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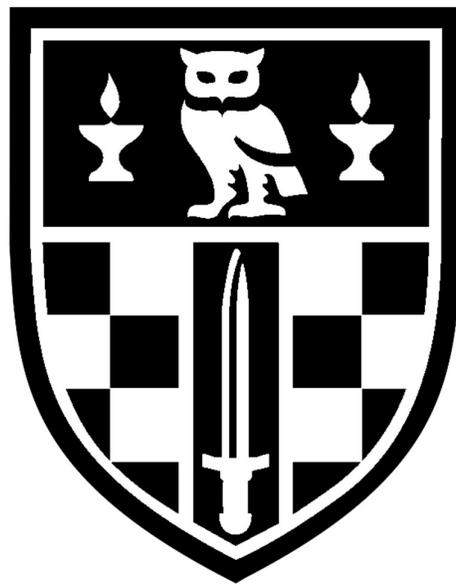
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Multilevel goal management in toddlers' and
preschoolers' action sequence planning and
execution

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PhD Psychology

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A thesis submitted in fulfilment of the requirements of the degree of Doctor of
Philosophy (PhD)

DECLARATION

I, Lisanne Schröer, hereby declare that this thesis has been composed solely by myself and that it has not been submitted, in whole or in part, in any previous application for a degree. Except where it state otherwise by reference or acknowledgement, the work presented is entirely my own.

This thesis includes research that has appeared in the following article:

Schröer, L., Cooper, R. P., & Mareschal, D. (2021). Science with Duplo: Multilevel goal management in preschoolers' toy house constructions. *Journal of Experimental Child Psychology*, 206, 105067.

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ABSTRACT

Action planning is the foundation of everyday behaviour, allowing us to interact with the world. Even infants are able to plan simple one or two steps actions. However, in daily life, adults plan, execute and control complex action sequences, often following multiple levels goals or multiple constraints. For example, even something as simple as making a cup of coffee in the morning involves following a goal hierarchy with a key goal, multiple subgoals and action steps. The actor has to keep track of the key goal of making a cup of coffee throughout the task, while maintaining which of the subgoals and action steps has already been executed and which should be executed next.

While previous studies suggest that the ability to plan and execute action sequences develops over the preschool years (Freier et al., 2017; Yanaoka & Saito, 2017; 2019), the exact underlying development mechanisms remain unclear. It has been suggested that both executive function improvements and motor competence could be related to development of action sequence planning and execution. The aim of this thesis is to understand action sequence development by using ecologically valid paradigms to investigate children's action sequence planning using wearable equipment allowing toddlers and children to act like they would in everyday life.

Chapter 2 shows that the ability to plan simple alternating sequences and action sequences with goal constraints improves over toddlerhood and that it is related to working memory. Next, Chapter 3 and 4 shows that the hierarchical action sequence planning of a Duplo house improved over the preschool period. Furthermore, this ability is related to updating and inhibition skills. Motion capture reveals that good planners shows relative freezing of their non-reaching hand when executing a subgoal, suggesting a greater cognitive focus while executing that subgoal. Chapter 4 uses fNIRS to show that the dorsolateral prefrontal cortex is more active at decision branch points (when a switch from one subgoal to another has to be made), but only in older children. This suggests that changes in the dorsolateral prefrontal cortex might be involved in the development of action sequence control in the preschool period. Lastly, in Chapter 5, modelling is used to explore the novel hypothesis that action sequence development might be related to immature action selection functionality in the basal ganglia. However, the modelling results shows that, while the action selection functionality of the basal ganglia might play some role in development role, changes in goal representations and/or action planning improvements in the prefrontal cortex are the main driver of goal-directed action sequence development in preschool years.

Together, these chapters enrich our understanding of the development of planning, selection, and control of action sequences, and their underlying and neural mechanisms in toddlerhood and the preschool period in naturalistic settings.

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CHAPTER 1

Planning, selection and execution of goal-directed manual actions and action sequences in infancy, toddlerhood and preschool period.

1. Introduction

‘People lead lives of both thought and action. One of the enduring puzzles of human existence is how we acquire physical and mental activities of such great complexity from our simple origins as a single cell. ... What enables our brains to control our limbs and body segments to perform intricate and skilled actions?’ (Thelen & Smith, 1994, p. xiii).

Our everyday life consists of an abundance of manual actions. For example, brushing your teeth, getting dressed and making a sandwich involves manual actions. Therefore, manual actions are essential in daily life. It underlies our everyday functioning and it is our way to interact with the world around us.

These manual actions need to be planned ahead. Furthermore, these actions should be adjusted to the demands of the environment and/or of the task. For example, during a grasping action, hand openings should be adjusted to the size of the object prior to contacting the object. Planning, selecting and executing an action successfully involves taking into account these constraints (von Hofsten, 1993, 2004).

Furthermore, actions are typically executed with the aim of achieving a desired goal or goal state (von Hofsten, 2004). For example, we reach towards a glass on the table to get hold of the glass and perhaps eventually drink its content. Simple actions can be combined to achieve more complicated goals, and one simple action can be used to achieve multiple different goals. For example, when reaching towards a glass on table, we can do this to achieve the goal of drinking some water, but we can also do this to achieve the goal of cleaning up the empty glass.

In this thesis, manual action is defined as *action performed with arms and/or hands with as goal to manipulate objects in the environment*. Examples are reaching for an object or moving this object. Manual actions can be studied and described at multiple interdependent levels. It has been proposed that actions can be categorized into four different levels increasing in abstractness: (i) the kinematic level containing the motion trajectories, (ii) the motor level containing patterns of muscle activity, (iii) the goal level containing the immediate purpose,

and (iv) the intentional level containing the higher level or overarching goals (Kilner, 2011). These levels are dependent, and can be hierarchically organised; the kinematic level is dependent on the motor level, the motor level on the goal level and the goal level on the intention level (Kilner, 2011). This thesis aims to investigate action sequences in children, focusing on the goal and intentional levels. However, it will, for example, use evidence from the kinematic level to study improvements in action sequences at the higher levels.

The forthcoming sections will provide an overview of actions and action sequences, its development and potential mechanisms and brain areas involved. First, different characteristics of adults' actions will be discussed. In this context, this thesis will review the evidence of adults' action sequences and potentially computational modelling explaining adult performance. Thereafter, various lines of developmental research will be reviewed to provide an account of the development of action and action sequences in infancy, toddlerhood and childhood. Furthermore, the potential underlying mechanisms supporting the ability to plan, select and control actions and action sequences – causal reasoning, executive functions and motor competence – will be summarised. Lastly, a broad overview of potential brain areas involved in manual actions will be given, reviewing developmental and relevant adult literature. This chapter aims to provide a review of a wide range of evidence relevant to the study of development of action sequences in children. Each subsequent chapter will discuss concepts introduced in the following sections in relation to specific studies in this thesis.

