et al., 2006; Norman & Shallice, 1986; Shallice, Burgess, & Robertson, 1996; Stuss, 2011). Theories of EF describe how actions are planned, executed, monitored, and adapted for changing behavioural
goals (Gilbert and Burgess, 2008). The common definition of theories of EF is the ability to modulate internal processes and select external inputs for goal-directed behavior when no well established response can, or should guide behavior, such as in changing environments and with changing goals (Gilbert and Burgess, 2008; Konow & Pribram, 1970; Luria, 1963; Walsh, 1985; Happeney & Zelazo, 2003; Zelazo, Frye, & Raptus, 1996). When there are insufficient cues to guide behavior in a novel context, inappropriate responses may occur (Merva Stedron, Devi Sahni, & Munakata, 2005).

Tests designed to measure EF incorporate novelty, and require flexibility in decision making (Burgess et al., 2006; Chan, Shum, Touloupiolou, & Chen, 2008; Juraldo, & Rosselli, 2007; Royall et al., 2002; Welsh, Pennington, & Grossier, 1991). Tests of EF often require forward planning, or the use of past experience for selecting among competing response options. For example, in the Wisconsin Card Sort Task (WSCT: Grant & Berg, 1948), the participant is presented with 4 stimulus cards that can be categorized according to shape, color, or number. The participant is required to match a target card to one of the 4 stimuli. With each incorrect response, the cards change until the correct category is found. The sorting rule may change without warning and the participant must discover the new sorting rule. Performance can be measured according to the number of categories completed, perseverative errors, and non-perseverative errors (Nyhus, & Barcelo, 2009). A recent review of the WCST concludes that a wide network of brain regions is recruited by the task, including the prefrontal cortex (Nyhus, & Barcelo, 2009). This is consistent with contemporary models of EF that emphasize the integrative functions of the prefrontal cortex (Burgess et al., 2006; Koechlin & Summerfield, 2007). However the WCST like many complex tasks designed to
measure EF, such as Tower tasks, or Trail-Making, have been criticized on the grounds that explanation for poor performance, at the level of cognitive operations, is not well understood (Burgess et al., 2006). The disruption to executive processes (e.g., working memory, goal maintenance), supporting functions (e.g., sensory processing, attention), or the domain itself (e.g., language, visuospatial or numerical processing) can produce sub-optimal performance on tests of purported executive functions (Chan et al., 2008; Royall et al., 2002). The clinical necessity for tests that are diagnostically useful and ecologically valid is different to the research demand for tasks that are theoretically defined for hypothesis testing (Burgess et al., 2006). However both approaches are augmented by the use of tests that measure the functions of a task, rather than infer those functions from tests with single measures of a construct, such as EF. One method that can accommodate this approach is to use tasks that can measure component processes that contribute to performance on the same test, and from which valid comparisons can be made using appropriate statistical methods. Such an approach need not assume how the underlying processes are organized, but can investigate associations between measures of the different component processes. In Burgess’ example using the Multiple Errands Test (Alderman, Burgess, Knight, & Henman, 2003), rule break errors and failure to initiate the task were related to clinically different cognitive deficits in neurological patients. The double dissociation of performance on different parameters of the same test are theoretically, as well as clinically important because they suggest that different cognitive systems are reflected in the different measures. Recent studies using the GMLT have also shown the clinical benefit of analyzing conceptually distinct errors, such as rule break errors and exploratory errors for differentiating groups, or measuring
cognitive change (Maruff et al., 2006; Pietrzak et al., 2008, Pietrzak, Maruff, & Snyder, 2009).

While there are methodological challenges for studying executive functions in adult populations, there are specific problems for understanding the development of EF in children. It is common to use modified versions of adult neuropsychological tasks for use in children, but it is not always clear whether children perform a task using the same cognitive processes as adults (Carlson, 2005; Wiebe, Espy, & Charak, 2008). Tests that are appropriate for use in children must fulfill criteria to address limitation in testing children that are less problematic for most tests designed for adults.

3.3 Executive Functions in the early school years

A large body of research has examined the emergence of EF in the preschool years (Andrews Espy, 2004; Carlson, 2005; Diamond, 2009; Zelazo, 2004). There are several compelling reasons to investigate the development of executive functions in children over 5-years of age. First, research suggests that rapid changes in cognitive abilities occur before 9-years of age (Best & Miller, 2010; Romine & Reynolds, 2005). Second, methodological challenges that exist in working with very young children are less problematic in older children. Finally, school-aged children can often perform adult tasks at low levels of difficulty therefore making it possible to examine the development of a construct across the lifespan.

Examination of changes in cognitive control functions after 5-years has been conducted with a strong emphasis on working memory models of component functions, such as inhibition, set-shifting, and memory span limits (Best, Miller &
Jones, 2009; Garon, Bryson, & Smith, 2009; Gathercole, Pickering, Ambridge, & Wearing, 2004). Working memory has been a central concept in many accounts of cognitive development in general, and executive functions in particular (Case, 1992; Andrews & Halford, 2002). Theorists have suggested that qualitative changes in executive development reflects improvements in attentional control (Backen Jones, Rothbart, & Posner, 2003; Cowan et al., 2005; Kane, & Engle, 2002), working memory capacity (Case, 1992), linguistic recoding (Baddeley, Gathercole, & Papagno, 1998), or processing speed (Kail & Ferrer, 2007). All of these factors operate together to maximize cognitive resources for performance on difficult or complex tasks. Research into the development of EF has been mainly concerned with pre-schoolers ability to manage increasingly complex information (Romine & Reynolds, 2005; Zelazo, 2004), or has focussed on the maturation of components serving working memory and executive functions in older children (Brocki, & Bohlin, 2004; Korkman, Kemp, & Kirk, 2001; Luciana & Nelson, 1998, 2002). For example, simple functions, such as the ability to shift attention and select responses from two competing stimuli develops in the early pre-school years (3- to 6-years of age: Carlson, 2005; Davidson, Amso, Anderson, & Diamond, 2006; Diamond, 2002; Garon et al., 2008; Marcovitch & Zelazo, 2009). More complex functions develop from around 8-years onwards, with the greatest increases in abilities occurring before the age of 9-years (Case, 1992; Luciana, 2003; Luciana & Nelson, 1998, 2002; Korkman et al., 2001). For example, set-shifting, updating, working memory span, temporal ordering, self-ordered planning, and error monitoring are evident in 7-to 9-year-olds and continue to develop into the teenage years and adulthood (Best & Miller, 2010; Bunge & Crone, 2009; Conklin, Luciana, Hooper, & Yarger, 2007; De Luca et al. 2003;
Garon et al., 2008; Henry & Bettenay, 2010; Luciana, 2003; Luciana & Nelson, 1998, 2002). These more complex forms of cognitive control require the orchestration of multi-step or multi-component processes in which immaturity in any sub-process, or their co-ordination can affect task performance. However, there is increasing criticism of componential descriptions of executive functions, without an accompanying account of how increasingly complex representations of a problem change and are coordinated (Garon et al., 2009; Marcovitch & Zelazo, 2009).

A developmental account of EF in childhood is now emerging that extends beyond identifying the basic components of working memory (Best & Miller, 2010; Bunge & Zelazo, 2006). Increasingly, researchers are interested in how memory systems interact and gain control of behaviour (Hartley & Burgess, 2005; Morton & Munakata 2002; Poldrack & Packard, 2003; Towse, Lewis, & Knowles, 2007). Models of action selection are consistent with models of executive function that characterize the function of feedback loops involving, but not exclusive to the frontal cortex in modulating behavior (Gilbert & Burgess, 2008; Koechlin & Summerfield, 2007; Stuss, 2011). For example, models of memory and action selection suggest that there is competition and co-operation between different processing ensembles for attentional selection of stimuli, and action responses (Deco & Rolls, 2005; Morton & Munakata, 2002; Poldrack & Packard, 2003; Marchovitch & Zelazo, 2009). In these accounts some form of ‘processing bias’, such as neural signal amplification, acts on competing representations, or responses, that in turn prioritizes attentional selection of some stimuli/responses over others, thereby making them more likely to be selected in attention and action response plans (Morton & Munakata, 2002). From a developmental perspective,
inappropriate responses may be regarded as failure to maintain nascent, or non-salient representations in the face of competition from more established processes or responses (Towse et al., 2007). It should be emphasized that perseveration refers to the neglect of intact skills and knowledge (even if nascent), not the absence of skills (as in developmental models of cognitive complexity: Zelazo, 2004). Therefore in order to study EF in children it is important to use tasks in which the underlying processes for task completion can be demonstrated to be intact. This requires an inclusion and exclusion criteria for children’s participation in studies based on assessment of task knowledge.

3.4 Methodological issues for studying executive functions in children.

Many EF tests used in children are adult tasks that are scaled in difficulty to identify the level at which efficient performance deteriorates: Self-ordered pointing and searching tasks, Tower tasks, and N-Back tasks are designed to measure capacity limits with increasingly complex stimuli, or increasing units of information. Optimal performance at high levels of difficulty on these tasks is achieved through the use of ordering strategies, such as serial searching, or the discovery of performance rules, such as in Tower tasks, or WCST. In many of these tests, children’s performance is below that of adult performance due to failure to use ordering strategies (e.g. The Spatial Working Memory Task in the Cambridge Automated Neuropsychological Test Battery [CANTAB]: Luciana & Nelson, 1998, 2002). Tests such as the Spatial Working Memory Test of CANTAB measure the breakdown in organizational skills when working memory for spatial information is exceeded (over the 6 box condition), but not how this process occurs, or how it is related to individual differences in working memory (Luciana & Nelson, 1998, 2002).
Many tests have complex rules that are given verbally only once before testing begins. Children’s ability to comprehend, remember and apply complex linguistic rules is likely to impact on their ability to complete a task in ways that are less problematic for adults with mature linguistic skills. One reason for children’s inferior performance to adults may be due to inferior task understanding and familiarity. Hence many tests of EF used in children may be confounded with language and intelligence. Many test batteries for children (see Carlson for a review of EF tests for preschoolers) and adults have a limited age-range for use, thereby limiting the use of task across the life-span. A test of executive function should examine the flexibility of cognitive procedures while minimizing the potential for consolidated knowledge to aid problem solving. Non-verbal tasks such as the CANTAB battery were designed for this purpose. Spatial search tasks have a long history in developmental psychology and have been used extensively to map the development of diverse spatial skills (Ellis, Katz, & Williams, 1987; Newcombe & Huttenlocker, 2000). Skills known to be developmentally stable in early childhood include cue-based searching (Foreman, Warry & Murray, 1990; Lehnung, Leplow, Friege, Ferstl, & Mehdorn, 1998; Leplow, Lehnung, Pohl, Herzog, Ferstl & Mehdorn, 2003; Overman, Pate, Moore & Peuster, 1996; Reeve et al., 1986) and object-location memory (Jansen-Osmann & Heil, 2007). Tasks that test EF within an early developing domain are therefore useful methodologically because they minimize variance due to individual differences in the cognitive domain in which EF is tested.

Many executive function tests were designed to be components of larger clinical test batteries. Consequently, the individual tests provide only a single objective outcome measure (e.g., all subtests of the Behavioral Assessment of the
Dysexecutive Syndrome for Children, or BADS-C: Emslie, Wilson, Burden, Nimmo-Smith, & Wilson, 2003; Engel-Yerger, Josman, & Rosenblum, 2009). From few measures it is not possible to determine which underlying cognitive functions improve on a task with age. Furthermore many adult tasks are time-consuming and children are more susceptible to fatigue effects because they often take longer than adults to complete them.

Although the concept of co-ordination is central to most theories of executive function, few tasks have been designed to investigate this construct in children. Dual task methodologies measure the ability to maintain multiple streams of information within working memory models (Cowan et al., 2005; Davidson et al, 2006; Guttentag, 1989), although they could also be interpreted within executive function models of coordination. For example, impaired performance in dual-task, but not single-task conditions are usually interpreted as a limitation in the quantity of simultaneous information that can be processed (Cowan et al., 2005). By contrast, theories of executive function emphasize how limited resources are allocated according to competing goals, and different processing demands (Marchovitch, & Zelazo, 2009). Because different cognitive skills often develop on different time-scales, it would be expected that they be differentially affected by load constraints. Cognitive co-ordination can be inferred from the breakdown in intact processing skills by identifying which processes are retained, and which are ‘forgotten’ when difficulty exceeds cognitive capacity.

3.5 The use of the GMLT for investigating children’s cognition

As described in chapter 2 the GMLT measures components of maze performance that have been shown to be differentially sensitive to differences in
There is compelling evidence that rule-use and pathway
exploratory errors in the GMLT depend on different cognitive processes that can
be dissociated through pharmacological or medical interventions. Therefore the
GMLT can be used to study task manipulations that affect the underlying processes
in children. As described in chapter 2, the GMLT has been used across the life-
span, from young children to the elderly in identical form (Mayes, Snyder,
Langlois, & Hunter, 2007; Schroder, Snyder, Sieski, & Mayes, 2004; Snyder,
Maruff, et al., 2008b). Therefore the same maze learning construct can be used to
understand the development of underlying functions. Tasks rules are trained and
practiced before testing, and when parallel versions of the task are used, practice
effects are absent (Maruff, Werth, Giordani, Caveney, Feltner, & Snyder, 2006;
Pietrzak, Snyder, Jackson, Olver, Norman, Pikulic, & Maruff, 2009; Snyder,
Bednar, Cromer, & Maruff, 2005; Snyder et al., 2008a; Snyder, Werth, Giordani,
Caveney, Feltner, & Maruff, 2005). HPMLT are useful for studying complex
cognition in children because the objective and rules of the task are grasped easily
from initial training, and performance does not depend on the discovery of
strategies. HPMLT’s have a game-like structure that is engaging for children and
the task is usually completed within a few minutes, thereby reducing motivation or
fatigue effects.

3.6 Summary of arguments and research agenda

There has been a hiatus in research into the development of executive
functions after the age of 5-years. Tasks are either designed for pre-schoolers, or
for children over the age of 8-years. The use of a task in which underlying
processes, and their coordination can be studied provides a valid method for
studying executive functions in children. The general claim is that the GMLT
meets the methodological requirements for the study of executive functions in children. It is suggested that protocols for administering the task and manipulation of the task structure are needed for such an investigation to take place.

The first study was designed to investigate the age related changes in performance on the hidden pathway maze learning task where the length of the pathway and size of the matrix was varied (and the pathway length). By investigating the interactions between maze matrix size and component spatial memory and rule use measures, it may be possible to identify different processing costs for developing spatial abilities. By characterizing the nature of errors under cognitive load challenge it was also possible to further characterize the nature of children’s difficulties in the GMLT. This study was also designed to develop protocols for training and testing children in the GMLT rules.

Study 2 was further designed to examine the nature of children’s difficulties in the GMLT and identify whether providing task support could improve performance. In this study, two additional versions of the GMLT were designed to highlight ‘legal’ move options at every choice-point. Issues identified in study 1 for the development of rule training were extended in study 2.

Study 3 investigated the independence of spatial memory and rule use in the GMLT by the ‘double dissociation’ procedure. Specifically in the first experiment, standard rule training was given to one group of children, and no rule instructions or training was given to another group. By limiting rule knowledge it was possible to assess the effect of rule understanding on spatial memory. Conversely, by changing the pathway on each trial, thereby preventing navigation from memory, it was possible to examine the effect of the absence of spatial memory on rule use.
Study 4 was designed to extend these studies and investigate the cognitive basis of memory and rule use aspects of the GMLT using external comparator tasks. Taken together, these studies were conducted to address the question of the independence of purportedly different processes underlying GMLT performance and factors that inhibit, or facilitate their coordination in young school-aged children.
Chapter 4


4.1. Introduction

The first study of this thesis was initially designed to address preliminary questions of the suitability of maze difficulty for children of different ages. Was there a level of difficulty that was optimal for discriminating performance within and between children from 5-to-9-years of age? Ceiling and floor effects are often observed in developmental data, and it is common to scale tasks in difficulty to optimize the discriminatory value of data, and to set a task at age-appropriate levels. It was argued in the last chapter that the GMLT is appropriate for children, and there is evidence that children can perform the task in the standard version (Mayes, Snyder, Langlois, & Hunter, 2007; Schroder, Snyder, Sieski, & Mayes, 2004; Snyder, Maruff, et al., 2008). However these studies were conducted with older children than in the current 5-9-year old group in the present study, and therefore it was unknown how the younger children would perform at the highest 10 by 10 level of difficulty, which is the standard maze format for the GMLT. It was also important to develop protocols for training largely pre-literate children in how to perform the task.
The practical concern of suitability of maze difficulty level for children of different ages dove-tailed with the theoretical question of how different cognitive operations of learning the maze sequence and direction, and following, or breaking the rules would be affected by increasing task difficulty as a function of age. Would task difficulty affect all children equally in their ability to remember the pathway and follow the rules? By examining when children can and cannot perform the task effectively, by increasing task difficulty, it was possible to ask the question of what happens at the point of task difficulty where performance deteriorates, and is it different or the same for children of different ages? This is an important question because developmental theorists suggest that when processing demands of a task with increasing difficulty exceed working memory, children selectively ignore or neglect elements of a task (Case, 1970; Towse, Lewis, & Knowles, 2007). However this interpretation has mostly been based on studies with preschoolers, and has received little attention in older children. The GMLT has rarely been used in school-aged children, but it provides a methodology to investigate the question of cognitive coordination of memory and monitoring functions in a novel task that has not been used before for this purpose. Characterizing age-related changes in exploratory and rule brake errors with task difficulty as a function of age provided a methodology to characterize the effect of task difficulty on the sub-ordinate functions required by trial-and-error learning in the GMLT. Because the GMLT software records many errors classified by the nature of the move, it was also possible to conduct post-hoc analysis of the precise profile of specific difficulties that arose in children.
Spatial memory and executive functions in children

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Spatial memory and executive functions in children

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A computerized hidden pathway maze-learning task was used to examine the development of spatial memory and executive functions in 6- to 9-year-olds. Pathway length was manipulated to investigate the impact of increases in maze matrix size on these abilities. Analysis showed that maze matrix size and low-factors pathway length) and age increased to affect executive functions but not spatial memory. Executive errors differed as a function of age on the most difficult maze. Results are discussed in terms of factors affecting the development of executive functions and spatial memory.