1.1 Manual actions

Executing manual actions consists of three interconnected processes that underlie actions in daily life; *action planning*, *action selection* and *action execution and control*. Action planning is the process of deciding how to achieve a desired goal, action selection is the task of selecting the activity or movement pattern to achieve the desired goal, and action execution and control is the processing of carrying out and regulating that specific goal-directed activity. Unless otherwise stated, the term *action* or *acting* reflects all three processes. These processes are interconnected and rely on each other. Without action plans, the appropriate action cannot be selected. Without action plans and a selected action plan, the appropriate action cannot be executed and controlled. It is particularly difficult to disentangle these processes in development (Thelen & Smith, 1994). When infants, toddlers or children are unable to execute a goal-directed action, it is unclear whether difficulties in planning, selecting or executing of that action (or a combination) underlie these problems in their acting. Successful action and

action sequence performance is the result of a process of planning, selecting and executing and involves the representation of this action or action sequence, and the generation and the control of that specific action or action sequence in the environment. Unless otherwise stated, actions or action sequences reflects all these related processes and is assessed by action or action sequence performance.

Actions in daily life can be divided into *goal-directed* or *intentional actions*, and *habitual actions*. Intentional goal-directed actions are selected, because it is expected that the selected action brings the desired outcome. In contrast, habitual actions are reflexively caused by cues or context associated with prior rewards (Raab & Hartley, 2018). Naturally, habitual actions can also have a goal. The key difference is that goal-directed actions are actively directed, intentional to achieve the goal, while habitual actions are driven by a stimulus or the context (Dezfouli & Balleine, 2012, 2013; Perez & Dickinson, 2020). Habitual actions are not influenced by manipulating the reward or outcome, while goal-directed actions are affected if the outcome or reward is modified (Dezfouli & Balleine, 2012). Put differently, habitual actions are not influenced by devaluation of the outcome by, for example, showing a video multiple times, while goal-directed actions are.

Several studies have shown that children as young as 18 months showed the first evidence of sensitivity to outcome devaluation in their goal-directed actions (Kenward et al., 2009; Klossek et al., 2008; Klossek & Dickinson, 2012). For example, children over 2.5 years old performed an action that was trained with a devalued outcome significantly less compared to an action that was trained with a consistently valued outcome. In this study, young children were trained to manipulate butterflies on a screen to gain different types of video clips as an outcome. Next, one of the outcomes was devalued by repeated exposure. Younger children did not show an influence of devalued outcome in their response (Klossek et al., 2008). However, in a similar study with more training over two sessions, there was evidence for the effect of outcome devaluation on the response in infants between 18 and 23 months (Klossek & Dickinson, 2012). Similarly, 24-month-old infants showed increase button presses to retrieve an object when the object value was increased (Kenward et al., 2009).

Furthermore, some studies have investigated whether young children act to achieve a goal. Bullock and Lütkenhaus (1988) assessed toddlers' ability to act appropriately to task standards and monitor actions with respect to outcomes. Toddlers between 15 and 35 months engaged in a series of tasks: a tower building task, a cleaning up (blackboard) task, and a figure dressing

task. All these tasks required a specific outcome, but there were attractive distractors in the playing area. Toddlers that were younger than a year and a half of age showed greater activity-oriented behaviour, rather than outcome-oriented behaviour. By 20 months of age, children have begun to pay attention to producing an outcome with their actions. Thirty-two-month-olds were able to understand the precise task standards, and were able to manipulate and correct separate components of their actions. It was argued that toddlers' problems with acting in a goal-directed way were due to an inability to avoiding distractions (Bullock & Lütkenhaus, 1988). In support of this conclusion, Silverman and Ippolito (1997) found that toddlers' goal-directedness in tower building and figure dressing tasks correlated with their inhibition abilities.

Actions in daily life can be further subdivided into *routine* and *non-routine actions*. Routine actions are actions or action sequences that are not necessarily constantly monitored and are automatic (Cooper et al., 2014). Examples include everyday actions like walking, making a cup of coffee, or brushing your teeth. These are actions that we can execute without attentional control (Cooper et al., 2014; Norman & Shallice, 1986). Non-routine actions require attentional control, and can be changed into routine actions by practice or learning. For example, the first time you are learning a new skill such as playing the violin or crocheting, it is a non-routine action that needs to be monitored. With practice, these actions might become routines that do not require constantly monitoring to be executed.

The subdivisions between routine vs. non-routine actions and habitual vs. goal-directed actions are not necessarily independent divisions, but these definitions are also not completely overlapping. For example, an action can be goal-directed and non-routine; you might decide to practice crocheting for the first time, or goal-directed and routine; you are a piano player and intentionally decide to execute your routine action of playing Mozart. Similarly, an action can be routine and habitual; you might start to execute the making a cup of coffee sequence based on the cue that you arrived in the kitchen when getting out of bed. However, actions that are habitual (automatically driven by the context) cannot be non-routine, as this would require constant monitoring of the task to be executed successfully

Problem-solving and planning are closely related; both involve a goal-directed activity, and involve overcoming obstacles in the way of achieving that goal (Ellis & Siegler, 2006). However, planning is an indirect process within problem-solving (Ellis & Siegler, 2006). Action plans are constructed in the prospect of a future actions, but the solutions of these

problems are not necessarily attained (Ellis & Siegler, 2006; Friedman et al., 1987). Furthermore, not all problem-solving tasks demand planning. In short, action planning is aimed to choose actions that when executed in the future will solve the problem (Ellis & Siegler, 2006).

In summary, manual actions can be divided into goal-directed or habitual actions, and routine or non-routine actions. There is plenty of evidence that already in toddlerhood, children are able to act goal-directed. The next section will discuss what happens when we group several manual actions together in an action sequence considering adult studies and computational models explaining adult and patient performance, including common action slips.

1.2 Action sequences in adults

Many of the goal-directed actions in our daily life are actions grouped together in an *action sequence*, and adults are proficient in planning and executing these action sequences. These action sequences often consists of multiple levels of goals, all set within a goal hierarchy (Jeannerod, 1997; Lashley, 1951; Rosenbaum et al., 2007). A hierarchical goal structure consists of a main goal, which in turn consists of several subgoals, which in their turn consists of several action steps (Figure 1.1). Something as simple as making a cup of coffee in the morning could be described in terms of a goal hierarchy. The main goal is making a cup of coffee, which consists of several subgoals such as adding the sugar or adding the milk. These subgoals in turn consists of several action steps such as picking up the milk package or pouring the milk. A subgoal is a goal that is secondary to achieving a larger goal consisting of multiple action steps, such as adding sugar for the overarching goal of making a cup of coffee. These action steps have to be selected in a specific order depending on the action sequence. For example, we have to first pick up the package of milk and move it towards the cup, before we can pour the milk. Furthermore, the actor has to maintain the main goal of the goal hierarchy throughout acting, and has to keep track of which subgoals and action steps have already been executed, and which subgoal and action steps should be executed next (Botvinick et al., 2009; Cooper et al., 2014; Cooper & Shallice, 2000, 2006; Miller et al., 1960). For example, when making a cup of coffee, the actor has to maintain the goal of making a cup of coffee and remember that the goal was not making tea. Furthermore, the actor has to keep track of which of the subgoals have already been executed, for example, to avoid adding sugar twice.