Keywords: Hidden pathway maze learning; Executive functions; Development; Children; Spatial memory.

Studies of the development of executive function in childhood show that simple functions such as the suppression of prepotent responses, shifting attention between competing and compelling streams of information, or the maintenance and manipulation of goal-relevant information in working memory develop from approximately 3 to 6 years of age (Carlson, 2005; Davidson, Anson, Anderson, & Diamond, 2006; Diamond, 2002; Garon, Bryson, & Smith, 2008; Marcevich & Zelazo, 2006). More complex executive functions such as problem solving, planning, and error monitoring appear between the ages of 7 to 9 years of age and continue to develop into adulthood (Best, Miller, & Jones, 2009; Brocki & Boblin, 2004; De Luca et al., 2005; Henry & Bertelsen, 2010; Luciana & Nelson, 1998, 2002; Routine & Reynolds, 2005; Welsh, Pennington, & Grossier, 1991). Understanding of the development of complex executive functions in school-aged children has been limited because many of the tests used to define this construct were developed for adults. Adult executive function tests tend to have linguistically complex rules, use language-based or complex visual stimuli material or require sophisticated motor or verbal responses (Hughes & Graham, 2002). Therefore, it can be difficult to determine whether poor performance on such tasks in children reflects immaturity of executive functions or...

Three of the authors of this manuscript are employees of CogState Ltd., who own and distribute the GMLT software.

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their ability to understand the task requirements (Best et al., 2009; Gareen et al., 2008; Hughes & Graham, 2002; Jarrard & Rosselli, 2007).

Understanding the development of complex executive functions in school-aged children could be improved through use of tasks that do not require language-based responses or depend on adherence to complex rules that are given only linguistically and then only once. Consideration of the nature of hidden pathway maze learning suggests that this paradigm may provide a useful basis for understanding the development of complex executive functions in young school-aged children.

The hidden pathway maze-learning paradigm has been used for many years to study complex executive functions in experimental psychological and neuropsychological contexts (Behar et al., 1984; Canavan, 1983; Flitman, O'Grady, Cooper, & Grafton, 1997; Milner, 1965; Milner, Corkin, & Trufter, 1968; Osterberg, Orbach, Karlson, Bergendorf, & Seger, 2003; Pietrzak, Cohen, & Snyder, 2007; Retten, Cheslow, Rappaport, Leonards, & Lemanu, 1991; Snyder, Bednar, Cromer, & Manipf, 2005; Snyder, Jackson, et al., 2008; Steinberg, Chakelison & Schwartzman, 1983; Van Horn et al., 1998). In this paradigm the individual is presented with a matrix of locations (also called tiles or stepping stones) and is required to locate and learn a pathway that is hidden beneath these locations. The pathway is learned one step at a time by following simple searching rules and on the basis of the feedback that is signaled after each step (Barker, 1931; Milner, 1965; Morrison & Gates, 1988; Walsh, 1985). Once the pathway has been found, a second trial begins where the individual returns to the start of the maze and seeks each step in the pathway once more. This process continues for a specific number of trials or until error-free performance occurs. Hence, the strength of the representation of the pathway in memory increases with each subsequent trial. The complexity of the task is based on the requirement that efficient performance depends on individuals' ability to integrate the ever-strengthening memory representation of the pathway with the rules for maze performance and the feedback signaled after each response (Pietrzak et al., 2008).

Although studies of hidden pathway maze learning express performance in terms of total errors made or total trials to criterion, analyses of the types of errors made have proven useful for understanding the neuropsychology of abnormal performance. For example, errors in contravention of the searching rules are infrequent in healthy adults (Pietrzak et al., 2008; Snyder, Jackson, et al., 2008). However, rule-break errors increase substantially in adult clinical groups where there has been damage, disease, or pharmacological disruption to prefrontal brain areas (Canavan, 1983; Milner, 1965; Retten, et al., 1991; Snyder et al., 2005; Snyder, Jackson, et al., 2008; Snyder, Manipf, Pietrzak, Cromer, & Snyder, 2008; Steinberg, Chakelison & Schwartzman, 1983; Thomas et al., 2008). By contrast, the same types of disruption have much less of an effect on errors related to spatial memory (Milner, 1965; Snyder, Jackson, et al., 2008; Snyder, Manipf, et al., 2008; Thomas et al., 2008). Importantly, hidden pathway maze-learning tasks have been used successfully with children from 6 years onwards; although the developmental trajectory of performance has not been well characterized for this paradigm (Clark et al., 2006; Jones & Batalla, 1944; Jones & Yoshioka, 1938; Mayes, Snyder, Langlois, & Hunter, 2007; Schroeder, Snyder, Sieski, & Mayes, 2004; Snyder, Manipf, et al., 2006). Most studies of hidden pathway maze learning in children show that performance is inferior to adults; although this has been investigated mostly for the total errors made (Clark et al., 2006; Kinella et al., 1995; Kinella et al., 1997; Seckfort et al., 2008; Williams et al., 2010). Thus, there is currently no basis from which to understand the neuropsychological processes responsible for age-related improvement in complex executive functions when defined by total errors on the hidden pathway maze-learning paradigm.
The development of spatial memory has been characterized using paradigms that require cue or direct navigation. These studies show spatial memory functions are generally intact at 7 years and are fully developed by 10 years (Lawrence, Learmonth, Nadel, & Jacobs, 2003; Lehongre, Leplow, Frieze, Feron, & Medori, 1996; Leplow et al., 2003; Overman, Pate, Moore, & Peuster, 1996; Pine et al., 2002). However, other studies of spatial memory using span paradigms have identified stepwise linear increases in forward block span of one to eight blocks from 4 years into adulthood with forward span size reaching an asymptote at about 13 years (Anderson & Lajoie, 1996; Gathercole, Pickering, Hambridge, & Wearing, 2004; Hamilton, Coates & Heffernan, 2003; Logie & Pearson, 1997, Luciana & Nelson, 1998, 2002). It is therefore likely that age-related differences in spatial memory will contribute to developmental changes in hidden pathway maze learning.

Tasks are often modified for use with children by reducing their complexity or making them briefer (e.g., Behavioral Assessment of the Dysexecutive Syndrome for Children [BADS-C]; Emslie, Wilson, Burden, Nimmo-Smith, & Wilson, 2003). However, simplification of adult executive function tasks may change the focal construct, thus limiting the extent to which performance can be compared to adults (Andrews-Essp, 2004; Carson, 2005). One interesting property of the hidden pathway maze-learning paradigm is that it can be simplified by reducing the size of the matrix under which the pathway is hidden. Reducing the size of the matrix decreases the length of the pathway and consequently reduces the demands of the task on spatial memory. Importantly though, reducing the size of the matrix does not reduce the direct demands on executive functions; i.e., the rules for maze performance remain the same irrespective of the matrix size. Despite this potential for simplification, most studies using the maze-learning task in children have adhered to the adult 10 × 10 matrix with a 28-step pathway format (Kinsella et al., 1995; Kinsella et al., 1997; Schröder et al., 2004; Snyder, Maruff, et al., 2008). This does raise the possibility that the relatively poorer performance in younger children may merely reflect their inability to cope with the demands of the adult task. The only developmental study of maze performance in children used an 8 × 8 matrix size; although they provided no rationale as to why this level of difficulty was selected or how performance on this version corresponded to performance on the standard 10 × 10 paradigm (Clark et al., 2000). No study has directly investigated the effect of different matrix sizes on maze performance in children of the same age.

The reduced demands on spatial memory associated with shorter pathways may allow more efficient rule-use. However, as the first trial on maze tasks is completed without any knowledge of the pathway, any reduction in demands on spatial memory would operate only for subsequent trials (Matheson, Dryan, Snyder, Tays, & Segalowitz, 2008). Therefore, analysis of data from the first trial may allow understanding of the effect of matrix size on rule-use without influence from spatial memory.

An examination of children’s performance on mazes, in which difficulty is systematically varied, may provide insight into the development of complex executive functions. Specifically, it would allow an analysis of how changes in abilities associated with rule-use and spatial memory impact developmental abilities. By investigating the interaction between matrix size and different components of maze performance, it may be possible also to determine whether simplification of the hidden pathway maze-learning task is necessary for study of complex executive functions in younger children. It would also allow understanding of the extent to which performance on simplified and standard versions of the maze-learning task were comparable. The aim of the current study is to investigate the age-related differences in performance on the hidden pathway maze-learning task where
the length of the pathway and size of the matrix were varied. These same relationships were also investigated in a group of healthy young adults for the purpose of providing a benchmark for mature performance.

The first hypothesis is that performance on the maze, as indexed by a reduction in errors, would improve with age. The second hypothesis is that performance will deteriorate as a function of increases in maze matrix size. Specifically, the deterioration is expected to be age related. Although the nature and frequency of errors related to rule-use and spatial memory are expected to increase as a function of matrix size and age, no prediction is made about the precise form of these errors.

METHOD

Participants

One hundred and five 5- to 9-year-olds attending school in a mid-sized Australian city, comprising thirty-five 6-year-olds (16 males and 19 females), twenty-three 7-year-olds (12 males and 11 females), twenty-eight 8-year-olds (21 males and 7 females), nineteen 9-year-olds (10 males and 9 females) (M = 5 years, 11 months; SD = 4.63 months; M = 7 years, 0 months; SD = 3.35 months; M = 7 years, 11 months; SD = 3.51 months; M = 9 years, 1 month; SD = 3.79 months, respectively), participated. According to their teachers, none of the children had a learning disorder. Twenty healthy young adults (12 males and 8 females; M = 27 years, SD = 8 years) were recruited from among people known to the researchers. All adults rated themselves as being in good health. All participants had normal or corrected-to-normal vision. The research was conducted in accordance with authors’ University’s Human Ethics Committee’s requirements.

Materials/Apparatus

The hidden pathway maze-learning task was given using the Groton Maze Learning Task (GMLT). The GMLT is a computerized hidden pathway maze search task (see Figure 1; see also Snyder et al., 2005; Snyder, Munuff, et al., 2008 and Thomas et al., 2008 for detailed descriptions of the GMLT and its administration in adults). The GMLT is presented using a personal computer and a touch screen. It comprises square arrays of tiles (e.g., 10 x 10 tiles) that appear on the touch-screen. Beginning at the top left corner tile and finishing at the bottom right corner tile, participants touch tiles with their index finger in an attempt to find the pathway hidden beneath them. If a correct tile is touched, it will turn white with a green tick, accompanied by a brief auditory tone. If an incorrect tile is selected, it will turn white with a red cross, and no tone is emitted. Tile selection is governed by five rules: (a) The next tile in a sequence should always be a tile adjacent to the current tile; (b) the next tile in the sequence will not be diagonally adjacent to the current tile; and (c) it will not be the previously selected tile. Participants are also instructed that (d) if an incorrect tile is selected, they should return to the last correct tile, and (e) they should touch each tile only once. GMLT software records each move and classifies it as correct or error. Performance was studied in pathways hidden under four different levels of matrix size: a 10 x 10 maze comprising a 24-location hidden pathway sequence; a 20-location 8 x 8 maze; a 12-location 6 x 6 maze; and a 6-location 4 x 4 maze. Twenty different pathways were generated for each maze, which were used randomly in testing.
Figure 1: The Gorino Maze Learning Test. Participants must find a 28-step hidden pathway concealed within the tile grid accord with the following rules: Do not move diagonally, backward, or more than one tile at a time. Return to the last correct location after an unsuccessful search. Each move is signaled by a correct green tick or an incorrect red cross on the current location.

Procedure

Children were tested in a quiet room at their school in either two or three 15-minute sessions, depending on the time taken to complete the mazes. Initial training involved a verbal description of the task goal and a demonstration of rules on the 10 x 10 maze. In the demonstration, probe for illegal move types were used to examine children's understanding (e.g., following a diagonal move, children were asked “Can I move here [no], followed by “Where should I move now [return]?”). Children completed two practice trials to ensure that they understood the rules before proceeding to the test phase. Pilot work with 14 children suggested this was adequate practice for children to understand the rule structure, as determined by observations of performance on the second practice trial. The interviewer corrected all errors verbally on the first but not the second practice trial. This included a statement of why the move was an error (e.g., wrong location, jumped), and remaining children of the next legal move, which was always to return to the head of path (the last correct location) after an error. Four children in the youngest group were excluded because they did not pass the training phase. In the test phase, participants completed five trials on each of the 4 x 4, 6 x 6, 8 x 8, and 10 x 10 mazes in ascending matrix size order. An ascending, rather than a random order, was used so that testing could be ceased if difficulty prevented a child from completing the task (this did not happen).

Measures

Errors were classified as exploratory or rule-break errors. Exploratory errors were classified when individuals selected a location that did not reveal the next step in the pathway but which was allowed by five rules. Rule-break errors were errors that violated one of the five tile selection rules (see Table I for a description of different rule-break errors). In addition, errors related to perseverative responding or selecting the
same incorrect location in succession, tapping between tiles or out of grid and repeatedly tapping the same incorrect location, were counted as rule-break errors. In accordance with standard maze analyses, each error type was summed over the five learning trials (e.g., Snyder et al., 2005; Thomas et al., 2008). However, in order to measure performance related only to rule-use (i.e., with no contribution from memory), the number of exploratory and rule-break errors on Trial 1 of each maze was also compared between groups.

Data Analysis

For each child participant and each matrix size, the number of total errors, rule-break errors, and exploratory errors were submitted to a series of linear mixed model (LMM) analyses. In each LMM, age and matrix size were modeled as fixed factors and subject as a random factor. To investigate the relationship between age groups and matrix size, an interaction term, Age Group × Matrix Size, was included. In this analysis, the main hypotheses were tested by the presence of any interaction term involving age and matrix size. When the Age × Matrix Size interaction was significant, slopes for Error × Matrix Size were compared for different age groups by examining the parameter estimates for matrix size in each age group. The age level factor in the LMM was defined such that the parameter estimates reflected comparisons between each age group and the 9-year-old group. The LMM analyses were repeated with adults included in the model for the purpose of comparison with the 9-year-olds. Analysis of performance on the first trials was conducted by summing the rule-break and exploratory errors made on the first trial of each matrix size level and comparing these between age groups with a one-way Analysis of Variance (ANOVA).

The nature of rule-break errors made on the maze was investigated further for the level of matrix size that discriminated best rule-break errors between the age groups. For each error subtype (see Table 1), a one-way ANOVA was used to compare performance between age groups. For these last two analyses, the performance of the adult group was shown graphically, but the adult data was not statistically compared to that of the children.
RESULTS

Figure 2 shows linear trends fitted to the relationship between total errors and matrix size for each age group. The LMM indicated that Age Group x Matrix Size interaction was significant, $F(3, 306) = 5.05, p < .01$. Post-hoc comparison of the slopes of the linear relationship between increase in total errors with increasing matrix size indicated that there was no difference between 9-year-olds ($M = 25.74, SE = 2.47$) and 8-year-olds ($M = 27.88, SE = 3.20, d = 0.15$). However, when compared to the 9-year-olds, the linear slopes for total errors in 7-year-olds ($M = 32.97, SE = 3.37, t = 2.15, p = .03, d = 0.54$) and 6-year-olds ($M = 36.01, SE = 3.07, t = 3.35, p < .01, d = 0.64$) were significantly smaller. The slope of total errors over increasing matrix size in adults is also shown in Figure 2 ($M = 13.58, SE = 2.71$) and was significantly different to that of the 9-year-old group ($t = 3.75, p < .01, d = 1.16$).

Figure 3 shows linear trends fitted to the relationship between exploratory errors and matrix size for each age group. The LMM indicated a significant effect of matrix size, $F(1, 306) = 2370.85, p < .01$, but no significant effect for age group, $F(3, 101) = 0.29, p = .83$, and no Age Group x Matrix Size interaction, $F(3, 306) = 1.6, p = .19$. Thus, there was no difference between age groups for the slopes of the trends for the increase in exploratory errors with increasing matrix size between 9-year-olds ($M = 15.86, SE = 0.77$), 8-year-olds ($M = 16.51, SE = 1.0, d = 0.21$), 7-year-olds ($M = 16.30, SE = 1.05, d = 0.18$), and 6-year-olds ($M = 17.55, SE = 0.96, t = 2.06, d = 0.4$). Furthermore, the magnitudes of differences ($d$) between slopes were by convention very small indicating that the absence of statistical significance was not due to low power. The slope of exploratory errors over increasing matrix size in adults is shown in Figure 3 ($M = 11.79, SE = 0.76$) and was significantly different to that of the 9-year-old group ($t = 3.48, p = .01, d = 1.12$).

Figure 4 shows linear trends fitted to the relationship between rule-break errors and matrix size for each age group. The LMM indicated that the Age Group x Matrix Size interaction was significant, $F(3, 306) = 4.09, p < .04$. Post-hoc comparison of the slopes of the trends for the increase in rule-break errors with increasing matrix size indicated that the slope for the 9-year-olds ($M = 10.18, SE = 2.12$) was no different than to 8-year-olds ($M = 11.37, SE = 2.75, d = 0.1$), but significantly less than the 7-year-olds ($M = 16.67$).
Figure 3 Linear relationships between task difficulty and exploratory errors for the four age groups and adults with standard errors. The five age groups are represented as filled diamonds (6-year-olds), unfilled squares (7-year-olds), filled triangles (8-year-olds), unfilled circles (9-year-olds), and unfilled triangles (adults).

Figure 4 Linear relationships between task difficulty and rule-break errors for the four age groups and adults with standard errors. The five age groups are represented as filled diamonds (6-year-olds), unfilled squares (7-year-olds), filled triangles (8-year-olds), unfilled circles (9-year-olds), and unfilled triangles (adults).