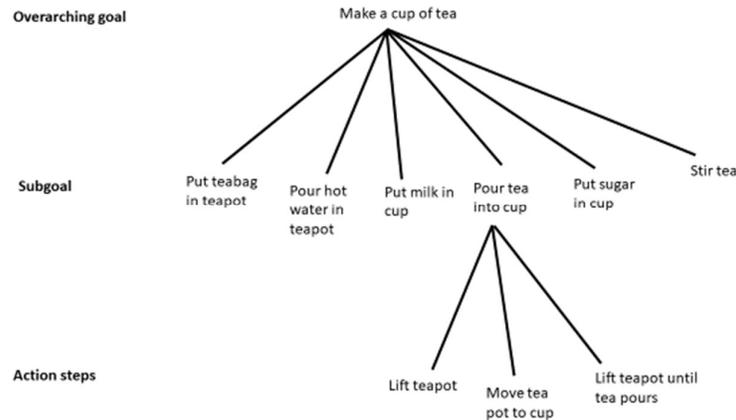


Figure 1.1. A goal hierarchy of an action sequence. Figure adapted from *Disordered action schema and action disorganization syndrome* (page 802) by G.W. Humphreys & E.M.E. Forde, 1998, *Cognitive Neuropsychology*, 15, 771-811.

As evidence in support of goal hierarchies, adults showed slowed-down action selection at decision boundary points (i.e. *branch points*) where a switch from one subgoal to another is required (Arnold et al., 2017; Ruh et al., 2010). For example, Ruh et al (2010) found that actions were slowed down at branch points when a switch had to be made from adding sugar to adding milk in a computer-based task where adults needed to make either coffee or tea (Experiment 1) or created a fertiliser for an artificial plan (Experiment 2). Similarly, action selection was slowed down at these branch points when adults were asked to build a Lego wall (Arnold et al., 2017). The process of selecting the next action from the next subgoal at these branch point was thought to require cognitive control and this was reflected in increased selection time (Ruh et al., 2010).

However, despite the fact that adults are proficient in planning and executing action sequences, they still occasionally show some lapses or slips (Cooper & Shallice, 2000; Norman, 1981). The most common types of unintentional errors are:

1. Capture errors: A different action sequence is performed instead of the intended one, but the new action sequence is appropriate given the environmental cues. For example, when opening the fridge to make dinner, instead taking cheese to make a sandwich.
2. Omission errors: A step or subgoal in an action sequence is not performed (i.e. omitted). For example, a person forgets to add milk to their coffee.
3. Anticipation errors: A step or subgoal is performed earlier in the actual sequence than usual. For example, a person already closed the box of tea before retrieving a tea bag.

4. Preservation errors: A step or subgoal is repeated. For example, a person adds twice sugar to their coffee when distracted.
5. Object substitution errors: An action is carried out with an unintended object. For example, trying to use a fork to spread your jam on the sandwich.

Atypical action control can occur after neurological damage. For example, action disorganisation syndrome arises from damage to frontal lobes, and is characterised by impairments to complete multi-step action sequences, even if these were mastered prior to the damage. These patients, for example, demonstrated omission, anticipation and object substitution errors in their attempts to complete action sequences (Humphreys & Forde, 1998).

In short, adults are able to plan, select and execute complex action sequences (e.g. Arnold et al., 2017; Ruh et al., 2010). But what are the underlying mechanisms of these abilities? Computational models provide one way of addressing questions of mechanisms and there are several computational models describing the selection of routine action sequence that can account for the lapses made in typical adults and action disorganisation syndrome (Botvinick & Plaut, 2004; Cooper et al., 2014; Cooper & Shallice, 2000, 2006; Trafton et al., 2011).

Many of these models consists of a hierarchical processing unit, because, as discussed above, action sequences can be planned and selected in a hierarchical manner (e.g. Jeannerod, 1997; Lashley, 1951; Rosenbaum et al., 2007). Indeed, an interactive activation network with a hierarchical structure (*contention scheduling model*) was able to explain routine action selection and account for action slips and action disorganisation syndrome (Cooper & Shallice, 2000, 2006). This model consisted of three interactive networks composed of an object representation network, an effector network, and schemas (Figure 1.2).

Schemas (or partial action plans) are goal-directed structures for achieving goals and that consist of partially ordered sets of subgoals. Different schemas compete for activation, which comes from triggers (i.e. activation from higher-order goals) and source schemas (i.e. activation from the previous action step). The selection for a schema is influenced by the current schema and environment. When an action sequence is intended to get executed, the intended schema is activated.

This activation is hypothesised to originate from the supervisory system. Subschemas become activated, and the action corresponding to this subschema is selected. After one action is executed, the next subschema is activated. This model fitted the neuroscience evidence better compared to simple recurrent network models (Cooper & Shallice, 2000, 2006)

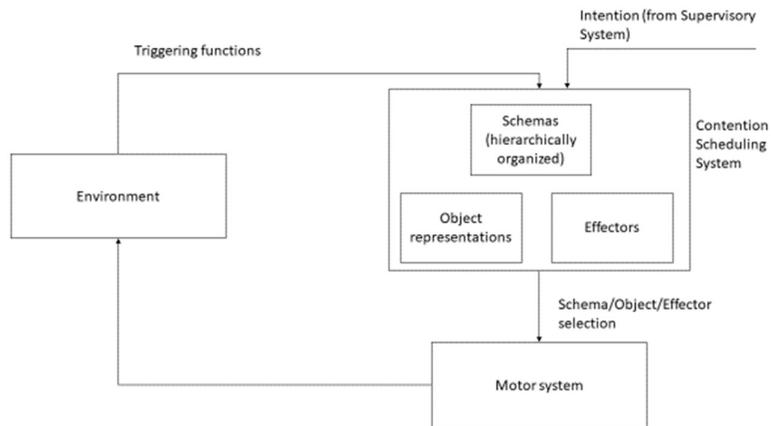


Figure 1.2. The contention scheduling model explaining routine action sequences. Figure adapted from *Hierarchical schemas and goals in the control of sequential behaviour* (page 889) by R.P. Cooper & T. Shallice, 2006, *Psychological Review*, 113(4), 887-916.

However, Botvinick and Plaut (2004) proposed an alternative framework based on a simple recurrent connectionist network to explain routine action sequences (Figure 1.3). Here, the network consisted of an input layer depicting the environmental stimuli through activation. Activation then continues to the hidden layer, which has the aim of transforming the input information. A pattern of activation is then forwarded to the output layer whose units represent the response to the input. The hidden layer is recurrent, meaning that this also receive inputs of its own internal connections from the step before the current one. This enables the system to preserve information across time.

This recurrent connectionist network explained errors in action as a result of lost information in the internal representation about a previous or current state. The simulation results were able to account for basic features of routine action sequence, meaning that the computational model was able to simulate normal-error-free performance, everyday slips of actions and action disorganisation syndrome (Botvinick & Plaut, 2004).

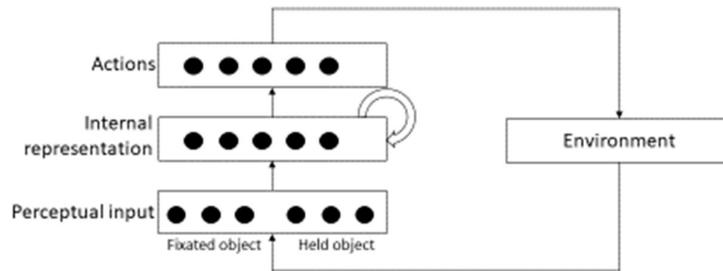


Figure 1.3. The interaction activation network explaining routine action sequences. Figure adapted from *Doing without schema hierarchies: A recurrent connectionist approach to normal and impaired routine sequential action* (page 400) by M. Botvinick & D. Plaut, 2004, *Psychological Review*, 111(2), 395-429.

Lastly, a framework based on the activation of memory elements was also able to explain routine action sequences (Trafton et al., 2011). This system selects the next step in an action sequence based on memory for the last step it has performed. It assumes sequential action is guided by episodic control codes generated for each action step. These codes decay with time, and can be reactivated by contextual retrieval cues. These control codes enable the system to infer the correct next action after interruption in execution. The model was able to account for different types of errors made in execution of an action sequence (Trafton et al., 2011), but it remained unclear whether the model also produced increased selection time at branch points as found in adults (Arnold et al., 2017; Ruh et al., 2010).

However, these three model only explain *routine* action sequences, but do not provide an underlying mechanism for non-routine action sequences. The *Goal Circuit* (GC) model provides a computational model of both routine and non-routine action sequences. This model extends the recurrent connectionist network of Botvinick and Plaut (2004), by providing a way that the executive system (also named the supervisory system or SS) can control actions that are not fully routinised using top-down control.

The lower level of the system consists of a hidden layer which receives recurrent activation from the representation of the task context that is fed back into the system together with current perceptual input, producing a new action selection output (Figure 1.4). Importantly, the GC model adds a goal circuit that consists of goal input units. Goal units are explicit representations that encode intent, and that can bias the lower system to select a desired action. In addition, the model has a learning mechanisms, enabling the system to respond to novel tasks or

environments by re-assembling already acquired sequences. However, the system is (as yet) not able to establish action sequences from scratch. The simulations demonstrated flexibility in the selection of actions, and showed how deliberate control can override a learned action sequence (Cooper et al., 2014).

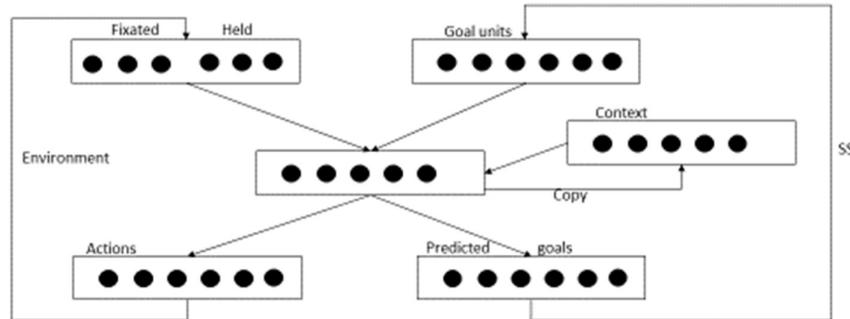


Figure 1.4. The Goal Circuit model explaining routine and non-routine action sequences. Figure adapted from *The goal circuit model: A hierarchical multi-route model of acquisition and control of routine sequential actions in humans* (page 251) by R.P. Cooper, N. Ruh & D. Mareschal, 2014, *Cognitive Science*, 38(2), 244-274.

To sum up, adults are proficient in planning, selecting and executing action sequences, despite an occasional slip or lapse. Action sequences can be explained in terms of a goal hierarchy with an overarching goal, several subgoals in the level below and several action steps in the lowest level. Adults showed increased selection time at branch points when they switch from one subgoal to another. Lastly, several computational models have successfully explained characteristics of action sequence performance in adults. However, it remains unclear how actions and action sequences develop in infancy, toddlerhood and early childhood. In the subsequent section, this thesis will summarize the evidence of the development of actions over the first six years of life.

1.3 The development of actions

Although the exact mechanisms remain unclear, the literature has demonstrated a strong improvement in action skills between infancy and early childhood. This section will start discussing the onset of intentional manual actions in infancy by discussing prospective motor control before moving on to more complex forms of planning that develop in toddlerhood or preschool period (i.e. means-end planning, tool-use and action sequences). In addition, the

development in performance on more standard planning tasks (e.g., Tower of London and Tower of Hanoi) is discussed.

Prospective motor control is the ability to adapt one's actions to future demands or action goals (von Hofsten, 1993). Generally, it is assumed that an infant or toddler is able to use prospective motor control if the infant or toddler is able to adjust their actions to a constraint from the outside world before actually touching the target object. An example can be to change the action or action kinematics in response to the size of target object (e.g. a large ball vs a small piece of Lego) or the location of the goal (e.g. a target location that is far vs close).

There is evidence that infants from 7 months of age were able to plan their actions and adapt prospectively to demands in the environment or task. For example, 7-, 9- and 11-month-olds slowed down their reaches towards the end of the movement when reaching for a smaller button compared to a bigger puppet (Zaal & Thelen, 2005). Similarly, both 9- and 13-month-olds adjusted their hand opening prospectively to the size of target object when reaching for different objects (von Hofsten & Rönqvist, 1988). Moreover, 7-month-olds were able to prospectively orient their grasp to match the object's orientation (Witherington, 2005). Furthermore, 9-month-olds were able to adjust the rotation of their hand early in the reach, whereas 5-month-olds were unable to adjust their hand rotation before tactile contact with the object (Lockman et al., 1984).

Actions in everyday life are often made up of more than one segment. Infants do not only grasp the object, but perform another action on it, such as throwing it away. Infants over the age of 10 months were able to prospectively control these multistep actions. Ten-month-olds' action kinematics of the reach towards an object was affected by the infants' consequent action, similar to adults. Infants reached for the ball faster if they are going to throw it (non-precision task) as compared to when they were going to fit it down a tube (precision task). This showed that 10-month-olds were able to plan both consecutive segments of an action in advance (Claxton et al., 2003). Similar findings were reported in toddlers between 18 and 21 months of age comparing performance in a tower building task (precision task) and placing-blocks-in-a-container task (non-precision task) (Chen et al., 2010). Lastly, 14-month-olds were able to adjust their reaching kinematics prospectively based on the difficulty of the next action; specifically, in response to differences in goal size and goal distance. In this study, the peak velocity of the first movement unit was taken as the measure of prospective motor control. The smaller the goal or the longer the distance to the goal, the slower the peak velocity was in the

first movement unit (Gottwald et al., 2017). A movement unit included one acceleration phase and one deceleration phase; the first movement unit was thought to reflect the movement plan before adjustments are applied (Gottwald et al., 2016).