SE = 2.89; t = 2.24; p = .03, d = 0.56), and 6-year-olds (M = 18.47, SE = 2.62; t = 3.14; p = .01, d = 0.61). The slope of rule-break errors over increasing matrix size in adults is shown in Figure 4 (M = 1.79, SE = 1.91) and was significantly different to that of the 9-year-old group (t = 3.06, p = .01, d = 0.94).

Analysis of Rule Learning

The ANOVAs for errors made on the first trials indicated no differences between age groups for the rule-break error score (6-year-olds: M = 27.14, SD = 17.20; 7-year-olds: M = 32.48, SD = 22.18; 8-year-olds: M = 23.25, SD = 13.72; 9-year-olds: M = 23.16, SD = 9.84). F(3, 102) = 1.57; p = .20, or exploratory error score (6-year-olds: M = 32.91, SD = 3.98; 7-year-olds: M = 32.00, SD = 3.29; 8-year-olds: M = 33.29, SD = 3.25; 9-year-olds: M = 33.26, SD = 3.46), F(3, 102) = 0.62, p = .60.
Exploration of Rule-Break Errors on the 10 x 10 Maze

Figure 5 shows the age means for rule-break errors for the 10 x 10 maze. The rates of failure-to-return errors were substantially greater than other individual rule-break errors and are not shown in Figure 5. The mean and standard deviation were as follows: 6-year-olds: M = 26.14, SD = 15.65; 7-year-olds: M = 25.43, SD = 17.45; 8-year-olds: M = 17.25, SD = 9.73; 9-year-olds: M = 14.47, SD = 6.27; adults: M = 3.75, SD = 3.34. When expressed as a ratio of successful return to last correct location, responses were as follows: 6-year-olds: M = 0.28, SD = 0.13; 7-year-olds: M = 0.30, SD = 0.17; 8-year-olds: M = 0.23, SD = 0.11; 9-year-olds: M = 0.21, SD = 0.08. Differences between age groups were observed for same-tile tap errors, F(3, 102) = 6.41, p < .01 (6-year-olds > 8-year-olds: M = 2.29, p = .002; and 9-year-olds: M = 4.67, p = .003); within-search errors, F(3, 102) = 4.55, p < .01 (6-year-olds > 8-year-olds: M = 3.42, p = .003); failure to return errors, F(3, 102) = 4.71, p < .01 (6-year-olds > 8-year-olds: M = 8.89, p = .05; and 9-year-olds: M = 11.67, p = .002), exploratory errors, F(3, 102) = 3.90, p = .01 (6-year-olds > 7-year-olds: M = 5.66, p = .03; 8-year-olds: M = 5.55, p = .02; and 9-year-olds: M = 8.4, p = .002), diagonal moves, F(3, 102) = 3.07, p = .02 (6-year-olds > 8-year-olds: M = 1.43, p = .03; and 9-year-olds: M = 1.38, p = .05; 7-year-olds > 8-year-olds: M = 1.9, p = .01; and 9-year-olds: M = 1.85, p = .02) and jump moves, F(3, 102) = 2.87, p = .04 (post hoc comparisons were not significant when homogeneity of variance was not assumed). Age groups did not differ on other errors.

DISCUSSION

Findings supported the first hypothesis. Performance on all aspects of maze learning improved with age. The second hypothesis was also supported: As matrix size increased, an age-related deterioration in performance in total errors and rule-break errors was observed (see Figures 2 and 4, respectively). Although the number of exploratory errors increased with increasing matrix size, the rate of increase was similar for all age groups (see Figure 3). These results suggest that the greater increase in total errors with increasing matrix size observed in the younger children was due to differences in the ability to use
rules and not spatial memory. Although rule-use was more efficient in the 9-year-olds than in 6-year-olds, overall it was inferior to adults (see Figure 4). Likewise, although no age differences were observed for the effect of matrix size on exploratory errors, the rate of adults’ increases in exploratory errors was less than the 9-year-olds. This indicates that the spatial memory processes necessary for optimal performance had not developed fully (see Figure 3).

Spatial Memory in Hidden Pathway Learning

For the smallest matrix size (i.e., 4 × 4 maze), the number of exploratory errors made by all participants was similar. Moreover, for the four youngest age groups, linear increase in exploratory errors across matrix sizes was similar. The absence of any age effects on exploratory errors suggests that the spatial memory processes necessary to solve the hidden pathway maze-learning task were well developed in all children. In the context of maze learning, spatial memory is often referred to as topographical memory (De Renzi, Faglioni, & Villa, 1977; Habib & Siriga, 1987) or spatial mapping (Bower & McBurney, 1973).

To our knowledge, there have only been two studies that have examined different topographical memory errors (i.e., exploratory errors as opposed to rule-break errors) in hidden pathway learning tasks in children. Most previous studies of hidden pathway maze learning in children have analyzed total errors and have not examined error types (Clark et al., 2006; however, see Jones & Yoshioka, 1958 for an exception). The findings of the current study are consistent with those of the two studies that have examined exploratory errors (Schrader et al., 2004; Snyder, Maruff, et al., 2008). Although the findings suggest that the spatial memory processes required by the current maze task were within the abilities of all children, it is possible that with greater memory demands (matrix sizes greater than 10 × 10), age-related changes in spatial memory might occur.

Executive Functions in Hidden Pathway Maze Learning

The current findings suggest that age-related differences in performance on the hidden pathway maze-learning task were due to immaturity of executive functions that subserve rule-use. We are confident that rule-break errors reflected problems in rule-use rather than in rule acquisition, or even in understanding the rules generally, as each of the rules were trained to criterion in individual sessions. It is worth noting that only 10% of the 6-year-olds recruited had to be excluded from the study because they could not learn the maze rules.

The fact that the errors on the first learning trial were similar across age, as well as on the smaller matrix sizes (i.e., 4 × 4, 6 × 6; see Figure 4), suggests that children could effectively use rules when memory load was low or when the pathway was novel. However, rule-use became less efficient with increases in memory load. This suggests that the ability to integrate the component cognitive processes necessary for efficient hidden pathway maze learning improved with age. Although increases in pathway length may affect memory for the pathway, logically it should not affect rule-use.

Because the difference between age groups on rule-break errors was greatest for the 10 × 10 matrix size, these errors were subclassified (see Table 1). The error comparison suggested that differences between age groups were greatest for failure to return to the correct location after an error, repeatedly tapping the same tile, and committing within-search errors (see Figure 5). Same-tile tapping in younger children may have been a location
marking strategy while they planned each next search, or a method for reducing the complexity of rule contingencies for correct and incorrect searches (i.e., if any move return to the last correct location). The relative rate of failure to return also reduced with age from approximately 36% in the younger children to approximately 22% in the older children. This suggests that failure to return was not a random occurrence and therefore did not reflect a misunderstanding of the rule. Similarly, avoiding within-search errors requires the use of prior error feedback to avoid previously searched locations. Together, these differences in the three error types suggest that problems in rule-use reflected a failure to use prior and immediate task error feedback in order to guide response choices. In contrast, rule-guided searching errors such as jumps and diagonal moves were infrequent. Together these findings suggest that the rule-break errors were well ordered as a function of age and relative prevalence.

Although these are post-hoc observations, they suggest that increasing spatial memory load increased the rule-break errors in younger children, which reflects problems with planning responses on the basis of error feedback and not problems of using search rules per se. This finding supports Darby and Walsh (2005) who suggest that errors in the Austin Maze reflect difficulties with error utilization due to dissociation in knowing the rules and failing to use them. As far as we know, our study is the first to identify the precise nature of maze-learning difficulties in children or indeed to identify this form of abolic dissociation in a nonverbal domain in children older than preschoolers (Towe, Lewis, & Knowles, 2007).

The finding that error monitoring in hidden pathway maze learning is highly sensitive to age-related changes is consistent with previous studies that have shown the late development of error monitoring in a variety of contexts (Bange & Crone, 2009; Crone, Zanollee, Van Leijenhorst, Westenberg, & Rombouts, 2008; Luciana & Nelson, 1998, 2002). For example, investigations of event-related potentials in Flanker and Go/No Go tasks show that the size of error-related negativity in error trials develops into adolescence. This relationship is considered a neurological marker of improvements in performance associated with error utilization (Crone et al., 2008). Neurologically, the basis of error feedback learning is not well understood, but theories of executive function suggest that monitoring can be impaired as a result of any factor in the sequential and hierarchical steps involved in problem solving (Cooper & Shallice, 2006). These include the ability to represent a problem, to plan solutions, and to execute them, and finally to evaluate the success of those choices (Bange & Zolazo, 2006; Luria, 1973). However, few paradigms can identify when and why the problem-solving process breaks down. In the current study, we have shown that children can demonstrate rule understanding with training and rule compliance at low levels of difficulty, but that error feedback utilization disintegrates at high levels of difficulty.

Rule-break errors in hidden pathway learning are usually interpreted as a form of perseveration (Milner, 1965; Peterson, 1920; Pietrata, 2007; Rosa, 1980; Sanderson & Albert, 1984). It seems reasonable to hypothesize that on the more difficult mazes younger children made assumptions about the path of the end goal, and this, in turn, led to them paying little attention to error messages. This is consistent with Jones and Yoshieka's (1936) hidden alley styles maze findings (which comprised a 5 x 5 maze grid with 22 or 23 steps). They termed end goal bias as "goal inertia," a proposition derived from Hullian theory in which the appetitive strength of a goal increases with temporal or spatial proximity to it (Hull, 1932).

Models of complex executive function propose that when the ability to process simultaneous information is exceeded, the default strategy is to ignore one or more task
requirements (Halford, Baker, McCredden, & Bain, 2005; Halford, Cowan, & Andrew, 2007). This in turn biases attentional selection among competing stimuli and response options (Ducom, Emslie, & Williams, 1996; Huntley & Burgess, 2005; Morton & Munakata, 2002; Pollock & Packard, 2003). Consistent with these models, the current findings suggest that as mazes become more difficult, younger children tended to focus on the representations of the expected pathway in spatial memory and paid less attention to error feedback signals. If this interpretation is correct, then it suggests that hidden pathway maze learning is a potentially useful paradigm in which to investigate bias effects in cooperation and competition models of cognitive development. The above interpretations are also consistent with developmental theories that suggest children’s errors in executive tasks reflect immaturity of the capacity to represent and coordinate task-relevant information, whether due to poor inhibition, representation, active reflection, or feedback salience (Hungr & Zelazo, 2006; Diamond, 2009; Halford et al., 2005; Happaney & Zelazo, 2003; Kirtham, Cruess, & Diamond, 2003; Towe, Redbond, Houston-Price, & Cook, 2000).

The findings of the present research are novel in that they show that at low levels of spatial memory load, young children are as efficient as older children in their ability to attend to, to represent, and to process concurrent information. However, as spatial load increased, the developmental abilities to coordinate the cognitive requirements of the task were limited in specific and identifiable ways. The findings show that young children (6-year-olds) can perform a complex executive function task when the linguistic requirements have been minimized and the goal of the task is clear. It cannot be ruled out that our findings reflect the use of verbal strategies by older children. This interpretation is unlikely because differences between children were greatest for rule and feedback use, rather than pathway encoding where verbal strategies could be used (Bowden, 1989). To our knowledge, no study has reported the effective use of verbal strategies for rule following or feedback use in hidden pathway maze learning (i.e., Milner, 1965). An examination of the relationship between verbal abilities and rule-use will need to be investigated in future studies.

REFERENCES


SpatiaL Memory and Executive Functions in Children


Chapter 5

Rule cues improve 5-year-olds rule use, but not error monitoring in hidden pathway maze learning.

5.0 Introduction

In the previous study it was shown that young children (5-and-6 year-olds) had difficulty coordinating spatial memory and rule use as a function of maze size/pathway length. This difficulty of the younger children was evident in specific difficulties monitoring errors, and repeatedly tapping on the correct location before searching. The aim of the current study is to extend the findings of study 1 by investigating the effect of visually cuing locations to aid young children’s searching and error monitoring activities. It is also designed to investigate the effect of the double tapping on the head of path on children’s other errors. Two studies are reported in chapter 5.
Abstract

Previous research found 6-year-olds are able to coordinate spatial memory and search rules locating hidden pathways in 6 x 6 mazes, but not in 10 x 10 mazes. To better understand the nature of young children’s coordination difficulties, two studies investigated the impact of (1) providing maze move feedback (Study 1), and (2) minimizing error information (Study 2) on 6-year-olds’ ability to locate pathways in the 6 x 6 (12 steps) and 10 x 10 (28 step) mazes. Children’s ability to coordinate spatial memory and maze rules improved when information about searched locations was provided; but not when error move information was minimized. Findings suggest that coordination is affected by specific capacity constraints. Implications for understanding the coordination of cognitive functions in childhood are discussed.
Chapter 5

Rule cues improve 5-year-olds rule use, but not error monitoring in hidden pathway maze learning.

5.1. Introduction

In the previous study it was shown that increasing task difficulty by increasing pathway length from 6, 12, 20, and 28 steps (and grid size from 16, 36, 64 and 100 squares) has a greater effect on 6- to 9-year-olds’ rule break errors than spatial memory errors. Importantly, the rules remain the same at all levels of task difficulty therefore the selective age-related impairment in rule use is both unexpected and unclear. A theoretical account of load effects in stepping-stone maze learning awaits description, either in terms of working memory systems or executive functions. However a tentative suggestion is that as task demands exceed processing capacity, attention is allocated to a subset of task stimuli and requirements at the expense of others (Cowan, Elliot, Saults, Morey, Mattox, Hismjatullina, & Conway, 2005; Gathercole, Pickering, Ambridge, & Wearing, 2004; Halford, Cowan, & Andrews, 2007). In this regard, the GMLT may be regarded as a test of the ability to co-ordinate rule use and spatial memory functions and thus a test of executive functions. Coordination failure may results in neglect of specific task functions that are generally intact when the task is sufficiently within capacity limits. A working memory, or competing memory account of stepping-stone maze learning derived from theories of spatial navigation is also possible (Hartney et al., 2007; Spiers & Maguire, 2007). The spatial and temporal extension of the problem solving process with increasing difficulty may also have unique effects. For example on longer pathways and
grids, the longer process may affect the salience of the rules, or the appetitive strength of the end-goal as a form of Hullian ‘goal inertia’ (Hull, 1934a, 1934b). In other words, counter-intuitive moves away from the end-goal may be more difficult to make if the problem space is bigger, and the pathway is longer. Although these interpretations are speculative, the theoretical nature of rule use and spatial memory navigation in the stepping-stone paradigm is poorly specified. As such, a preliminary investigation of factors that affect maze-learning sub-processes is warranted. Here, we test the hypothesis that reducing the cognitive load associated with locating hidden pathways in 10 × 10 mazes will improve 6-year-olds' maze abilities. The aim is to better understanding factors affecting the processing of, or coordination of underlying maze functions in young children.

A first step in conceptualizing age-related changes in maze learning functions is to understand how the underlying functions are affected by changes in cognitive demands. Insofar as capacity to perform the task is exceeded by increases in difficulty (i.e., as in the 10 × 10 maze), minimizing difficulty should increase the ability to coordinate functions. Two aspects of Thomas et al.’s (2011) methods may have affected 6-year-olds’ maze learning ability: (1) the relative increase in memory load associated with an increase in move errors; and (2) “inappropriate” error feedback associated with Rule 4 (i.e., “Single touch” rule).

It has long been known that reducing task demands by providing feedback improves children’s problem solving (Andrews Espy, 2004; Bohlman & Fenson, 2005; Flavell, 1999; Kuhn, Black, Keselman & Kaplan, 2000; Kuhn, 2000, Kuhn & Dean, 2004; Reeve, Campione & Brown, 1986). However, it is unclear how feedback operates cognitively. Providing feedback in the Standard GMLT, such as providing information about previously searched locations, and the requirement to
return to the “head of path” after an error, may allow 6-year-olds to better coordinate spatial memory and rule-use. Also, providing external move information likely highlights the salience of task features and focuses attention on task goals (Case, 1975; Ciaramelli, 2008; Duncan, Emslie, Williams, Johnson, & Freer, 1996; Marchovitch & Zelazo, 2009; Nieuwenhuis, Broerse, Nielen, & de Jong, 2004; Towse, Lewis, & Knowles, 2007; Zelazo, 2004).

GMLT move Rule 4 states that a maze square should be touched, and only once, before the next square is selected. Thomas, Reeve, Fredrickson, & Maruff, (2011) found that 6-year-olds (but not older children or adults) frequently ignored this rule. Interestingly, they often tapped a square twice before selecting the next location—which is recorded as an error in the GMLT program. Six-year-olds who ignored the “tap once only” rule received additional error information, which may have increased memory load compared to participants who followed Rule 4. Removing error feedback associated with double tap behavior should reduce task difficulty and allow coordination.

To better understand factors affecting 6-year-olds’ maze learning ability that are evident in the more difficult 10 × 10 GMLT mazes, two experiments are conducted. In Experiment 1 previously searched locations are highlighted in an attempt to reduce cognitive demands in the 10 ×10 and 6 × 6 GMLT; and in Experiment 2 error feedback associated with the “double tap” behavior is eliminated, thus reducing memory demands in the 10 ×10 GMLT. The manipulations in Study 1 and 2 differ in at least one important way. Providing visual cues (Study 1) is designed to draw attention to the maze rules so they are available to guide move decisions. In both studies the negative feedback for repeatedly tapping the correct tile (Rule 4) is replaced by positive feedback, but the
double tap behavior is still recorded as a measure. It is possible that repeated tapping on a correct tile is an unintentional action. Experiment 2 is designed to determine whether double tap activity (positive or negative) affects maze performance. It is expected that in both experiments fewer move rule errors would occur, compared to those observed in (Thomas et al., 2011), but that spatial memory errors would be unaltered.