Infants can use multiple sources of information to plan actions prospectively. For example, 14-month-olds can use visual and sensorimotor information about an object to prospectively control lifting actions. When visual information about the weight of an object was absent, infants' sensitivity to sensorimotor information was heightened (Gottwald & Gredebäck, 2015). Infants can also use visual information about the structure of an object, such as rigid hard plastic or soft flexible structure, to select the appropriate grasp in the anticipation of grasping that object (Barrett et al., 2008). Finally, children can use their past experience to adapt their actions prospectively. For example, 12-month-olds planned the force of their actions prospectively according to the expected object weight, gained from previous experience of acting on that object (Upshaw & Sommerville, 2015). Furthermore, 9- 12- and 15-month-olds used object experience to anticipate manipulative force on the object prior to contact (Mash, 2007). The use of different types of information to plan actions altered over development. For example, infants between 4 and 8 months of age were able to adjust their grip configuration to adapt for the object properties. However, 4-month-olds would primarily use haptic information, while 8-month-old infants used visually information (Newell et al., 1989).

Toddlers might still struggle to combine their motor and perceptual representations of objects appropriately. Toddlers between 18 and 36 months old demonstrated scale errors; for example, they attempt to slide down a miniature slide. This suggested a dissociation between toddlers' use of visual information for planning and controlling their actions, and a failure of inhibition (DeLoache et al., 2004). Integrating motor and perceptual representations continued to develop over childhood. For example, while young children were able to plan, execute and control appropriate actions to sort shapes in their corresponding openings in a shape-sorting box, adults outperformed the children in terms of speed. Preschoolers showed a delay in adjusting the object to the opening, and this resulted from a delay in looking at the target shape and corresponding openings. This suggested that looking towards the object and target location as the basis for planning actions prospectively is still developing in early childhood (Ossmy et al., 2020).

In short, infants are able to prospectively plan their actions and adapt their actions to the demands of task or environment around 7 months of age. Ten-month-old infants are able to

prospectively control actions that consists of more than one action segment. Fine-tuning of acting abilities still continues until childhood, especially on more complex forms of planning, which evidence this chapter now continues to review.

A more sophisticated type of action planning is *means-end planning*. This is the deliberate execution of sequence of steps to achieve a goal when an obstacle is preventing the achievement of the goal must be first removed (Willatts, 1999). For example, when an infant wanted to reach for a fun toy that is placed out of reach on a cloth, the infant had to pull the cloth first to achieve the goal of grasping the toy. Willatts (1999) showed that the production of intentional means-end actions increased between 6 and 7 months of age. Six-month-olds' actions were unaffected by the presence or absence of toys on the cloth, but 7-month-olds produced more pulling-the-cloth actions when a toy could be retrieved. In addition, 8-month-old infants were able to adjust their means-end actions to the distance of the toy.

Another indication of action planning is *end-state comfort* effect. When adults plan actions, they prefer to perform an awkward but uncomfortable start grip to finish with a comfortable end position. This initial uncomfortable grip that is performed allows for a smooth transition to a more efficient and comfortable end-state position; this provides evidence of planning with the end state in mind. When asking participants to rotate objects around 180 degrees, adults did indeed perform an uncomfortable grip to end in a comfortable end position. The number of grips with end-state comfort increased with age between 3 and 5 years of age (Jovanovic & Schwarzer, 2017). In addition, 2-year-olds were able to adapt their grip prospectively to a comfortable end-state in terms of height, while 3-year-olds were able to adapt their grip to a comfortable end-state in terms of grip type (Jovanovic & Schwarzer, 2011). Furthermore, end-state comfort effect in action planning of the subsequent action became more proficient between 5 and 12 years of age (Krajenbrink et al., 2020).

Eighteen-month-olds already showed the first indication of adjusting hand movements to assure a comfortable hand position at the end of the movement (Jovanovic & Schwarzer, 2011). Similarly, if a spoon with food was placed with the handle oriented either left or right, 19-month-olds were able to anticipate the orientation of the spoon with food, and used the hand most appropriately for the orientation of the handle. This provided evidence of planning of the grasping action. However, 14-month-olds corrected the movement, but did not anticipate the orientation and reached with their preferred hand, showing an intermediate stage. In contrast,

9-month-olds often corrected their action after the spoon has reached the mouth and always reached with their preferred hand (McCarty et al., 1999).

End-state comfort can also be used to investigate tool-use development. For example, a hammering study showed an increase in the use of end-state comfort in tool-use over childhood from 4 to 12 years of age (Comalli et al., 2016). Furthermore, 4-year-olds were shown to be in a transitional stage during which several different strategies were exhibited in a single session (Comalli et al., 2016). When toddlers were asked to use a tool to retrieve a target object, 2-year-olds did not adapt their actions to goal-related information. In contrast, 3-year-olds adjusted their actions to the goal state of the target object (Cox & Smitsman, 2006a). The way that the toddlers used a tool to retrieve the object was not determined by its starting location or orientation relative to the object (Cox & Smitsman, 2006b).

While means-end planning develops in infancy, more sophisticated types of planning develops in toddlerhood and early childhood, such as end-state comfort effect and tool use. Standard lab-based tasks that were initially developed for use with adults, have also been used to investigate the development of planning across childhood. The Tower of Hanoi (Simon, 1975) or the Tower of London (Shallice, 1982) tasks, were originally developed in the 1970's and 1980's. The Tower of Hanoi task involves three pegs, and disks of different sizes. Participants were instructed to move the disks in order to reach the goal state in as few moves as possible. They have to take into account that only one disk can be moved at a certain time, that only the top disk from a peg can be moved, and that no larger disk can be placed on top of a smaller disk (Simon, 1975; Figure 1.5). The Tower of London task is similar, but the disks (or balls) are now from the same size, and there is the constraint that the pegs have a maximum number of disks possible (Cooper & Marsh, 2016; McCormack & Atance, 2011; Shallice, 1982; Figure 1.5).

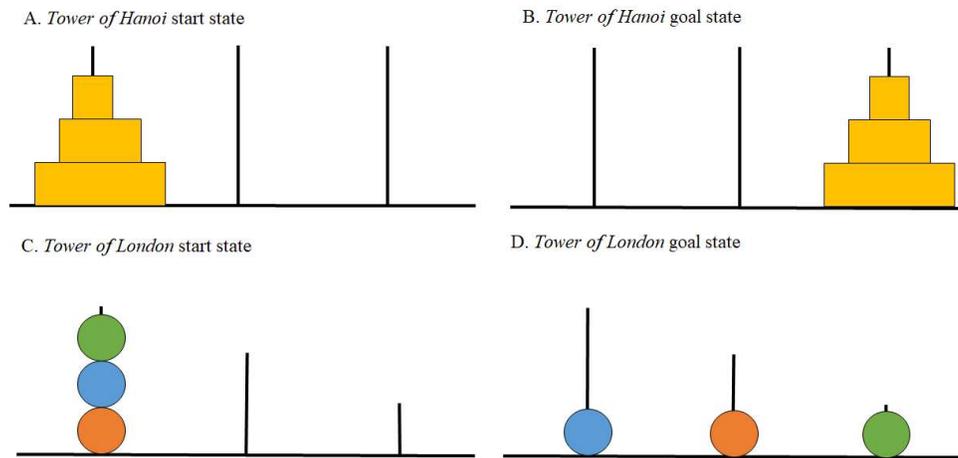


Figure 1.5. Examples of the start state (A) and the goal state (B) of the Tower of Hanoi task, and the start state (C) and the goal state (D) of the Tower of London task.