5.2. Overview of Experiments

5.2.1 Overview

The aim of Experiment 1 was to test the hypothesis that move feedback cues would decrease rule use errors in the 10 × 10, but not the 6 × 6 maze. Three versions of the GMLT were developed to investigate the effect of providing visual cues on maze learning. The first version is identical to the Standard GMLT, except positive feedback occurred when a correct tile was tapped more than once (see Figure 5.1.1). We refer to this latter version as the Repeated Tap GMLT (however, the number of repeated taps was still recorded). In the second and third GMLT versions, locations for the next pathway move were highlighted. In the second version, the Within Search Maze Task (WMT), the three possible locations remained highlighted until the next correct move was made. In the third version, the Reference Memory Task (RMT), the cue for an incorrect location disappeared after it was selected (see Figure 5.1.1). After removal of a cue, only the one or two remaining possible move locations remained highlighted. For both the WMT and RMT versions of the GMLT, the head of pathway was indicated after every error. Each version had the same task requirements as the Standard GMLT. It is expected that the increase in rule break errors on the 10 × 10 Repeated Tap GMLT
would be reduced by visual cue feedback, but exploratory errors would be unaffected.

**Figure 5.1.1.** Depiction of differences in task feedback to error responses and post error task display on the Repeated Tap GMLT, WMT, and RMT. The top image shows the $10 \times 10$ matrix with a dark grey tile indicating the current location. This section of the maze has been re-drawn below indicating differences in display and feedback in the Repeated Tap GMLT (first horizontal row), The Within Search Maze Test, or WMT (second horizontal row), and the Reference Maze Test, or RMT (third horizontal row). Vertical row 1 shows the different feedback given to
subjects for an incorrect selection accompanied by a cross on the first search. The GMLT displays the error information only. The WMT and RMT also signals all forward horizontal locations that can be searched prior to the move. Vertical line 2 shows the feedback given 250 ms after the error display. The GMLT marks the selected tile and the WMT and RMT signal the head of path with a flashing tick. After returning to the head of path (horizontal line 3), the WMT shows all forward horizontal locations and the highlighting of the last selected tile remains extinguished in the RMT.

5.3 Experiment 1

5.3.1 Participants and procedure

Twenty 6-year-olds, comprising an equal number of boys and girls ($M = 74.95$ months, $SD = 3.98$), completed the 6 × 6 and 10 × 10 maze versions of the Repeated Tap GMLT, WMT, and RMT versions of the GMLT in a random order across three test sessions.

Children were tested individually in a quiet room at their school. Training was conducted using two trials on an 8 × 8 GMLT maze. Training began with a demonstration of rules via the touch screen. The interviewer checked children’s rule understanding with standard questions: “Can I move here (diagonal/jump/back etc)?” And “Where must I go now?” Verbal feedback on error types was provided on the first, but not the second practice trial. Four children were excluded because they were either distracted or did not understand maze move rules after two practice trials.
5.3.2 Data analysis

Consistent with previous research, errors were classified as exploratory or rule break errors. Repeated tap errors were classified separately to other errors. Exploratory errors occur when search locations followed task rules, and comprise the three adjacent locations to the last correct location. Rule break errors, in contrast, include moves that violated one of the five tile selection rules. Errors related to preservative responding or selecting the same incorrect location in succession, tapping between tiles or out of grid and repeatedly tapping the same incorrect location were classified as rule break errors. Consistent with maze error analysis, errors were summed over the five learning trials (e.g. Snyder, Bednar, Cromer, & Maruff, 2005; Thomas et al., 2008).

Hypotheses were tested by analyzing exploratory and rule break errors in 2 × 3 (Difficulty [low, high] × Maze [Repeated Tap GMLT, RMT, WMT]) ANOVA. To investigate how support affected rule break errors, they were classified in terms of errors described in Table 1. Median performances for each rule break error subtype were computed and between maze conditions were compared using Friedman’s tests (see Table 5.3.1).

5.3.3 Results and discussion

Group mean rule break errors under the low and high difficulty level for the Repeated Tap GMLT, WMT and RMT conditions are shown in Figure 5.3.1. ANOVA indicated a significant Maze × Difficulty level interaction \( F(2, 18) = 3.56, p = .05 \). Follow-up one-way ANOVAs comparing the number of errors between three types of maze within each level of difficulty indicated that for the 6 × 6 maze there was no significant differences in rule break errors between conditions \( F(2, 38) = .68, p = .51 \). For the 10 × 10 maze, the ANOVA was
significant $F(2, 38) = 4.4, p = .02$. Post-hoc t-tests indicated that the number rule break errors for Repeated Tap GMLT were greater than for the WMT $F(1, 19) = 8.8, p = .008, d = .82$. There were no differences in rule break errors between the WMT and the RMT $F(1, 19) = .58, p = .46, d = .19$.

**Figure 5.3.1.** Total rule break errors on the three GMLT versions on the $6 \times 6$ (filled diamonds), and $10 \times 10$ (unfilled diamonds) mazes. Error bars represent standard error. *= post-hoc tests indicated adjacent means significantly different ($p<0.01$)

For exploratory errors, ANOVAs indicated a significant effect of maze difficulty $F(1, 19) = 638.6, p = .000$. No other main effects or interaction were significant.

The group medians (and range) for the different types of rule break errors made in the $10 \times 10$ maze are shown in Table 5.3.1. Friedman’s tests comparing the rule break errors between the three types of maze task were significant for preservative errors $\chi^2(2, N = 20) = 25.41, p = .000$, diagonal moves $\chi^2(2, N = 20) =$
21.73, \( p = .000 \), back moves \( \chi^2 (2, N = 20) = 18.62, p = .000 \), and double tap errors \( \chi^2 (2, N = 20) = 8.09, p = .02 \). No other comparisons were significant.

Table 5.3.1

*Median and Range for Rule Break Errors on the 10 x 10 Maze Versions:*

Repeated Tap (R-T) GMLT, WMT, and RMT. \( * = p < .05, *** = p < .001 \)

<table>
<thead>
<tr>
<th>Error</th>
<th>R-T GMLT</th>
<th></th>
<th>WMT</th>
<th></th>
<th>RMT</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mdn</td>
<td>Rng</td>
<td>Mdn</td>
<td>Rng</td>
<td>Mdn</td>
<td>Rng</td>
</tr>
<tr>
<td>back</td>
<td>5</td>
<td>1-11</td>
<td>4</td>
<td>0-7</td>
<td>1</td>
<td>0-11***</td>
</tr>
<tr>
<td>between</td>
<td>5.5</td>
<td>1-15</td>
<td>5</td>
<td>0-14</td>
<td>4.5</td>
<td>0-14</td>
</tr>
<tr>
<td>diagonal</td>
<td>6</td>
<td>1-14</td>
<td>1</td>
<td>0-4</td>
<td>1</td>
<td>0-8***</td>
</tr>
<tr>
<td>dbl-tap</td>
<td>0</td>
<td>0-8</td>
<td>1</td>
<td>0-5</td>
<td>1</td>
<td>0-3*</td>
</tr>
<tr>
<td>return</td>
<td>25.5</td>
<td>3-45</td>
<td>19.5</td>
<td>7-32</td>
<td>19.5</td>
<td>3-65</td>
</tr>
<tr>
<td>jump</td>
<td>2</td>
<td>0-4</td>
<td>2</td>
<td>0-5</td>
<td>2</td>
<td>0-12</td>
</tr>
<tr>
<td>out</td>
<td>1</td>
<td>0-10</td>
<td>1.5</td>
<td>0-9</td>
<td>1</td>
<td>0-5</td>
</tr>
<tr>
<td>within</td>
<td>5.5</td>
<td>0-11</td>
<td>4</td>
<td>0-15</td>
<td>5</td>
<td>0-13</td>
</tr>
<tr>
<td>persever</td>
<td>1</td>
<td>0-6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0-1***</td>
</tr>
</tbody>
</table>

The first hypothesis is supported: rule break errors decreased when visual cues were available to aid decisions at high maze difficulty. Rule break errors at low maze difficulty and errors related to spatial memory were unaffected by visual cues (see Figures 2 and 3). Both exploratory and rule break errors increased in number from the low to high difficulty versions of the maze, confirming that the increase in pathway length increased the spatial memory load. The only difference between
error types on the three tasks was an increase in rule break errors at the $10 \times 10$
level of the Repeated Tap GMLT.

The second hypothesis was partially supported: that rule break errors are due
to difficulty using error feedback. Under high difficulty, visual cues decreased rule
break errors associated with searching, but not those related to error feedback.
Although the presence of visual cues did result in a reduction in diagonal,
backward moves, and perseverative errors (see Table 5.3.1), the cues did not
reduce the number of within search errors, or failure to return to head of pathway
errors. Consistent with previous findings (Thomas et al., 2011), children showed
no difficulty with rule use at the low maze difficulty; with or without visual cues.

5.4 Experiment 2

5.4.1 Participants

Forty 6-year-olds ($M = 74.65$ months, $SD = 3.17$), comprising an equal
number of males and females, from schools in a mid-sized Australian city
participated. The research was conducted in accordance with the authors’
University Human Research Ethics Committee’s requirements.

5.4.2 Procedure

Two versions of the $10 \times 10$ GMLT mazes were used: the Standard GMLT in
which a red cross is displayed for repeatedly tapping the correct location, and the
Repeated Tap GMLT in which feedback is given as a green tick (see Figure 5.4.1).
Figure 5.4.1. Graphic depiction of the differences between the GMLT and Repeated Tap GMLT. The current location is indicated by a dark grey tile and has been re-drawn beside indicated by arrows labelled “1. Last correct tile” on the first line. Line two, shows negative feedback for a second tap on the current correct location in the GMLT, and positive feedback in the Repeated Tap GMLT. Line 2 shows that after feedback was given, the location is marked in the GMLT, but the tick remained on screen on the Repeated Tap GMLT. In order to advance through the maze, a third tap was required in the GMLT, but not in the Repeated Tap GMLT (row 4).
Children were randomly assigned to one of the two GMLT conditions, with an equal number of boys and girls in each group. Children completed five learning trials on the $10 \times 10$ maze to discover the location of the hidden pathway.

5.4.3 Data analysis

The hypothesis that eliminating error feedback associated with double tap behavior would decrease the frequency of rule break errors was tested by comparing the number of rule break, exploratory errors and in the Standard GMLT and Repeated Tap GMLT, using independent samples t-tests.

5.4.5 Results and discussion

Means and standard deviation for errors are shown in Table 5.4.1. No significant differences were found between the two GMLT groups in rule break errors or exploratory errors. Nevertheless, as expected, children made significantly more repeated tap errors on the Repeated Tap GMLT than the standard GMLT. It is evident that eliminating double-tap feedback did not result in an increase in the ability to coordinate spatial memory and rule use in 6-year-olds.
Table 5.4.1

Mean and Standard Deviation for Exploratory, Rule Break and Repeated Tap Errors, t, and, Cohen’s d for the GMLT and Repeated Tap GMLT (RT-GMLT)

<table>
<thead>
<tr>
<th>Error Type</th>
<th>GMLT</th>
<th></th>
<th>RT- GMLT</th>
<th></th>
<th>t</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exploratory</td>
<td>57.90</td>
<td>8.75</td>
<td>57.85</td>
<td>6.98</td>
<td>1.48</td>
<td>0.006</td>
</tr>
<tr>
<td>Rule Break</td>
<td>51.45</td>
<td>25.85</td>
<td>50.60</td>
<td>18.53</td>
<td>0.12</td>
<td>0.04</td>
</tr>
<tr>
<td>Repeated tap</td>
<td>7.05</td>
<td>4.77</td>
<td>20.85</td>
<td>20.17</td>
<td>2.98*</td>
<td>0.94</td>
</tr>
</tbody>
</table>

*- significant at p<0.01

5.5 General Discussion

The research reported herein provides additional information about young children’s difficulties solving complex EF problems; and more specifically some of the factors that affect the coordination of spatial memory and rule use by 6-year-olds. The findings of Experiment 1 partially supported the hypothesis that providing move cues would support the co-ordination of spatial memory and rule use in 6-year-olds’ performance on the 10 x 10 GMLT. While the provision of move cues in the RMT and WMT versions of the GMLT had no effect on rule use in the 6 x 6 maze, they had a positive effect in reducing rule use errors on the 10 x 10 maze. However, eliminating double tap errors via the Repeated Tap GMLT in Experiment 2 did not reduce rule use errors. Nevertheless, within search and “returning to the head of path” errors still occurred in the WMT and RMT versions of the GMLT, despite the provision of cues designed to minimize this error.
Overall, the results of Experiment 1 support the hypothesis that providing cues about to-be-searched locations on the GMLT would result in fewer rule-break errors. Compared to performance on the standard GMLT, fewer rule break errors occurred when WMT and RMT responses options were provided. However, this only occurred on the more difficult GMLT maze (the 10 × 10 maze). In contrast, the feedback manipulation did not affect spatial memory errors on either the easier (the 6 × 6 maze) or more difficult maze (the 10 × 10 maze). In combination, these findings support the claim that 6-year-olds’ performance on the GMLT reflects difficulty coordinating the cognitive operations that underlie rule use and spatial memory when task demands are high.

The findings of Experiment 2 partially replicated those of Experiment 1. Eliminating error feedback for double-tap behaviors, and ipso facto the memory load associated with the activity (i.e., remembering additional error information), had little impact on rule use or spatial memory errors. This suggests that double taps did not distract or interfere with children’s maze performance. However, the functional significance of the double-tap strategy in young children’s learning is unclear.

It is possible that the double tap behavior functions similar to pause behaviors in speech. It has been suggested that pauses behaviors in complex verbal tasks (i.e., pauses in meaningful speech filled with monosyllabic non-words such as “um” or “ah”) reflect the effort required to structure the production of new and complex sentences (Esposito, Marinaro, & Palombo, 2004; Hudson Kam & Edwards, 2008; MacWhinney & Osser, 1977). By analogy, it is possible that young children’s GMLT double tap error functions as a “thinking time pause” that provides an opportunity to consolidate monitoring/planning behaviors. Insofar as
this hypothesis is correct, preventing the double tap strategy in young children would lead to marked deterioration in their maze learning ability.

Cuing the location of legitimate moves had an unexpected impact on children’s performance. Although cueing move locations reduced rule break errors in the 10 × 10 maze, the reduction did not appear associated with move cues per se. Children continued to check previously searched locations, even though a signal indicated that it had been searched (RMT). Children also failed to “return to the head of pathway”, even though its location was signaled by a flashing green mark (RMT and WMT). Nevertheless, the provision of move cues reduced some errors, specifically diagonal and back moves errors. It appeared that cuing only reduce errors associated with simple search rules. This finding is consistent with developmental research which has showed that simple cognitive skills first emerge when cognitive demands are minimized and that such skills are fragile and easily disrupted when task demands increase (Reeve et al., 1986).

It appears that the cues were insufficient to support more demanding rule procedures that guide response selection (Bohlman and Fenson, 2005; Flavell, 1979; Morton & Munakata, 2002; Schwenck, Bjorklund, & Schneider, 2007; Towse et al., 2007; Zelazo, Frye, & Raptus, 1996). The findings show that children’s difficulties on the 10 × 10 maze were related to difficulties coordinating cue feedback with rule compliant decisions at each choice point (i.e., return to “head of pathway” after an error and avoid searched locations). They also support the claim that complex EF development is limited by difficulties coordinating means and goals (i.e., pathway memory and rules). The relative independence of spatial memory and rule use suggest that they must be coordinated rather than integrated (Halford et al., 2007).
The differential impact of visual cues on errors further illustrates the relative independence of spatial memory and rule use found by others (Snyder et al., 2008; Thomas et al., 2008; Thomas et al., 2011). Here we extend these findings by demonstrating for the first time, the independence of rule use and error processes hypothesized to affect maze performance in clinical groups (Darby & Walsh, 2005). Konow and Pribam (1970) first made a distinction between symbolic error evaluation and error utilization associated with prefrontal injury. In their analysis “evaluation” refers to the recognition of signal or response saliency (i.e., errors are registered), while “utilization” refers to the inability to transfer symbolic instructions into action in complex contexts. Darby and Walsh (2005) suggest that error utilization deficits in prefrontal patients are evident by the rapid reduction in errors, but the inability to obtain stable error-free performance. It is not possible to discover hidden maze pathways unless every error is registered and the return rule is understood and applied. Children demonstrated persistent deficits in applying rules as a function of error signals, despite the provision of visual cues. Although it is not possible to determine if children’s difficulties were the result of failure to notice error information or the ability to use it at the high level of difficulty, the current findings broadly support the ‘error utilization’ hypothesis. Further studies will be required to explore the cause of difficulties in error use.

Several issues warrant further investigation. Findings from Experiment 2 suggest repeated tapping had no effect on spatial memory or rule use. The function of this behavior remains unclear. It is possible that it reflects an immature prefrontal working memory system. It would be interesting to examine whether repeated tap errors are evident in adults with prefrontal cortex disorders, often characterized by working memory limitations. The finding that young children
were unable to use feedback effectively has implications for interactive computer programmes in education, at least in young children. Of particular interest is the development of complex EF, especially changes with age in the coordination of functions and the circumstances under which this occurs. It is evident from the present findings that reducing task demands does not always affect behavior in expected ways, but may nevertheless lead to the emergence of simple strategies. Also of interest are the conditions under which older children exhibit the meta-cognitive skills necessary to benefit from visual cuing in the GMLT (Zelazo, Hong Gao, & Todd, 2006).
Chapter 6


6.1 Introduction

The overall aim of this thesis is to understand the development of executive functions in children through analysis of spatial memory and rule use in hidden pathway learning and factors that influence children’s ability to coordinate them. Study 1 provided preliminary evidence that rule use and spatial memory were partially independent in the GMLT, at least in children. However the veracity of this claim requires further investigation. The current paper uses the double dissociation methodology to establish the independence of rule use and spatial memory in the GMLT. In two studies the effect of withholding rules had no effect on rule break errors, and then changing the pathway on each trial had no effect on rule break errors.
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Disentangling component learning and executive processes in hidden pathway maze learning in children: A process-based approach

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Disentangling component learning and executive processes in hidden pathway maze learning in children: A process-based approach

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Identification of cognitive processes that affect children’s ability to manage complex information is critical to understanding the development of executive functions. However, characterization of these processes is hampered by a lack of appropriate tasks and reliance on single outcome measures that are unsuitable for studying complex aspects of executive function. The current study aimed to circumvent these limitations by employing a hidden maze learning paradigm (Gronen Maze Learning Test; independent of component cognitive GMU) to evaluate the processes—spatial memory and rule use—that underlie hidden pathway maze learning in children. Specifically, we investigated the impact of withholding rule instructions (Study 1) and reorienting pathways on each trial (Study 2) on the ability to use rules and to locate pathways in a 10 × 10 maze in a sample of 8- to 9-year-old children. Results of these studies suggested that manipulations of task rules did not affect spatial memory and that manipulations of the maze pathway did not affect rule use. These findings demonstrate the independence of spatial memory and rule use on the GMU and provide evidence of a “double dissociation” of cognitive processes that underlie hidden maze learning in children. Implications for understanding the coordination of component cognitive processes that underlie executive function in childhood are discussed.

Keywords: Spatial memory; Executive functions; Hidden pathway maze learning; Development.

Identifying processes that influence the ability of children to manage complex information is critical to understanding the development of executive function (EF). Simple EF, such as the ability to shift attention, to select responses from competing stimuli, or to maintain information in working memory, develops between approximately 3 to 6 years of age (Carlson, 2005; Davidson, Amso, Anderson, & Diamond, 2006; Marovitch & Zelazo, 2009). More complex EF, such as the ability to coordinate component cognitive operations, to generate problem-solving strategies, and to monitor error-related information appear around 7 years of age but develop into early adulthood (Best & Miller, 2010; Garon, Bryson, & Smith, 2008; Heary & Bettenay, 2010).

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Most aspects of complex EF require that multiple cognitive operations, including simple EFs, be coordinated in pursuit of the behavioral goal. However, because many tests of complex EF are not appropriate for use in young children (Best, Miller, & Jones, 2009) relatively little is known about how the ability to coordinate cognitive operations contributes to the development of complex EF in children. The hidden pathway maze learning paradigm requires individuals to locate and learn the location of a 28-step pathway hidden beneath a 10 × 10 matrix of tiles using search rules and error feedback. The Groton Maze Learning Test (GMLT) is considered a measure of complex EF (Pietrzak, Cohen, & Snyder, 2007; A. M. Snyder, Maruff, Pietrzak, Cromer, & Snyder, 2008; Thomas, Reeve, Freidickson, & Maruff, 2011) and has been used to study complex EF in children as young as 4 and 7 years (Clark et al., 2006; Thomas et al., 2011).

Converging evidence from studies using a computerized version of the hidden pathway maze learning task suggests that the rule use and spatial memory function contribute independently to maze learning performance. For example, poor performance on the GMLT and similar tasks in adults with diseases or lesions involving the prefrontal cortex reflect mainly impairment in rule use often with intact spatial memory (Pietrzak et al., 2007; P. J. Snyder et al., 2008; A. M. Snyder et al., 2008). Conversely, in patients with focal lesions of the hippocampus, impaired performance on the Milner stepping stone maze reflected impairment in spatial memory with intact rule use (Milner, 1965; Milner, Corkin, & Tiber, 1986). The independence of spatial memory and rule use components of the GMLT is consistent with current neuropsychological models, which link spatial memory to the integrity of hippocampal and para-hippocampal brain regions (De Renzi, Figlioni, & Villa, 1977; Habib & Sirigu, 1987) and rule use processes to the integrity of the prefrontal cortex and subcortical connections (Clark et al., 2006; Darby & Walsh, 2005; Pietrzak et al., 2007). Adults typically make almost no rule break errors (Thomas et al., 2011). Therefore validation studies of total errors as measure of visuospatial construction and learning confirm the spatial memory construct of exploratory errors in this paradigm (Bowden et al., 1992; Crowe et al., 1999). Furthermore, reduction in the randomness of exploratory errors from the first trial, when the pathway is unknown, suggests that trial-and-error strategies are increasingly replaced by navigation from memory with repeated pathway exposure (Bowden & Smith, 1994). The memory component of hidden pathway learning is usually regarded as a form of topographical memory (De Renzi et al., 1977; Habib & Sirigu, 1987).

A recent study of EF in primary-school-aged children using the GMLT found developmental differences in spatial memory, rule use, and their coordination (Thomas et al., 2011). First, overall performance on increasingly difficult versions of the GMLT improved with age. However, when performance was analyzed at the level of the spatial memory and rule use components, it was observed that spatial memory and rule use abilities were equivalent between 5- and 9-year-olds provided the difficulty of the GMLT was low (i.e., when the hidden pathway was less complex: a 4 × 4 grid with six steps and a 6 × 6 grid with 12 steps). Increasing maze difficulty (8 × 8 and 10 × 10 grids with 20 and 28 steps) affected spatial memory to the same extent in the younger and older children. However, increases in maze difficulty decreased rule use abilities to a much greater extent in younger children than in the older children. This finding suggests that the age-related improvement in performance on the GMLT reflected maturation in the ability to coordinate spatial memory and rule use process under cognitive load, rather than the development of either cognitive process independently.
MEMORY AND RULE USE IN MAZE LEARNING

In all of these studies of hidden maze learning conducted to date, conclusions about the independence of the spatial memory and rule use components of maze performance have been based entirely on post hoc analyses of study data. Therefore, direct experimental challenges are necessary to confirm the independence of rule use and spatial memory processes in hidden maze learning and to show that this independence is present in children. One model that is commonly used to demonstrate independence of cognitive operations in neuropsychology is the “double dissociation.” A double dissociation is demonstrated when two experimental manipulations have different effects on two dependent variables (Treuber, 1955). Hence, in the context of hidden maze learning, a double dissociation is demonstrated when one experimental manipulation can be shown to modulate rule use and not spatial memory and another manipulation modulated spatial memory but not rule use. For the rule use operation, a previous study showed that young adults who had not received training made more rule break errors on the first trial, although errors reflecting spatial memory were not affected by the absence of pretraining (Pietrzak, Manuff, & Snyder, 2009). Although younger children trained on the GMLT make more rule use errors than trained adults (Thomas et al., 2011), it is possible that, without training, rule use errors will increase further without affecting spatial memory. For the spatial memory operation, errors related to memory for the hidden pathway reduce with repeated exposure to that pathway (i.e., across learning trials). However, if the pathway changes on each trial, then each trial would be the same as the first and performance would not depend on spatial memory processes but only on the ability to use the rules. If rule use and spatial memory are independent, the absence of pathway memory should have no effect on the capacity to use the rules.

The aim of the current study was to challenge performance on the GMLT by separate experimental manipulations that interfered either with the ability to use rules or to use spatial memory in order to perform optimally. We selected a sample of 8-year-old children because they are known to be developing self-ordered planning skills and are therefore likely to be able to complete the task uninstructed (Luciana, 2003). In Study 1, the ability to use rules was diminished by withholding pretask rule training. In Study 2, the ability to use spatial memory was diminished by requiring children to locate a novel pathway on each trial of the GMLT. We hypothesized that (a) the absence of training on the maze rules would increase rule break errors made learning the pathway but would have no effect on spatial memory errors and (b) locating the hidden pathway on unique GMLT mazes would prevent any contribution from spatial memory to performance but have no effect on EF.

GENERAL METHOD

Overview

In this article, two studies are reported that examine the relationship between rule use and spatial memory in the GMLT by manipulating rule acquisition and training in Study 1 and spatial memory load in Study 2.

Participants

Children attending an independent primary school in a regional Australian city participated. Forty children participated in Study 1. Twenty-one children (13 boys and 8 girls) were randomly assigned to the Untrained condition (Age = 90.86 months, SD = 8.27;...
range = 73–104 months). Nineteen children (7 boys and 12 girls) were randomly assigned to the Trained condition ($M_{age} = 90.60$ months, $SD = 7.74$; Range = 74–102 months). The 19 children in the Trained condition from Study 1 formed the Repeating condition of Study 2. Fifteen children (6 girls and 9 boys) were separately recruited and assigned to the Novel condition of Study 2 ($M_{age} = 91.88$ months, $SD = 6.09$; Range = 82–101 months).

From the initial sample of 19, two children were excluded because they could not complete the training phase, and two children were excluded as outliers with the number of rule book errors greater than two standard deviations above the group mean. All participants had normal or corrected-to-normal vision. Prior to assessment, the main teacher for each child was interviewed to determine whether any of the children selected met exclusion criteria that consisted of receiving daily medication, a learning disability, a low intelligence quotient or intellectual disability or did not speak English as their first language. To ensure willingness to participate, children were individually asked if they would like to “play computer games” prior to testing and asked if they wished to continue throughout testing. All children agreed to participate and no child expressed a desire to cease testing. The research was approved by and conducted in accordance with the authors’ university’s human ethics committee’s requirement.

Stimuli

The Groton Maze Learning Task (GMLT) is a computerized hidden pathway search test based on the Barker, Austin, and Milner mazes in which a pathway traversing the contralateral corners of the grid is concealed beneath a $10 	imes 10$ grid of “stepping-stone” tiles (R. G. Barker, 1931; Milner, 1965; Walsh, 1985). Each tile represents move locations, and the grid refers to the tile array (i.e., $10 \times 10$). The task was administered on a 27 × 34 cm touch screen. The GMLT requires participants to find and relocate a pathway guided by four search rules. These rules are: do not move diagonally, more than one tile (i.e., do not jump), do not move back on the pathway, and return to the last correct location after an error (P. J. Snyder, Bednar, Croner, & Manufo, 2005; P. J. Snyder et al., 2008; Thomas et al., 2008). At each step, only the most recently selected tile is shown. Feedback is given with visual and auditory cues (green ticks and red crosses) to indicate whether the selected tile is correct or incorrect. The head of path, or the last correct location, flashes with a green tick when two errors are made in succession (failing to return errors). The GMLT software records each move as an error or as a correct move. Errors also include tapping between tiles and out of grid, repeated selection of the same location previously identified as incorrect (within search errors), and successive moves to the same location (perseverative errors). In Studies 1 and 2, ten trials of a $10 \times 10$ maze grid with 28 steps and 11 turns were administered and 20 different pathways were randomly used between subjects. The pathway was either the same repeating pathway (Trained and Untrained conditions) or a different pathway (Novel condition) on each trial.

Procedure

All children were tested individually in a quiet room at their school. In the Untrained condition of Study 1, children were shown the $10 \times 10$ GMLT with 28 steps and asked to find the hidden pathway starting at the top left tile and proceeding to the bottom contralateral right tile. No other help was given, except when children failed to return to the head
Memorization and Rule Use in Maze Learning

Table 1: Definition of Errors on the Crotzer Maze Learning Task.

<table>
<thead>
<tr>
<th>Error Type</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exploratory</td>
<td>Moves in accordance with task rules.</td>
</tr>
<tr>
<td>Failure to return</td>
<td>Failing to return to the last correct location after an incorrect move.</td>
</tr>
<tr>
<td>Preservative</td>
<td>The same error repeated after returning to the head of path.</td>
</tr>
<tr>
<td>Back</td>
<td>Moving backwards on the pathway.</td>
</tr>
<tr>
<td>Jump</td>
<td>Moving more than one tile from the current correct location.</td>
</tr>
<tr>
<td>Diagonal</td>
<td>Moving to locations diagonal to the current correct location.</td>
</tr>
<tr>
<td>Double tap</td>
<td>Tapping the same incorrect location twice.</td>
</tr>
<tr>
<td>Same tile tap</td>
<td>Tapping the correct location twice.</td>
</tr>
<tr>
<td>Between</td>
<td>Moves between tiles.</td>
</tr>
<tr>
<td>Out</td>
<td>Moves out of grid.</td>
</tr>
<tr>
<td>Within</td>
<td>Re-searching locations allowed by the task rules that have been identified as</td>
</tr>
<tr>
<td></td>
<td>the incorrect location for the next step in the pathway.</td>
</tr>
</tbody>
</table>

Note: All measures are summed errors on each trial (10 trials in total).

of path on four successive occasions. When this occurred, children were asked what they thought the flashing signal at the head of path meant.

In the trained conditions of Studies 1 and 2, children were informed of the maze rules and completed two practice trials of an 8 × 8 maze. The first practice trial comprised highlighted locations for exploratory legal searches at each step in the pathway. That is, from the current position in the maze, the three forward adjacent “legal” locations were colored light blue against the background grey of surrounding tiles in the grid. Prior studies have shown that children acquire the rules structure of the GMLT more easily when the rules are visually cued in this manner (Thomas et al., 2011). After describing the rules, children were trained using an error-free process; specifically, each move was dictated by the researcher on the first few steps (search, return; Baddeley & Wilson, 1994; Kessels & De Haan, 2003). When each child could follow the instructions without hesitation, an error correction training strategy was used. That is, children chose locations without instruction from the researcher. The researcher verbally corrected errors that contravened the task rules. Prior to the second practice trial, children’s understanding of each rule was checked by questions regarding legitimate and erroneous moves on the maze.

The second practice trial was an 8 × 8 version of the standard GMLT used in the testing phase of the study. The standard GMLT does not contain visual highlighting for possible search locations. On completion of the second practice trial, the test phase began on the 10 × 10 maze.

Measures

All moves were classified in terms of whether they were consistent or inconsistent with the search rules defined in Table 1.

Study 1

Study 1 tested the hypothesis that absence of rule training has no effect on exploratory errors.
Results and Discussion

Exploratory and rule break errors were each submitted to a separate 2 (Condition: trained, untrained) × 10 (Trial: 1–10) repeated measures analysis of variance (ANOVA). Due to small sample sizes, relevant nonsignificant results are reported. Condition was entered as a between-subjects factor while trial was entered as a repeated measure. Figure 1 shows the group means for number of exploratory memory errors made under the trained and untrained conditions. An ANOVA of exploratory errors indicated a significant main effect for trial, $F(9, 30) = 15.97, p < .001, \eta^2_p = .83, \eta^2_g = 1.00$. However the Trial × Condition interaction was not significant, $F(9, 30) = 0.56, p < .82, \eta^2_p = .14, \eta^2_g = .22$. A univariate analysis of between-subjects effects for condition was not significant, $F(1, 38) = 0.61, p = .44, \eta^2_g = .02, p = .12$.

Figure 2 shows the group mean (SE) number of rule break errors made under the trained and untrained conditions.

A repeated-measures ANOVA of rule break errors indicated a significant Trial × Condition interaction, $F(9, 27) = 4.50, p < .001, \eta^2_p = .57, \eta^2_g = .99$. Univariate analysis of between-subjects effects for condition were significant, $F(1, 38) = 26.53, p = .001, \eta^2_p = .41, \eta^2_g = 1.0$. Post hoc $t$-tests with $p < .01$ were used to compare conditions at each trial. Results indicated that mean rule break errors were significantly different between conditions across the first four trials, after which performance under the trained and untrained conditions no longer differed (summarized by asterisks in Figure 2).

Together, these findings indicate that the absence of training did alter rule use but not memory processes.

![Figure 1](118.png)

**Figure 1:** Exploratory errors for 10 trials for children who were trained on the maze rules (squares) and untrained (triangles) with standard error bars.
MEMORY AND RULE USE IN MAZE LEARNING

![Graph showing rule break errors for 10 trials for children who were trained on the maze rules (squares) and untrained (triangles) with standard error bars. Asterisks indicate significance < .01.](image)

**STUDY 2**

Study 2 tested the hypothesis that minimizing spatial memory effects would have limited impact on rule break errors.

**Results and Discussion**

Mean number of exploratory and rule break errors to five, and ten trials are shown in Table 2. Exploratory and rule break errors were each submitted to a separate 2 (Condition: repeating, novel) × 10 (Trial; 1–10) repeated-measures analysis of variance (ANOVA). Condition was entered as a between-subjects factor, while trial was entered as a repeated measure. Figure 3 shows the mean of exploratory errors in the two groups. An ANOVA of exploratory errors indicated the Trial × Condition interaction was significant, F(9, 24) = 2.89, p = .02, η²p = .52, p = .88. A univariate analysis of between-subjects effects for condition was significant, F(1, 32) = 31.90, p = .001, η²p = .49, p = 1.00. Post hoc t-tests with p < .01 were used to compare mean exploratory errors between conditions.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Rule break 5</th>
<th>Rule break 10</th>
<th>Exploratory 5</th>
<th>Exploratory 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untrained</td>
<td>165.14</td>
<td>132.38</td>
<td>51.33</td>
<td>85.67</td>
</tr>
<tr>
<td></td>
<td>(98.23)</td>
<td>(86.07)</td>
<td>(7.34)</td>
<td>(17.96)</td>
</tr>
<tr>
<td>Trained</td>
<td>26.89</td>
<td>46.42</td>
<td>55.65</td>
<td>91.05</td>
</tr>
<tr>
<td></td>
<td>(21.65)</td>
<td>(21.65)</td>
<td>(21.65)</td>
<td>(21.65)</td>
</tr>
</tbody>
</table>

*Note.* Standard deviations are in parentheses.
at each trial and the results of these are summarized in Figure 3 with statistically significant differences indicated with asterisks. The mean number of exploratory errors was significantly different between conditions from Trial 4 to Trial 10 (see Figure 3).

As can be seen in Figure 3, there was no reduction in exploratory errors across the 10 trials for the novel condition.

The mean of rule break errors in the two conditions from Trial 1 to Trial 10 are shown in Figure 4.