In this type of task, moves have to be planned ahead and the consequences of each moves should be anticipated (McCormack & Atance, 2011). Performance on the Tower of Hanoi problems improved with age; with increased age, children were able to solve longer multistep problems (Spitz et al., 1982). Similarly, using a child-friendly variant of the Tower of Hanoi task, about half of the 4-year-olds were able to plan a 3-move problem successfully, whereas most 5-year-olds and nearly all 6-year-olds were able to plan for a 4-move problem. Lastly, half of the 6-year-olds were able to plan a 6-move problem successfully (Klahr & Robinson, 1981).

In short, in their first year of life, infants obtain prospective motor control. Means-end planning develops at the end of this first year as well. End-state comfort effect and tool use improve over toddlerhood and preschool period. Lastly, performance on tower tasks involving multiple action steps improves also over preschool period. But what about action sequences? The next section will describe the development of imitation, verbal planning and execution of action sequences.

Imitation is of fertile means of learning for infants, toddlers and children. Toddlers in their second year of life can imitate simple action sequences consisting of two or three actions (Bauer & Hertsgaard, 1993; Bauer & Mandler, 1989; Bauer & Shore, 1987; Bauer & Thal, 1990). Infants as young as 11 months old were able to imitate two action step sequences depicting both familiar and novel events (Bauer & Mandler, 1992). This ability improved over toddlerhood, enabling toddlers to imitate longer action sequences and allow for more time

between demonstration and imitation (Bauer & Mandler, 1989; Bauer & Shore, 1987; Bauer & Thal, 1990).

Imitation is guided by goals in childhood (Bekkering et al., 2000). Remembering the exact order of action steps in action sequence imitation was of low cognitive priority in both children (Loucks & Price, 2019) and adults (Loucks et al., 2020). Instead, action sequence imitation followed canonical hierarchical goal structure scripts as early as from the preschool period. For example, 3-year-olds did not differ in how they imitated intact goal sequences as compared to interleaved sequences (i.e. with actions from one goal interwoven with actions from a distinct second goal). Thus, the two action sequences were represented similarly according to the goal hierarchy (Loucks et al., 2017; Loucks & Meltzoff, 2013).

However, the ability *to follow* (and not just to represent in memory) the hierarchical goal structure in action sequences increased between 3 and 5 years of age. Older children imitated the hierarchical goal structure more faithfully than younger children, but there were no age improvements in imitation of specific action steps (Flynn & Whiten, 2008). Furthermore, 3-year-olds were more likely to re-enact an action irrelevant to the hierarchical goal structure of making a sandwich than 5-year-olds, demonstrating that 3-year-olds were poor at identifying the goal-relevant versus goal-irrelevant information in action sequences (Freier et al., 2015).

Imitation studies have provided evidence that fledgling hierarchical goal representation is already present in 3-year-olds (Loucks et al., 2017; Loucks & Meltzoff, 2013; Whiten et al., 2006), but these hierarchical goal representation or the ability to plan and control actions according to these representations is still developing over the preschool period (Flynn & Whiten, 2008; Freier et al., 2015; Yanaoka & Saito, 2019). This idea is consistent with the notion of *graded goal representation*, which suggests that goal representations become gradually stronger over development (Munakata, 2001).

Some researchers have investigated whether preschoolers can produce verbal plans for routine action sequences (Hudson et al., 1995; Hudson & Fivush, 1991; Shapiro & Hudson, 2004). With increasing age, young children were able to verbally generate plans for familiar events such as grocery shopping or going to the beach (Hudson et al., 1995). In addition, 5-year-olds were able to produce prevention plans to prevent adverse events from occurring suggesting flexibility in the ability to adapt their goals (Hudson et al., 1995). Furthermore, while 3-year-olds and 4-year-olds were better at carrying out their action plans in a successive condition compared to a simultaneous condition when shopping for a birthday party and for breakfast,

there was no difference in performance between these conditions for 5-year-olds (Hudson & Fivush, 1991). Interestingly, the causal structures in the action sequences did not influence the children's verbal plans, but it did influence the children's execution of these action sequences (Shapiro & Hudson, 2004). All these studies provided evidence for an improvement in the ability to plan familiar action sequences over the preschool years (Hudson et al., 1995; 1997; Hudson & Fivush, 1991; Shapiro & Hudson, 2004).

Lab studies investigating children's ability to execute action sequences have also provided evidence for a development in action sequences. Two-year-olds were already able to learn and reproduce a six-element sequence with moving a cat to different spatial locations (Bremner et al., 2007). However, preschool period is an important period for the improvement in the ability to plan and control action sequences in accordance with a goal hierarchy. For example, when children were asked to take into account both a lower-level goal (i.e. colour all farm animals according to the direction of the arrow) and a superordinate goal (i.e. use each of the three colours equally often) in a drawing task, 3- and 5-year-olds were capable of aligning their action sequence planning according to the lower-level goal. However, only 5-year-olds were able to access and follow the goal at the superordinate level (Freier et al., 2017). As a further example, in a task involving several action steps to dress a doll, 4-year-olds achieved the subgoals rather than maintaining and achieving the main goal. In contrast, 5-year-olds were able to control their action sequence execution based on maintaining the main goal (dress the doll in school uniform) of the hierarchical goal representation (Yanaoka & Saito, 2017).

Furthermore, when executing a familiar action sequence, 5-year-olds showed more errors after a disruption in the middle of a subtask than after disruptions at the end of the subtask (Yanaoka & Saito, 2019), suggesting that they organise action sequences into goals and subgoals like adults (Botvinick & Bylsma, 2005). In contrast, 4-year-olds showed similar error rates as a result of interruptions occurring either within or between subtasks, suggesting that they were not organising these in terms of goals and subgoals (Yanaoka & Saito, 2019). Lastly, preschoolers were reported to show *goal neglect* relatively often. They failed to execute the task according to the main goal, despite showing and understanding and remembering of this goal (Blaye & Chevalier, 2011; Chevalier & Blaye, 2008; Marcovitch et al., 2007, 2010; Yanaoka et al., 2020).