A repeated-measures ANOVA for rule break errors suggested no significant main effect of trial, $F(9, 24) = 0.79, p = .63$, $\eta^2_p = .23$, $\omega^2 = .29$, or Trial * Condition interaction, $F(9, 24) = 0.47, p = .88$, $\eta^2_p = .15$, $\omega^2 = .18$. A univariate analysis of between-subjects effects of condition for rule break errors was not significant, $F(1, 31) = 3.57, p = .07$, $\eta^2_p = .10$, $\omega^2 = .05$. Together, these findings show that minimizing the impact of spatial memory had no effect on rule use.

**GENERAL DISCUSSION**

The results of the first study supported the first hypothesis that children who were trained on the rules of the GMLT prior to assessment displayed a stable and unchanging rate of rule break errors over the 10 learning trials of the GMLT. In untrained children, the number of rule break errors reduced from a mean of 90 to 15 errors after only three trials and were higher than those of trained children until the eighth learning trial. However, untrained children made no more exploratory errors than trained children. Thus, the additional cognitive demands imposed by the necessity to learn the maze rules from experience...
had no effect on spatial memory processes. The results of Study 2 supported the hypothesis that children who were required to discover a new pathway on each trial continued to make high levels of exploratory errors over the 10 trials on the GMLT. The ongoing need to learn a new pathway on each trial did not affect the number of rule break errors. Taken together, these opposing results from experimental manipulations suggest that there is a double dissociation between the spatial memory and rule use components of complex executive function when children are challenged with the hidden pathway maze learning paradigm (Thomas et al., 2011).

The large reduction in rule break errors made by children who were not trained on the maze in Study 1 is consistent with the results of a study that compared performance on the GMLT between trained and untrained adults (Pietrzak et al., 2009). However, in the Pietrzak et al. study, untrained adults demonstrated normal levels of rule break errors by the second trial. Despite the more protracted learning of the maze rules by the children in the current study this did not affect the rate of spatial memory errors compared to children who were pretrained on the rules. Both groups displayed an equivalent reduction in exploratory errors from Trial 1 to Trial 10 (Figure 1). This finding suggests strongly that the spatial memory component of maze learning is not dependent on intact rule knowledge and use and that it was not altered by processes associated with acquisition of the rules.

Even with extensive training, children were still unable to comply with the rules at every choice point. After five trials children in the trained condition made approximately 27 rule break errors (this stage adults make approximately 5 rule break errors; Thomas et al., 2008; see Pietrzak et al., 2009, for similar results). The rate of rule break errors was similar to children of the same age observed in a previous study (Thomas et al., 2011). The reason for children's difficulty in rule use remains unclear; however, one explanation is that
when the cognitive cost of attending to multiple aspects of a task exceeds the capacity to 
hold task instructions “on-line,” this may result in a selective neglect of task requirements 
(Thomas et al., 2011). This difficulty in rule use is consistent with the concept of “goal 
eglect” described in adults with deficits in EF who perseverate on dimensional switch-
ing rules in card-sorting tasks (e.g., Duncan, Emstlie, Williams, Johnson, & Freer, 1996; 
Thomas et al., 2011; and in children: Towse, Lewis, & Knowles, 2007).

In Study 2, children had to learn a new pathway on each trial or the same pathway 
across all trials (i.e., the standard administration of the GMLT). Children who learned a new 
pathway on each trial showed the same high number of exploratory errors across trials, 
while exploratory errors reduced across trials in the children who learned the same pathway 
from the first to the tenth trial. The reduction in exploratory errors on the standard 
GMLT was qualitatively similar to that observed previously in adults (e.g., Bowden, 1988; 
Snyder et al., 2005). However, children in the current study made more total errors than 
observed in adult studies (adults usually make between 40 and 60 errors: Bowden, 1988; 
M. J. Barker, Greenwood, Jackson, & Crowe, 2005; Crowe et al., 1999; Mathias & Kent, 
1998; Österberg, Karlson, & Hanson, 2009; Retlew et al., 1991). In Study 2, there was no 
difference in the rate of rule break errors between the groups, and there was no difference 
between groups from the first to the last trial. The magnitude of the difference between 
the number of rule break errors in the two conditions in Study 2 was by convention very 
small (r(12) = .10), suggesting that the absence of any statistical significance was not due 
to low statistical power. If the ability to navigate from memory-freed resources for rule 
compliance, then there should have been a reduction in rule break errors in children in 
the repeating pathway condition, and no reduction in children in the novel pathway condi-
tion. However, there was no change in either group in the rate of rule break errors. Taken 
together, these findings support the claim that spatial memory does not aid rule use in chil-
dren performing the GMLT and further demonstrate the independence of the memory and 
EF processes involved in hidden maze learning.

The independence between rule break and exploratory errors observed in Studies 1 
and 2 is consistent with previous research that demonstrated dissociation between spatial 
memory and rule use in the GMLT (Thomas et al., 2011). For example, manipulations 
of neurotransmitter systems underlying prefrontal cortex function (e.g., acetylcholine, 
dopamine) have different effects on rule break and exploratory errors in healthy adults: 
P. J. Snyder et al., 2005; Thomas et al., 2008; children with attention deficit/hyperactivity 
disorder (ADHD): A. M. Snyder et al., 2008). For example, in P. J. Snyder et al. (2005) 
and Thomas et al. (2008), administration of central acetylcholine antagonist (scopolamine) 
impairs measures of executive function (rule break and perseverative errors) to a greater 
extent than exploratory errors. Codeadministration of scopolamine with acetycholinelagonist 
(donepezil) ameliorated the effects of scopolamine on executive functions to a greater 
extent than exploratory errors. In A. M. Snyder et al. (2008), children with ADHD made 
more perseverative and rule break errors but not more exploratory errors than age-matched 
controls. However, in the children with ADHD, administration of stimulant medication 
was associated with a greater reduction in exploratory errors than perseverative or rule 
break errors (A. M. Snyder et al., 2008, Figure 1 and Table 5), suggesting that stimulant 
medication has a greater effect on memory than EF in children with ADHD.

The independence of spatial memory and rule use in this paradigm supports the inter-
pretation that, in children, performance requires the coordination of independent streams
of information, rather than the integration of that information into a unified representation. Prior researchers have suggested that manipulations that disrupt related procedures that are integrated should affect them equally (Case, 1975; Halford, Baker, McCrdden, & Bain, 2005). Further, the ability to integrate information into a transformed representation may be regarded as a marker of intellectual development that relies on different skills to those required to prioritize and maintain separate streams of information associated with EF (Marcovitch & Zelazo, 2009). As such, the independence of spatial memory and rule use processes in the GMLT is particularly salient to understanding the nature of cognitive processes that underlie performance in the GMLT. In summary, the results of the current studies suggest that children are efficient at finding a hidden pathway in the absence of any instruction. They further demonstrate the independence of spatial memory and EF by manipulation of rule acquisition and spatial memory load. This approach was novel because it allowed for a direct comparison of these processes and provides a stringent test of the relationship between spatial memory and rule use on the GMLT. Further studies will be needed to validate the constructs of the GMLT in children using independent measures of spatial memory and EF. Future studies should explore the developmental trajectories of performance on the GMLT and related measures of complex EF across the lifespan, as the contribution of component aspects of cognition that underlie performance on these tasks may change as a function of development.

REFERENCES


Chapter 7


7.1 Introduction

In the last study compelling evidence was found to support the interpretation that spatial memory and rule use/error monitoring functions in the GMLT are independent in children. Independence of functions suggests that they must be coordinated and deployed simultaneously in trial-and-error learning. The aim of this experiment is to test this hypothesis, using comparator measures to validate the GMLT sub-measures. In this experiment the Corsi Block Span Task was used to validate the spatial memory measure of the GMLT, while a visuo-spatial Continuous Paired Associate Learning task was used to validate rule break errors as a measure of rule use/error monitoring.
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Spatial sequence memory and spatial error monitoring in the Groton Maze Learning Task (GMLT): A validation study of GMLT sub-measures in healthy children

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Spatial sequence memory and spatial error monitoring in the Groton Maze Learning Task (GMLT): A validation study of GMLT sub-measures in healthy children

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The stepping-stone variant of the hidden pathway maze learning (HPML) task paradigm has been extensively used to investigate cognitive functions in neuropsychology and neuropsychology. Previous studies have used error across trials, as well as rule-break errors and learning errors, to define spatial memory and/or executive function in healthy and impaired adults and children. However, the construct validity of performance measures on HPML tasks has not been established in healthy children. To assess the construct validity of measures of exploratory and rule-break errors on the Groton Maze Learning Task (GMLT) measures of spatial sequence memory (Corsi Block Task) and spatial error monitoring (Continuous Paired Associate Learning; CPA1L) were used. The results indicate that Corsi span predicted GMLT spatial sequence memory and CPA1L accuracy predicted GMLT spatial error monitoring. The construct validity of the GMLT as a measure of spatial memory and executive function are discussed with regard to prior research using HPML tasks in neuropsychological contexts.

Keywords: Rule use; Error monitoring; Spatial memory; Hidden pathway maze learning; Validation.

The Groton Maze Learning Task (GMLT) is a computerized version of the hidden pathway maze learning (HPML) task paradigm based on Barker’s (1931) Milner’s (1965) stepping-stone mazes. In HPML tasks, a pathway must be located and learned over successive trials within a grid of tiles according to a set of simple searching rules (Snyder, Bednar, Croome, & Maruff, 2005). HPML paradigms are now considered neuropsychological tests of complex executive function in adults and children because successful performance requires the coordination of cognitive functions for goal-related behavior (Pietrzak, Cohen, & Snyder, 2007; Pietrzak et al., 2008; Pietrzak, Maruff, &

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Paul Maruff is employed by Cogstate Ltd, the company that distributes the GMLT and the CPA1L task, two of the tests used in the current study. However, Cogstate was not involved in the design, data collection or analysis of the research reported herein.

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Snyder, 2009; Thomas, Reeve, Fredrickson, & Manuff, 2011). The GMLT is a computer-administered HPML task that has been shown to be a sensitive measure of rule use and error monitoring functions in children as young as 5 years of age (Snyder, Snyder, Sienk, & Mayes, 2004; Thomas et al., 2011). Like most neuropsychological tests of complex executive function, optimal performance in the GMLT requires moves planned on the basis of prior behavior, feedback from errors and memory of information learned on previous trials (Best & Miller, 2010; Ramnani & Owen, 2004). Thus, multiple cognitive operations must be organized, integrated and applied for optimal performance.

Most studies using HPML tasks in adults have examined performance in terms of total errors summed across learning trials (e.g., Bowden & Smith, 1994; Walsh, 1985). However, studies using the GMLT have found that it is also possible to obtain indices that validly reflect the different component cognitive processes necessary for performance (Manuff et al., 2006; Pietrzak, Snyder, et al., 2009; Snyder, Manuff, Pietrzak, Cromer, & Snyder, 2008; Snyder et al., 2005; Snyder, Jackson, et al., 2008). For example, on the GMLT, rule-break errors are errors that violate the maze rules, and are considered to reflect difficulty in rule use and error monitoring (Thomas et al., 2011; Thomas, Reeve, Pietrzak, & Manuff, 2013). Responses to locations that are allowed by task rules are considered legitimate searches in the absence of pathway knowledge and are therefore classified as exploratory or legal errors (Snyder, Jackson, et al., 2008; Thomas et al., 2011) and are considered to reflect spatial memory (Haleb & Srigu, 1987; Milner, 1965; Thomas et al., 2011).

Evidence suggests that the rule-break and exploratory errors made during performance on the GMLT reflect partially independent cognitive processes, since each error type can be differentially disrupted by different brain disorders, aging, or neuropharmacological challenge (Pietrzak et al., 2007; Snyder, Manuff, et al., 2008; Snyder et al., 2005; Thomas et al., 2008). For example, children and adults with neuropsychiatric disorders that involve disruption to the prefrontal cortex, or adults with lesions to the prefrontal cortex, typically show abnormally high numbers of rule-break errors but not exploratory errors (Snyder et al., 2005; Snyder, Jackson, et al., 2008; Thomas et al., 2008). Further, patients with lesions of the medial temporal lobe make more exploratory errors than rule-break errors (Milner, 1965). In general, these findings are consistent with the known psychological effects of focal brain disorders to the frontal cortex and hippocampus (Owen, Morris, Sahakian, Polkey, & Robbins, 1996; Saling, 2009; Teuber, 1963, 1966, 1972). They support the hypothesis that GMLT measures are sensitive to deficits and improvement in error monitoring (e.g., see Snyder, Jackson, et al., 2008 for greater improvement in rule-break than exploratory errors with pharmacological treatment in schizophrenia). See Snyder, Manuff, et al., 2008 for the opposite pattern of findings in children treated with stimulant medication for Attention Deficit Hyperactivity Disorder.

In the context of cognitive development, the most compelling evidence for independence of rule-break and exploratory errors in GMLT performance is in the double dissociation of these errors observed in young (8-year-old) school-aged children (Thomas et al., 2012). In these studies, changing the pathway on every trial had no effect on the rate of rule-break errors but did increase exploratory errors. Repeating the same pathway over trials, but without prior explanation or training of the rules, increased rule-break errors without affecting exploratory errors (Thomas et al., 2013).

While the findings from these studies with adults and children suggest that component cognitive processes can be validly assessed using the GMLT, most of the evidence supporting the independence of rule-break and exploratory errors has been inferred from the GMLT itself. Only three studies have examined the external validity of rule-break and
exploratory errors, and all of these in adults (GMLT; Pietrzak et al., 2007; Pietrzak, Maruff, & Snyder, 2009; Milner maze in adults with prefrontal injuries; Canavan, 1983). Studies using the GMILT have reported correlations with the Paced Auditory Serial Addition Test and the Tower of Toronto Test (Pietrzak et al., 2007). A correlation between a visual two-back task and GMILT rule-break errors has also been reported in healthy older and younger adults (Pietrzak, Maruff, & Snyder, 2009). A study using the Milner stepping stone maze found that exploratory errors were correlated negatively with spatial intelligence, while rule-break errors were correlated negatively with the verbal intelligence quotient in patients with frontal lobe injuries (Canavan, 1983). However, verbal abilities are not usually associated with rule-break errors (e.g., aphasia; Milner, 1965). While these findings are consistent with the hypothesis that GMILT rule-break and exploratory errors are partially independent, none of the studies provide direct evidence for the convergent and divergent validity of both measures using external tasks.

Support for the independence of rule-break and exploratory errors on the GMILT depends on showing that the two errors are differentially associated with related constructs. Previous research with children has shown that rule-break errors reflect difficulties using error information for effective trial-and-error search behaviors, rather than from an inability to follow rules per se (Thomas et al., 2011). For example, children make few errors that violate search rules, but make errors repeatedly searching previously searched locations (within search errors). Progress through the GMILT cannot be made unless participants use error information to guide searching. Developmental studies have shown that children can use environmental and intra-task cues for taxon navigation from approximately 3 years of age (Newcombe & Huttenlocher, 2003). Research using the GMILT has shown that 5- and 6-year-olds are as competent as older children (8- and 9-year-olds) in learning a spatial pathway on the most difficult 10×10 grid, 28-step pathway (Thomas et al., 2011). The ability to use error information, or error monitoring, is known to be a later developing executive function skill that continues to improve into the late teenage years (Bange & Crone, 2009).

Previous work on the GMILT has also shown that error monitoring is specifically impaired in young children (5- and 6-year-olds) when task difficulty increases (e.g., when pathway length and grid size increases: Thomas et al., 2011). In a recent review paper of HPML, Thomas, Snyder, Pietrzak, and Maruff (2014) argued that the GMILT and similar stepping-stone maze learning tasks are based on early maze learning paradigms used throughout the twentieth century (see Hull, 1934; O’Keefe & Nadel, 1978; Olton, 1985; Tolman, 1938, 1948) and should be understood within the context of deliberative or autonominative learning in pursuit of a distal goal (Lasley, 1925; Thelen et al., 2014). It is argued that the validity of the GMILT (as a memory and executive function task) is best investigated by examining its performance properties in a related task that is sufficiently dissimilar to HPML but that shares its theoretical foundation (i.e., a maze learning task).

Validation of the GMILT as a test of error monitoring requires a comparison task from which inferences can be made about conceptually similar task demands (e.g., error monitoring in self-guided searching). Such a task needs to be appropriate for young children and provide error information and assess error feedback use. The Zoo Map Test (Wilson, Evans, Ensmele, Alderman, & Burgess, 1998), self-ordered pointing and search tasks (Luciana & Nelson, 1998, 2002) are conceptually similar to the GMILT, but do not provide within-task error information. The GMILT is also a learning task and therefore requires a “parallel” learning task to potentially validate measures. We suggest
that visuo-spatial continuous paired associate learning (CPAL; Harel et al., 2011) can offer an appropriate comparison task.

The CPAL task is a visuo-spatial paired associate learning task that assesses spatial memory and error monitoring (Harel, Pietrzak, Snyder, & Manuff, 2013). Early studies using the CPAL task described it as a memory task (Dingwall, Lewis, Manoff, & Cairney, 2010; Dingwall, Manoff, Fredrickson, & Cairney, 2011; Pietrzak et al., 2012; Shah et al., 2014). However, the CPAL task, and similar tasks (e.g., the Spatial Working Memory Task [SWMT] from the Cambridge Automated Neuropsychological Test Battery [CANTAB]; see Owen et al., 1996), also assess error monitoring and planning components of executive functions, especially when task demands are high (when individuals must learn six or more associations).

Most paired associate learning tasks depend on the mnemonic retention of associations from a single exposure of object locations immediately before a recall trial. The CPAL task is unlike other paired associate learning tasks (e.g., the Paired Associate Learning [PAL] task in the CANTAB; see Nunn, Polkey, & Morris, 1998) in that correct and incorrect responses are signaled within each learning trial. Like the SWMT, task demands are high in the CPAL task, performance depends on the ability to monitor error information and organize searching to avoid incorrect locations (Luciana & Nelson, 1998, 2002; Owen et al., 1996). The CPAL task is a relatively new test that has mostly been used in patient groups with known spatial memory and executive functions difficulties, such as Mild Cognitive Impairment, Alzheimer’s disease (Harel et al., 2011; O’Donnell, Pietrzak, Ellis, Snyder, & Manuff, 2011), and volatile solvent abuse (Dingwall et al., 2010, 2011). However, the CPAL task requires active searching when mnemonic associations of object locations have not been formed, and therefore requires planning and monitoring, as Owen et al., (1996) have suggested in relation to the SWMT. The CPAL task, like the SWMT and the GMLT, is also a variant of maze learning paradigms that shares a common history and has mostly been interpreted in terms of prevailing theories of complex cognition prior to the classifications and definitions of executive functions in neuropsychology from the 1980s (for a review of IPML, see Thomas et al., 2014). The GMLT and the CPAL task therefore have a common basis from which theoretical inferences of task performance can be made.

For exploratory errors in the GMLT, a neuropsychological test of spatial sequence learning without error monitoring, such as the Corsi Block Task would offer a test of the same construct (Kessels, van Zaandvoort, Postma, Kappelle, & de Haan, 2000; Ornini et al., 1987).

The aim of this study was to determine the extent to which measures of error monitoring and spatial sequence learning on the GMLT were associated with performance on independent tests of the same construct in children aged between 5 and 8 years. While it is expected that all measures depend on spatial memory and will share some common variance, the presence of intuitions between age and the performance measures from the different tasks would suggest different developmental trajectories for the underlying cognitive operations of each measure (i.e., memory, and memory plus error feedback use as an additive function). A developmental approach to validation should provide a more complete representation of the findings than using aggregate data for all ages.

The first hypothesis was that rule-break errors would be more strongly associated with errors made on the task of spatial memory and monitoring (CPAL) than on spatial sequence learning. The second hypothesis was that exploratory errors would be associated
more strongly with performance on a measure of spatial sequence learning (Corsi) than with measures of error monitoring.

**METHOD**

**Participants**

A total of 147 5- to 8-year-olds participated: 31 5-year-olds ($M = 68.84$ months, $SD = 1.83$, 19 females, 12 males); 47 6-year-olds ($M = 78.17$ months, $SD = 3.21$, 28 females, 19 males); 49 7-year-olds ($M = 89.27$ months, $SD = 3.31$, 55 females, 24 males); and 20 8-year-olds ($M = 99.20$ months, $SD = 2.89$, 8 females, 12 males). The children attended schools in a large Australian city. All children had normal or corrected-to-normal vision and, according to school personnel, none had any diagnosed learning difficulties or known neurological issues. Children participated with parental and school consent and the research was conducted in accord with the authors’ university’s human ethics requirements.

**Materials and Procedure**

The children completed three tasks: (1) the GMLT (Snyder et al., 2005); (2) the Corsi visual memory span task (Kessels et al., 2000); and (3) the CPAL task (Harel et al., 2011), a test of spatial working memory and error monitoring. Tasks were completed in a random order, each one on a separate day. All tasks were completed in a quiet room in the children’s schools and each took 15 to 20 minutes to complete.

**Groton Maze Learning Task (GMLT)**

The GMLT is a computerized touch screen search task comprising a 10×10 grid of tiles. The aim of the task is to follow move rules to locate and remember a hidden 28-step pathway (Snyder et al., 2005). Visual feedback (crosses and ticks) and auditory cues indicate correct and incorrect tile selection. For any tile selected, only feedback for that location and the end goal are visible: the pathway remains hidden beneath the grid of tiles. The rules include: do not move more than one tile; do not backtrack along the pathway; do not move diagonally; and do return to the last correct tile after an error. Participants are instructed to search a tile/location only once. On completion of a trial (defined as traversing the maze from the top left-hand to the bottom right-hand corner), participants attempt to relocate the pathway on a subsequent trial. Five trials were completed in succession. The GMLT software records move responses and, for each, the nature of correct and error responses.

The children completed two familiarization/practice trials (see Thomas et al., 2011). In the first, an 8×8 maze with 20 steps was used. The instructions were given verbally and moves demonstrated by the interviewer:

There is a pathway that goes from here to here [pointing] and you have to find it one step at a time, but you cannot move to these locations [pointing to diagonal locations], and you cannot jump tiles [pointing]. You can only search in these locations [pointing to forward diagonal and horizontal locations]. If the place is wrong, then go back and look in another place. Let me show you.
The first few steps were demonstrated, before the child was encouraged to complete the trial by the interviewer asking: "Do you think you could find the next step?" Errors were corrected and the next move was explained by telling the child, "no, it is not there/ you can’t jump tiles, so now go back and try again".

On the second familiarization trial, errors were corrected initially, but once children appeared to follow moves rules, no further feedback was given. At the end of the second trial (if the child did not move randomly between tiles), to ensure rule understanding the interviewer examined children’s understanding of each rule: “Can I move here [pointing]? Why not? [Because it would be an error]. So where must I go now? [You must go back].” If children demonstrated rule compliance and answered rule questions correctly, they completed five trials on the 10×10 maze.

The Continuous Paired Associate Learning (CPAL) Task

CPAL involved a touch screen spatial learning task in which a picture is matched to a previously identified location following a standardized procedure (see Harel et al., 2011). In the acquisition phase, all six pictures are matched to one of eight locations (i.e., there are two distracter locations); and in the test phase, pictures are located one at a time. A trial is complete when all pictures are correctly located. The task consists of four trials. In the acquisition phase, all target locations are shown around the periphery of the screen. Each image appears one at a time in the center of the screen. The participant is required to touch the screen location of the associated picture. In the test phase, all images are hidden under blue location markers. A picture appears at the center and the participant is asked: “In what location does this picture belong?”. Following an incorrect search, the picture hidden in that location is revealed briefly and the participant taps the central picture to be found before searching resumes. The picture remains on-screen until its location is found. The CPAL software records all moves.

The Corsi Blocks Task

The Corsi Blocks Task comprised a 25×25 cm board with nine 2.5×2.5×2.5 cm blocks affixed to it in a random pattern. The procedure from Kessels et al. (2000) was used to administer the task. The interviewer taps a block sequence at a rate of one block per second, following which the child attempts to repeat the tap sequence in the same order. Only a forward version of the task was administered.

Two practice trials were administered to ensure task understanding. Two blocks were tapped and the child was asked to repeat exactly the tap sequence (all children were able to do so without error). Tap sequences began with two trials of two block tap sequences and, if correct, the number of to-be-tapped blocks was increased by one block until the tap sequences were incorrect. Two attempts at each sequence were given.

Measures

GMLT. Exploratory errors and rule-break errors were assessed on each trial and summed over the five learning trials.
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CPAL. Assessed by the total number of errors, derived as an accuracy score. Accuracy is automatically calculated by the GMLT software as the aresne of the total number of correct responses expressed as a proportion of total responses.

Corsi. The average highest block span for the forwards condition was recorded.

ANALYSIS AND RESULTS

Mean and standard deviation (in brackets) for all measures by age shown in Table 1. The values in Table 1 are included to provide a general overview of the values of each measure in each age group. The overall correlation between Corsi and CPAL total errors was not significant, \( r = .107 \) (ns).

Performance for the Corsi span and CPAL tasks was used to predict exploratory and rule-break errors on the GMLT using Multiple Linear Regression (MLR; Preacher, Curran, & Bauer, 2006). Age-related changes in the predictive value of Corsi and CPAL measures on GMLT exploratory and rule-break errors were assessed by the inclusion of age group as an interaction term in each analysis.

Predicted relationships derived using MLR were all significant (see Table 2): (1) Corsi and GMLT exploratory errors: \( R^2 = .24, F(3, 143) = 14.83, p < .001 \); (2) CPAL and GMLT exploratory errors: \( R^2 = .19, F(3, 143) = 11.40, p < .001 \); (3) Corsi and GMLT rule-break errors: \( R^2 = .19, F(3, 143) = 10.99, p < .001 \); and (4) CPAL and GMLT rule-break errors: \( R^2 = .23, F(3, 143) = 13.96, p < .001 \).

The main effects of Task and Age were examined to determine whether the Corsi and CPAL measures and age independently predicted the GMLT exploratory and rule-break errors. Interaction effects were examined to determine whether age moderated the relationship between the Corsi and CPAL measures and the GMLT exploratory and rule-break errors (i.e., is the relationship between the Corsi and GMLT exploratory errors the same for children of different ages?).

Following Preacher et al. (2006), the main effects and interaction effects were explored by regressing the GMLT errors during Corsi and CPAL task performance for different levels of the variable age. Figures 1–4 show predicted regression lines for each age group in all of the MLR equations shown in Table 2.

Table 2 shows that the main effects of Corsi performance and Age on exploratory errors were not significant; however, their interaction effect was significant, as 6- to 8-year-olds made significantly less GMLT exploratory errors as the Corsi span increased.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Means and Standard Deviation (SD) by age for Average Corsi and CPAL Total span Errors, and GMLT Exploratory and Rule-break Errors.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (Yrs)</td>
<td>Corsi</td>
</tr>
<tr>
<td>5</td>
<td>3.32 (0.69)</td>
</tr>
<tr>
<td>6</td>
<td>3.72 (0.54)</td>
</tr>
<tr>
<td>7</td>
<td>4.10 (0.75)</td>
</tr>
<tr>
<td>8</td>
<td>3.82 (0.63)</td>
</tr>
</tbody>
</table>
Table 2. MLR Equations to Predict Exploratory and Rule-Break GMILT Errors.

<table>
<thead>
<tr>
<th>Y =</th>
<th>b0</th>
<th>b1X</th>
<th>b2Z</th>
<th>b3XZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Exploratory Errors</td>
<td>Intercept</td>
<td>Corsi</td>
<td>Age</td>
<td>Corsi × Age</td>
</tr>
<tr>
<td>b-value (s.e.)</td>
<td>30.53 (7.59)</td>
<td>11.14 (7.38)</td>
<td>6.72 (4.35)</td>
<td>-2.54 (1.22)</td>
</tr>
<tr>
<td>β</td>
<td>1.01</td>
<td>1.41</td>
<td>1.56</td>
<td>-2.65*</td>
</tr>
<tr>
<td>partial eta²</td>
<td>.008</td>
<td>.014</td>
<td>.016</td>
<td>.030</td>
</tr>
<tr>
<td>(2) Exploratory Errors</td>
<td>Intercept</td>
<td>CPMa</td>
<td>Age</td>
<td>CPMa × Age</td>
</tr>
<tr>
<td>b-value (s.e.)</td>
<td>66.87 (11.13)</td>
<td>18.20 (16.94)</td>
<td>-1.19 (1.72)</td>
<td>-4.28 (2.66)</td>
</tr>
<tr>
<td>β</td>
<td>0.52</td>
<td>-0.12</td>
<td>-0.78</td>
<td></td>
</tr>
<tr>
<td>partial eta²</td>
<td>.003</td>
<td>.008</td>
<td>.018</td>
<td></td>
</tr>
<tr>
<td>(3) Rule-Break Errors</td>
<td>Intercept</td>
<td>Corsi</td>
<td>Age</td>
<td>Corsi × Age</td>
</tr>
<tr>
<td>b-value (s.e.)</td>
<td>164.08 (55.50)</td>
<td>-19.29 (24.42)</td>
<td>-12.17 (13.06)</td>
<td>1.13 (3.78)</td>
</tr>
<tr>
<td>β</td>
<td>-0.42</td>
<td>-0.40</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>partial eta²</td>
<td>.005</td>
<td>.006</td>
<td>.001</td>
<td></td>
</tr>
<tr>
<td>(4) Rule-Break Errors</td>
<td>Intercept</td>
<td>CPMa</td>
<td>Age</td>
<td>CPMa × Age</td>
</tr>
<tr>
<td>b-value (s.e.)</td>
<td>179.58 (32.73)</td>
<td>-104.37 (49.78)</td>
<td>-18.76 (5.07)</td>
<td>11.72 (7.83)</td>
</tr>
<tr>
<td>β</td>
<td>-0.58</td>
<td>-0.62</td>
<td>0.71</td>
<td></td>
</tr>
<tr>
<td>partial eta²</td>
<td>.087</td>
<td>.088</td>
<td>.015</td>
<td></td>
</tr>
</tbody>
</table>

Note. CPMa: CPM accuracy; b-value (s.e.) = unstandardized coefficient (standard error); β = standardized coefficient; *p < .05, **p < .01, ***p < .001.

Figure 1. Interaction plots of Corsi span predicting GMILT exploratory errors at different levels of age (5-year-olds, p = .45; 8-year-olds, p = .92; 7-year-olds, p < .001; 8-year-olds, p < .001).

There was no main effect of Age or CPM accuracy on exploratory errors and no interaction (Figure 2).

There were no significant main or interaction effects of Corsi span and Age in predicting GMILT rule-break errors (Table 2, Figure 3). Both CPM accuracy and Age were significant predictors of rule-break errors, but no interaction was observed (Table 2). Figure 4 shows that CPM accuracy predicted rule-break errors in all but the oldest children.
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Figure 2: Interaction plots of CPAL accuracy predicting GMLT exploratory errors at different levels of age.

Figure 3: Interaction plots of Corsi span predicting GMLT rule-break errors at different levels of age.

Figure 4: Interaction plots of CPAL accuracy predicting GMLT rule-break errors at different levels of age (5-year-olds, $p < .001$; 6-year-olds, $p < .001$; 7-year-olds, $p < .02$; 8-year-olds, $p < .001$).
In summary, Corsi span predicted GMLT exploratory errors, and CPAL accuracy predicted GMLT rule-break errors. An examination of the interaction effects revealed that age moderated only the relationship between exploratory errors and Corsi span.

To determine the unique variance of CPAL and Corsi measures in predicting GMLT rule-break and exploratory errors, two separate linear regression analyses were conducted to provide an indication of the predictive value of each test (CPAL and Corsi). In these analyses age was not used as a covariate because of collinearity issues.

Table 3 shows that Corsi span predicted exploratory errors. Increases in Corsi span predicted fewer exploratory errors. Table 4 shows that Corsi and CPAL accuracy predicted rule-break errors, and the interaction between Corsi and CPAL was significant. Higher CPAL accuracy, as well as a larger Corsi span, predicted fewer GMLT rule-break errors.

**DISCUSSION**

The hypothesis that GMLT rule-break errors would be more associated with performance on spatial memory test that required error monitoring than with performance for a test of spatial sequence memory was supported. Overall, CPAL errors predicted GMLT rule-break errors (see Table 2, equation 4), and this relationship was not moderated by age. The interaction between Corsi span and CPAL accuracy predicted GMLT rule-break errors (Table 4). This finding supports the claim that spatial memory and spatial error monitoring (as indexed by Corsi span and CPAL accuracy, respectively) both contribute to error monitoring ability in the GMLT. In contrast spatial sequence memory (i.e., Corsi span) was not associated with spatial error monitoring (see Table 2, equation 3).

The second hypothesis that GMLT exploratory errors would be more associated with performance on a test requiring sequence learning than with performance on the test of error monitoring was also supported. Spatial sequence memory span (Corsi) predicted GMLT exploratory errors, although this relationship was moderated by age (see
Table 2, equation 1). Analysis also showed that spatial span (Corsi) was a unique predictor of GMLT exploratory errors (Table 3). In contrast, exploratory errors were unrelated to the measure of error monitoring (see Table 2, equation 2). Importantly, performance on the tasks of error monitoring (CPAL) and spatial sequence memory (Corsi) were themselves not correlated, supporting claims for the independence of these two measures. Taken together, these findings are consistent with the claim that rule-break and exploratory errors made during GMLT performance reflect independent cognitive processes (Maruff et al., 2006; Pietrzak, Snyder, et al., 2009; Snyder et al., 2005; Snyder, Jackson, et al., 2008).

The results of previous studies using the HPML task paradigm have shown that healthy adults make very few rule-break errors (1 to 5 errors in trials to criterion for 17 trials [Milner, 1985], 20 trials [Chuikelsson & Schwartzman, 1983], and 10 trials [Retewe et al., 1991]; 8.30 in 5 trials on the GMLT [Pietrzak, Maruff, & Snyder, 2009]; and 2 to 4 errors in 5 trials on the GMLT [Snyder et al., 2005]). By comparison, rule-break errors are frequent in children even with pre-test practice (approximately 10 rule-break errors in 6- to 18-year-olds [Snyder, Maruff, et al., 2008] and 30 – 60 rule-break errors in 5- to 9-year-olds [Thomas et al., 2011]). However, compared to rule-break errors, children do not make substantially more exploratory errors than adults (Thomas et al., 2011). The current study extends previous research findings in suggesting that spatial sequence memory is partially different to spatial error monitoring in the GMLT, and by demonstrating the convergent and divergent validity of the rule-break and exploratory error measures in normally developing children.

Developmental models of executive functions suggest that age-related differences in complex spatial search tasks are evident as task difficulty increases (Luciana & Nelson, 1998, 2002). Cognitive capacity models suggest that an increasing aptitude in the ability to maintain concurrent information (i.e., working memory) scaffolds higher cognitive functions by decreasing the amount of effort required to process more complex information (Case, 1992; Zelazo, Gao, & Todd, 2006) and allows for the discovery of more efficient modes of processing information (Halford, Cowan, & Andrews, 2007). It is commonly understood that developmental differences often emerge as specific deficits when the amount of information exceeds the ability to process it (Cowan, 2010). Prior research has shown that younger children’s performance on the GMLT shows qualitative differences in rule-break and exploratory error at high levels of difficulty, or the 28-step 10×10 format (Thomas et al., 2011). Specifically, in Thomas et al. (2011), younger children were more impaired than older children in monitoring functions as task difficulty increased, but not in terms of their memory for the pathway. In the current study, high-difficulty versions of the GMLT and CPAL task were used, and this was reflected in the age-related differences observed. In general, younger children were less efficient than older children in remembering the GMLT pathway and also made more rule-break errors. The predictive strength of CPAL accuracy and Corsi span in relation to GMLT measures changed differentially as a function of age. This provides further evidence of their partial independence. For example, performance in the CPAL task predicted the number of rule-break errors in all but the 8-year-olds, whereas performance in the Corsi tasks predicted exploratory errors in all but the 5-year-olds. This finding suggests that ceiling and floor effects may have been operating in some of the task measures.