In summary, the ability to plan and control action sequences according to a hierarchical goal structure develops throughout the preschool years. While 5-year-olds were able to

accommodate their action sequence planning and execution according to the hierarchical goal structure of the task, like to adults, 3- and 4-year-olds experienced problems in maintaining the highest level goal in action sequence planning (Freier et al., 2017; Yanaoka & Saito, 2017; 2019).

Yanaoka and Saito (2021) suggested that the two critical aspect of action sequences developing over preschool years are: (i) the ability to flexibly change contextual representations, and (ii) the ability to detect conflicts with the hierarchical goal representations. The ability to flexibly change actions developed over preschool period, as reflected in the susceptibility to interruptions in 5-year-olds (Yanaoka & Saito, 2019; 2020; 2021). In addition, there was evidence that young children gradually develop a system helping them to detect conflict with a goal (Freier et al., 2015; Loucks & Meltzoff, 2013; Yanaoka & Saito, 2017, 2020).

An extensive literature has demonstrated that infants are able to prospectively plan simple one or two step actions. The ability to plan and control more complex actions develops over toddlerhood and preschool period, such as the ability to plan and control action sequences. But what mechanisms underlie these improvements? The next section will investigate three potential underlying mechanisms – improvements in causal reasoning, executive functions and motor competence.

1.4 Cognitive processes related to action planning

1.4.1 Causal reasoning

Planning actions with the aim to manipulate the world around us involves causal reasoning (Frye et al., 1996). Children must understand the causality of physical effects in the world (i.e. if your hand pushes a ball, the ball will move) to select and perform the correct action to cause these events in the world (Frye et al., 1996). There is now a wealth of evidence showing that preschoolers are able to construct representations of causal relationships among events (e.g. Gopnik et al., 2001; Shultz, 1982; Sobel et al., 2004). For example, if children were presented with a novel ‘blicket detector’ machine for which some objects but not others made the machine work, young children took this information into account in their causal judgement about which object would make the machine work (Gopnik et al., 2001). For example, if object A activated the machine, and object B did not, we would conclude that if the combination A and B made the machine work that this would be because of object A. There were some developmental improvements in causal reasoning found between 3- and 4-year-olds (Shultz, 1982; Sobel et al., 2004).

Similarly, 24-month-old toddlers were able to make these causal inferences about which objects activate the machine, however, children younger than 2-year-olds lacked the ability to make these causal inferences (Sobel & Kirkham, 2006). Moreover, in an anticipatory eye-tracking paradigm, infants of 8 month old showed causal inferences similar to 24-month-olds and preschoolers (Sobel & Kirkham, 2007). Lastly, the same rules might underlie executing causal actions as well as predicting causal actions, suggesting that action and causal inferences in preschool period are related (Frye et al., 1996).

In sum, prior research has demonstrated that by 24-month-olds, toddlers have developed an appropriate causal interference abilities to allow them to execute actions. This thesis therefore assumes that all participants tested (between 2 and 6 years of age) have suitable causal understanding to support their action sequence planning, selection and execution. Therefore, improvements in causal reasoning are not a primary driver of improvements in action sequences in preschool period. The next section explores whether improvements in executive functions might be a mechanisms for improvements in action.

1.4.2 Executive functions

It remains unclear what exactly drives the improvements in the control of actions and action sequences over infancy, toddlerhood and preschool period. It has been suggested that working memory, set shifting and inhibition could underlie planning development (McCormack & Atance, 2011; Yanaoka & Saito, 2021). These three abilities are commonly considered as the core aspects of executive functions (EFs). EFs are cognitive processes that regulate a person's goal directed-behaviour (Barkley, 2012; Miyake & Friedman, 2012). Planning is often considered a more complex and higher-level EF skill that is likely to be dependent on all three core aspects of EFs (working memory, inhibition and set shifting; Figure 1.6) (Diamond, 2013; Downes et al., 2017; McCormack & Atance, 2011; Miyake & Friedman, 2012).

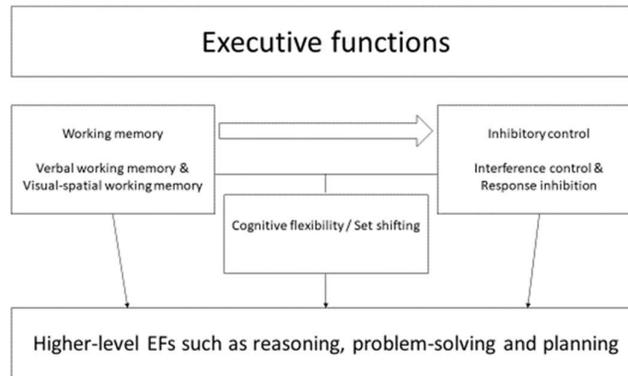


Figure 1.6. Relations between different core aspects of executive functions. Figure adapted from *Executive Functions* (page 152) by A. Diamond, 2013, *Annual Review of Psychology*, 64(1), 135-168.

In adulthood, inhibition, set shifting and working memory are distinct but related aspects of EF (Miyake & Friedman, 2012). This means that these three core aspects are correlated but functionally separated (Miyake & Friedman, 2012). This distinction into three separate but related core aspects of EF was not as clear in infancy (Hendry et al., 2016), although several studies have detected separable components in 2- and 3-year-old children (Garon et al., 2014; Skogan et al., 2016). The structure of the three core components of EF was not completely clear until 7 years of age (de Haan, 2013). There is a debate whether core EF components are functionally dissociated in the early preschool period with conflicting evidence have been reported (de Haan, 2013; Garon et al., 2014; Hendry et al., 2016; Skogan et al., 2016). Nevertheless, this thesis takes a standard approach of using different tasks to measure different components of executive functions while remaining fully aware that there is never a pure task to assess a component, and that these components might still not be fully separate during the preschool years.

The core components of executive functions have a foundation early in life (Downes et al., 2017). As it has been suggested that the first 5 year of life are critical in the development of EFs (Garon et al., 2008), thus the development of EFs is a strong candidate for explaining the development in action planning and selection in this period. Consequently, this thesis will explore how the three core components of executive functions relate to action planning development in preschool years. Each of the core components (working memory, set shifting and inhibition) is discussed in turn below, before moving on to discussing the evidence of the relation between the core components and actions.

Working memory (WM, or working memory updating) is the ability to hold information in mind for a short period of time and mentally manipulate this information if necessary (de Haan, 2013; Diamond, 2013; Miyake & Friedman, 2012). Examples of simple working memory tasks are *delayed response*, and *digit or word span* tasks (Garon et al., 2008). Delayed response tasks involve a hidden object, which the infant or child needs to find after a delay. Evidence suggested that this capacity to hold a representation in mind over a delay developed over the first 6 months of life (Pelphrey et al., 2004; Reznick et al., 2004). Digits or word span tasks require the child to repeat a list of numbers or words correctly. Several studies have provided evidence for the development of this ability across preschool years; the number of different items remembered increased between 3 and 5 years of age (Bull et al., 2004; Espy & Bull, 2005; Gathercole, 1998; 1999).