In previous studies, HPML tasks have been proposed to measure specifically topographical memory (Bowden & Smith, 1994) or error utilization (Walsh, 1985). However, the validity of these propositions has not been assessed formally using independent but conceptually similar tasks. Previous studies in healthy adults indicate
that the Austin maze (a manual predecessor of the GMLT based on Milner, 1965) is a test of visuo-spatial construction and visuo-spatial memory and acquisition (Bowden et al., 1992; Crowe et al., 1999; Tucker, Knisella, Gawith, & Harrison, 1987). Our findings support this conclusion with regard to exploratory errors. However, our results suggest that rule-break errors constitute a separate cognitive function to exploratory errors and therefore can be analyzed separately from the total errors in GMLT performance scores. Tests of executive functions in children are regarded as complex, multi-component tests (Hughes & Graham, 2002; Lehto, Jaajavaara, Koistinen, & Pulkkinen, 2003). However, they are treated as general tests of a construct, such as multi-step planning, and provide few outcome measures other than speed and accuracy (for reviews, see Best & Miller, 2010; Carlson, 2005). The "process-led" approach in the current study advances understanding of the development of executive functions in children by demonstrating that the components of a complex task can be reliably measured and validated.

The findings of the current study are consistent with previous studies showing the independence of the spatial memory and error monitoring measures of the GMLT in children and adults (Snyder, Jackson, et al., 2008; Thomas et al., 2008, 2011, 2013). One limitation of the present study is that it was cross-sectional and not longitudinal. Understanding the development of cognitive functions in children would be better accomplished by using a model of individual change over time. In developmental data it is common to see large variance across and within age or grade proxy measures of development (Siegler & Araya, 2005). This poses problems for interpreting differences in children on the basis of summary outcome measures: children of different developmental status may not execute tasks in the same manner (Wiewe, Espy, & Charak, 2006). The ability to identify separate but interacting cognitive systems from performance on a single neuropsychological task appropriate for use in children is potentially valuable for advancing empirical approaches to childhood development. For example, children can often perform component operations of a task when measured in isolation, but have difficulty when these operations must be deployed simultaneously (Bange & Crone, 2009; Carlson, 2005; Case, 1992).

Qualitative and quantitative analysis of task components can provide information regarding developmental changes in the ability to coordinate cognitive functions with age and task complexity (Siegler & Araya, 2005). We assert that the validity of the GMLT sub-measures, obtained by the changing age-related associations with similar tasks, provides a comprehensive analysis of the development of distinct cognitive functions and their coordination. Although the tasks were chosen because they were expected to be closely aligned with the measures of the GMLT, and they were not correlated, replicating this study with tasks that can differentiate between the spatial processing and executive components of the GMLT would advance understanding of the cognitive basis of HPML and its development. For example, taking advantage of the automatic recording of the GMLT response has allowed researchers to identify different developmental trajectories in young school-aged children that reflect rule-break errors (jumps, diagonals, backtracking), monitoring and perseveration errors (within search, failing to return to the head of path, and repeated tapping), correct error monitoring (returning after errors), visuo-motor control (tapping between tiles and out of grid), and pathway learning errors (exploratory errors), as well as response speed for each move and move category (Thomas et al., 2011). Given the relatively high rates of these errors in children, it should be possible to characterize performance more
precisely than is usually reported and develop a theoretical analysis of HPML task performance using a wider range of tasks measuring different constructs than memory and error monitoring in the GMLT.

REFERENCES


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Chapter 8

Discussion

8.1. Summary

The concept of EF is described within neuropsychology as the ability to coordinate cognitive processes to achieve a behaviorally relevant goal (Banich, 2009; Best & Miller, 2010; Burgess, et al, 2006; Cooper & Shallice, 2006; Desimone & Duncan, 1995; Henry & Bettenay, 2010; Koechlin & Summerfield, 2007; Stuss, 2011). The overarching hypothesis of this thesis was that understanding the development of complex executive function (EF) could be advanced by investigating how children coordinate component cognitive processes in a complex task of trial-and-error learning. To test this hypothesis, it was important to determine whether the component cognitive processes necessary for performance on the complex EF task were themselves developed in children. Once determined, it was then possible to examine the extent to which the coordination of these component processes could be disrupted or facilitated by age, manipulation of task characteristics or training. It was also important to show that different component processes considered necessary for performance on the executive function task were themselves independent (Studies 3 and 4). Children from 5-to-9-years of age were selected for the studies of this thesis for two reasons. First the development of EF in children over the age of 4-years is not well understood (Carlson, 2005; Best & Miller, 2010; Best, Miller, & Jones, 2009; Crone, Zanolie, Van Leijenhorst, Wetberg, & Rombouts, 2008). Second, understanding the normal development of EF is important for investigating
disorders of EF in childhood (Thomas & Karmiloff-Smith, 2002), as well as providing a sound theoretical basis for theories of adult EF.

Four empirical studies were conducted using different versions of the GMLT to test the hypothesis that development of complex EF in children reflects the ability to co-ordinate simple processes that are separate and intact (spatial memory, and rule use). The first study observed that performance on the GMLT was impaired in younger children (5 and 6 year-olds) compared to older children (8 and 9 year-olds) and this impairment increased with pathway complexity (grid size and pathway length). This age related impairment in complex EF was found to be due to limits in younger children’s ability to use task error information to adjust ongoing performance and to avoid further errors on the longer pathways. No age related effects were identified for children’s ability to utilize memory processes to acquire and remember the pathway itself. Thus younger children were limited in the ability to coordinate pathway memory with rule-use functions and this limitation was increased with task difficulty.

The second study examined the extent to which the limitations in rule-use functions in young children, observed in the first study, were due to difficulty using error feedback information to select appropriate responses for rule following under conditions of high task difficulty. This study found that while children could use additional visual task cues to improve rule use, such cues did not influence error monitoring or spatial memory. This cue-based improvement in rule use was observed only at high task difficulty. Thus, error monitoring functions in young children were not developed sufficiently to benefit from visual cuing of erroneous responses. However some aspects of rule use were improved by the additional
visual support in the form of highlighting move options that were allowed by the rules.

Study three challenged the assumption made in studies one and two, that the spatial memory and rule use components of performance on the GMLT could be conceptualized as independent cognitive processes. The first experiment found that removing demands on spatial memory did not affect performance on the GMLT that was dependent on rule use. The second experiment found that withholding rule training, thus increasing demands on trial and error learning, did not affect aspects of spatial memory necessary for performance on the GMLT. This double dissociation indicated that the contributions of spatial memory and rule use for optimal performance on the GMLT are independent in children.

Study four examined the independence of spatial memory and rule use components of performance on the GMLT by determining the extent to which each was predicted by independent neuropsychological models of the same constructs. The data showed that the spatial memory component of performance on the GMLT was associated with another neuropsychological test of spatial memory, but not a neuropsychological test of trial and error learning and error monitoring. The rule use component of the GMLT was associated with another neuropsychological test of trial and error learning and error monitoring, but not spatial memory. These findings demonstrate the convergent and divergent validity of the GMLT as a test of executive function that measures separate components of spatial memory, and rule use.

There are two outstanding issues from study four (Chapter 7). First, the Continuous Paired Associate Learning Task (CPAL) is derived from a class of
tasks in which the location of objects in a spatial array must be learned and identified by associating spatial and visual cues provided within the test environment (e.g. CANTAB spatial working memory task: Luciana & Nelson, 1998, 2002). Processes of visuo-spatial binding are clearly important for successful performance in this task. However they were not discussed because the study focus was on the development of memory and executive processes from a neuropsychological perspective. The neuro-cognitive basis of multisensory integration was no considered a significant factor, according to the objectives of the study.

When considered together, the conclusions of the reviews, and outcomes of the experiments in this thesis supported the overarching hypothesis that the co-ordination of component processes in a complex task of EF can be characterized by specific deficits in error monitoring when cognitive load increases (e.g. pathway length). The children in the studies of this thesis demonstrated proficiency with the individual processes of the GMLT. Younger children had difficulty coordinating ongoing information with component cognitive processes when task difficulty was high (i.e. 10 x 10 maze). The studies presented here therefore demonstrate that the ability to coordinate cognitive processes develops in early childhood and is not mature by the age of 9-years. This is an important finding because prior research has focused on the development of single executive processes (Best & Miller, 2010), not the ability to co-ordinate processes in an EF task in school-aged children.

8.2 Implications of the current findings for theories of executive functions

The model of EF developed in this thesis was that complex cognitive processes that are essential to forward planning in EF tasks could be characterized
as the ability to maintain rules and goals for trial-and-error learning in a hidden pathway paradigm, the GMLT. Theoretical analyses of hidden pathway maze learning paradigms indicated that the GMLT could be considered as a measure of complex EF (Pietrzak, Cohen, & Snyder, 2007; Pietrzak, Maruff, & Snyder, 2009) although this claim had not been tested in children before the studies conducted in this thesis. It was important to show that the component processes of memory and rule use were distinct, and intact in the children included in the studies. Therefore any change in performance, with task manipulations, could be interpreted as immaturity in the ability to co-ordinate multidimensional task demands, or EF.

The findings of this thesis showed that the individual processes of pathway memory and rule use were developed to same extent in 5 and 6-year-old children as they were in 7-to-9-year olds. However, pathway memory and rule use processes were still below adult ability in all the children. Increasing task difficulty was associated with increased difficulty in error monitoring abilities in the younger children even though they were still able to complete the task at the highest level of task complexity (i.e. the 10 x 10 maze). It is therefore unlikely that the difference in the ability to monitor errors in younger children was due to a lesser capacity to notice errors. Rather the data suggests that younger children had difficulty using information to alter behaviour and thereby avoid further errors.

The specific performance cost to error monitoring processes in the younger children was not a direct consequence of attention, working memory, or capacity limitations in representing task requirements. This is because the demands on attention, working memory, or task representation for choice-point decision-making do not change with increasing pathway length, and thereby task complexity. Furthermore, prior to assessment all task rules were trained and
assessed for comprehension. The findings of this thesis, that the development of executive functions can be represented by an increasing capacity to act on changing information according to rules and error information, are consistent with neuropsychological models that define EF development as the ability to represent and successfully manipulate increasingly complex information (Case, 1992; Halford, Baker, McCleod, & Bain, 2005; Gathercole, Pickering, Ambridge, & Wearing, 2004).

The findings of this thesis suggest that the development of complex EF in children reflects development of the ability to co-ordinate component processes in pursuit of a task goal. The methodology used in this thesis established that the underlying processes to complete the GMLT are separate, intact, but easily disrupted by increasing task difficulty, with a specific cost to error evaluation and response in young children. This is an important finding because error monitoring has not been characterized as a process involved in the coordination of other process in a complex task in children. Error monitoring in children has been examined with simple tasks that require response inhibition (i.e. Go- no Go), response-set switching (Bunge, 2004; Bunge & Crone, 2009), or as a process central to error-feedback learning (Bjork, 1994; Hesketh, 1997). Theories of EF development consider error-monitoring processes as a form of ‘meta-cognition’ that requires consideration of prior actions-outcomes, and flexible forward planning with regard to new information provided by task feedback (Bunge & Crone, 2009; Marcovitch & Zelazo, 2009). One hypothesis is that co-ordination of cognitive processes are necessary for meta-cognitive skills, hence meta-cognition requires that multiple streams of complex information be coordinated for goal-directed activity: Trial and error learning requires active reflection on the decisions
arising from this coordinated approach. The emergence and stability of conscious cognitive control in goal-directed problem solving are a consequence of developing neural systems that are understood as interacting, but developmentally distinct, such as brain regions associated with domain specific memory, or domain general area’s implicated in input evaluation, and action-selection (Casey, Giedd, & Thomas, 2000; Casey, Tottenham, Liston & Durston, 2005). It is therefore important to understand the contribution and interactions of individual behavioural processes in goal-directed tasks, as opposed to focussing on the development of memory, language, or reasoning skills in relation to EF (Marcovitch & Zelazo, 2009). Understanding complex EF is aided by a multi-dimensional approach that goes beyond identifying the developmental trajectories of domain specific processes, such as inhibition, working memory, updating, or error monitoring and investigates instead how such processes are selected, inhibited and co-ordinated (Burgess et al., 2006; Ramnani & Owen, 2004).

8.3 Limitations and Future directions.

The model of EF developed in this thesis considered rule use, and spatial memory as components of EF in healthy children. One limitation of the work presented in this thesis is that participant numbers were relatively small in studies 2 and 3, although sufficient to meet statistical power requirements. A second limitation is that initial screening of children for visuo-spatial or executive function difficulties was not possible because of the author’s University’s Human Ethics Committee requirements.

The proposition that EF can be characterised according to the ability to co-ordinate processes in a complex task, could be challenged in children with known
disorders in EF. While the studies in this thesis focussed on normally developing children, challenging the models developed from the data collected here, by examining the performance of children with disorders characterised by a deficit in EF, could provide insight into the conditions necessary for co-ordination of component cognitive processes in complex EF. The hypothesis that EF development reflects the ability to co-ordinate component processes could be challenged by repeating the first experiment from the current thesis in children with known deficits of EF, such as ADHD (Polanczyk, de Lima, Horta, Biederman, & Rohde, 2007). If children with ADHD show a profile of performance deficits on the GMLT that is consistent with that of the younger healthy children in the current study, that is with a limited ability to monitor errors at high task difficult, then this would indicate that the ability to coordinate component processes in complex EF was not age specific but rather reflected optimal function of a specific neural network: Such as a network that was dysfunctional in ADHD. On the other hand, impairment in the component processes, or in their co-ordination, in ADHD would be evident from a qualitatively different profile of errors to age-matched controls, or normally developing younger children. For example, children with ADHD might exhibit more rule break-errors associated with rule deployment on more difficult versions of the GMLT (e.g. 10 x 10), rather than repeating errors. Such a finding would provide evidence that component cognitive operations must be normal for optimal performance on this measure of complex EF. A correlational study of GMLT measures with other measures of executive function and spatial processing could help characterize the nature of GMLT sub-measures. One of the main indicators of immaturity in maze performance was error monitoring ability. Error monitoring is
a complex skill that requires the conscious and effortful capacity to update new information and shift cognitive set in response to errors (Bunge, 2004; Bunge & Crone, 2009). Younger children could monitor errors, but did so inconsistently, and were therefore less efficient in maintaining the processes necessary for performance to complete the GMLT under conditions of high task difficulty. This was likely due to selective neglect of task elements when limited capacity, with high task demands to maintain information at difficult turns led to repeated errors. That is, consistent with historical accounts of behaviour in maze learning (Chapter 2), children continued to search locations that violate the task rules when the pathway turned in an unexpected direction. Understanding the nature of how children co-ordinate cognitive functions could be examined in more detail using the GMLT by investigating factors associated with children’s increasing ability to monitor their errors with age. For example, a comprehensive analysis of working memory capacity, spatial reasoning, and error monitoring in other spatial contexts, such as Go-no-Go paradigms or self-ordered planning tasks (Carlson, 2005; Luciana & Nelson, 2002) could be examined with GMLT measures, including response times to individual moves that have not been previously reported, but are recorded by the GMLT software (response times to individual move categories). As described at the end of chapter 2, Mathewson, Dywan, Snyder, Tays, & Segaelowitz (2007), showed how the GMLT could be used to identify patterns of neural response in error monitoring with aging using event-related potential analysis in the Anterior Cingulate Cortex. More precise behavioural measures of moves in the GMLT could be coupled with similar neural electrical activity or magnetic experimental intervention analysis to delineate the processes of error-feedback responses. Such an analysis could further understanding of the neural
basis of the proposed separate and independent processes underlying EF co-
ordination that have been identified in the GMLT. It has been shown that EF tasks
often elicit different patterns of neural response in adults compared to children, and
among children of different ages (Casey et al., 2000, 2005). However the imaging
studies using children have mostly used simple response, or traditional complex EF
tasks that were critically reviewed earlier in this thesis (Chapter 1 and 3). If
limited capacity to monitor errors in the GMLT at high levels of difficulty is a
consequence of capacity limitations in complex EF, then it would be expected that
this would be evident in neural signatures that could be measured by imaging,
EEG, or MEG methods targeting brain regions that are known to be late
developing, and are associated with input selection and competing action-response
planning (Ramnani & Owen, 2004; Stuss, 2011).

Providing instructions in the training phase to emphasise the importance of
noticing errors and avoiding repeating the same error could be useful in reducing
younger children’s errors in the GMLT. If the failure to monitor errors is a result
of limited capacity, then the additional instruction should make no difference to the
rates of errors related to error monitoring in young children. If, however,
monitoring errors are reduced with instructions to avoid repeating errors, then it
could be concluded that children can monitor errors, and their failure to do so is
not a consequence of any capacity limitation. Limiting children’s responses to one
move every few seconds, rather than self-pacing might encourage children to
reflect on their errors, and improve rule compliance. Evidence that delaying
children’s responses could be a useful intervention for reducing children’s rule
break errors in the GMLT was suggested in study 2. In this study, younger
children’s tendency to double tap on the correct tile was interpreted as a ‘pause-time’ used to construct move plans for the next tile selection (Study 2).

8.4 Conclusion

In conclusion, the studies of this thesis have shown that the development of complex EF can be characterised by the development of component processes for goal directed trial-and-error learning in the spatial domain. The model of EF development that was advanced in this thesis was consistent with theories of complex problem solving in adult neuropsychology and childhood neurodevelopment (Best & Miller, 2010; Burgess et al., 2006; Marcovitch & Zelazo, 2009). However further studies are required to investigate the development of EF in childhood using a range of tasks that are theoretically defensible, and provide methodologically sound protocols from which valid inferences regarding change or difference in EF can be characterised in order to further understanding of this construct in child neuropsychology and development.
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