More complex tasks assessing working memory include the *spinning pots* or *backward digit span tasks*. These tasks not only assess holding information in mind over a delay, but also involve updating and manipulating this information (Garon et al., 2008). The spinning pots task involves a number of pots, some of which contain stickers. Children have to find all stickers, but refrain from re-opening pots they have previously opened. This task is used to assess working memory in toddlerhood (Garon et al., 2008; Hughes & Ensor, 2005, 2006). Backward digit span tasks require children to repeat a list of number or words backwards. The ability to update this digit or word list improved over preschool period (Carlson et al., 2002; Marcovitch et al., 2010).

Set shifting is the ability to shift attention between different tasks and mental sets (de Haan, 2013; Diamond, 2013; Miyake & Friedman, 2012). Set shifting can be divided into *response* and *attention shifting* (Garon et al., 2008). Response shifting is the ability to shift from an arbitrary stimulus-response pair to a new arbitrary stimulus-response pair (Garon et al., 2008). Examples of tasks assessing response shifting are the *A-not-B task* (Diamond, 1985; Garon et al., 2008) or the *trucks game* (Hughes & Ensor, 2005, 2006). The widely investigated A-not-B task involves a child looking for a reward hidden at location A for a number of consecutive trials. In the next trial, the object is hidden at location B, and whether the child is able to shift their search from location A to location B is assessed. Performance improved over the first year of life and through preschool period (Cuevas & Bell, 2010, Espy et al., 1999; Thelen et al., 1991). The trucks game involves shifting from receiving a reward (i.e. a sticker) when pointing to one truck in the first phase to receiving the reward when pointing to the other truck. This

task is used to assess shifting in toddlerhood and early preschool period (Hughes & Ensor, 2005, 2006).

Attention shifting involves shifting mental attention to another aspect of the stimuli (Garon et al., 2008; Peng et al., 2018). Probably the most famous task to assess attention shifting is the *Dimensional Change Card Sorting* (DCCS) task. A child is shown cards with stimuli that differ in two dimensions: colour and shape. The cards can be sorted either according to colour or according to shape. First, the child has to sort the card according to one dimension, for example colour. Next, the child has to shift sorting to the other dimension, for example shape (Frye et al., 1995; Garon et al., 2008; Zelazo, 2006). Most 3-year-olds can sort the cards according to one dimension rule, but they cannot shift their sorting to adjust to a new dimension rule. However, children older than 4 years were able to shift their sorting behaviour to the new dimension rule (Frye et al., 1995; Kirkham et al., 2003; Zelazo et al., 1996, 2003).

Inhibition is the ability to control one's attention, behaviour, thoughts, and/or emotions to override a strong internal predisposition or an external temptation (de Haan, 2013; Diamond, 2013; Miyake & Friedman, 2012). Inhibition is also sometimes called *response inhibition*: the ability to suppress a prepotent response. Simple (response) inhibition, the ability to suppress a dominant response, developed in the first year of life and improved over toddlerhood. For example, when children were instructed to not touch an attractive toy, their latency to touch increased with age over toddlerhood (Friedman et al., 2011). Examples of tasks that assess simple response inhibition are *delay paradigms* and *don't paradigms* (Garon et al., 2008). In don't paradigms, infants or children are required to inhibit a prepotent response by, for example, not touching an attractive toy. This ability improved over infancy, toddlerhood and preschool years (Garon et al., 2008; Kochanska & Aksan, 1995; Kochanska et al., 2008; Miyake & Friedman, 2012). In delay paradigms, children have to wait or choose for a larger delay to get a bigger reward (Carlson, 2005; Garon et al., 2008; Mischel, 1974), and this ability also improved over preschool period (Carlson, 2005; Garon et al., 2008).

Complex (response) inhibition involves holding a rule in mind, inhibiting a prepotent response and acting according to the rule in mind (Garon et al., 2008). Examples of complex inhibition tasks are the child-friendly version of *go/no-go task* (Drechsler et al., 2010; Kaller et al., 2008; Sobeh & Spijkers, 2013), *day-night-like task* or *less-is-more task* (Garon et al., 2008). The less-is-more task involves asking children to point one of the two trays with either more or fewer rewarding items. Children will receive the tray that they do not point towards. Three-year-olds

failed this task (Garon et al., 2008; Lemmon & Moore, 2007), but the capacity to complete this task successfully developed over preschool years (Lemmon & Moore, 2007; Moriguchi & Shinohara, 2019). Day-night tasks involve children having to say *night* to a card with the sun, while saying *day* to a card with the moon. Children improved their performance on this type of task between 3 and 5 years of age (Diamond et al., 1997; Garon et al., 2008). Child-friendly Go/No-go inhibition tasks are similar to those used in adults; one stimulus (that occurs most often) requires a response, whereas another stimuli (that occurs rarely) requires the participant to inhibit that prepotent response. Again, children improved on this inhibition task as they get older (Kaller et al., 2008).

Importantly, working memory, set shifting and inhibition are all skills that improve dramatically over infancy, toddlerhood and especially preschool period (Anderson & Reidy, 2012; Diamond, 2013; Garon et al., 2008). There is already some evidence that EFs are related to simple action planning in infancy and toddlerhood. For example, prospective motor control as measured by the peak velocity of the first movement unit was shown to be related to working memory and simple inhibition in 18-month-old infants (Gottwald et al., 2016).

Similarly, inhibition and working memory were related to a motor planning task in children between 4 and 7 years of age. In this planning task, children had to plan their actions to move eggs as efficient as possible from boxes to the basket. The task required inhibition as suppression of prepotent, inappropriate response, and working memory was involved in manipulation of strategies (Pennequin et al., 2010). Moreover, motor performance of 5- and 6-year-olds was also related to response inhibition (Livesey et al., 2006). Furthermore, inhibition was important for strategic motor control in a motor problem-solving task (DeMasi & Berger, 2021). Lastly, working memory and inhibition have been found to be related to goal neglect in DCCS task in preschoolers (Marcovitch et al., 2007, 2010).

It is also hypothesised that planning on Tower planning tasks relies on EFs. For example, in adults, Tower of London performance was significantly reduced when participants had to complete a set shifting secondary task at the same time. This suggests that set shifting could be the critical EF skill underlying Tower of London performance in adults (Cooper & Marsh, 2016). Similarly, in children around 4 years of age, performance on a task assessing set shifting predicted performance on the Tower of Hanoi task. However, none of the EF tasks was related to performance on the Tower of London task in this young age group (Bull et al., 2004). This

latter results suggests that these tasks cannot be used interchangeable when studying planning in young children.

Furthermore, inhibition and working memory predicted Tower of Hanoi performance in young children. Here, inhibition was the strongest predictor for performance in younger children, while working memory was the strongest predictor in older children (Senn et al., 2004). In contrast, neither inhibition, nor working memory accounted for performance in a variant of the Tower of London task in 4- and 5-year-olds (Kaller et al., 2008). In addition, Tecwyn and colleagues (2014) found no relationship between inhibition and problem-solving in 4-year-olds using a variant of the tower task. In sum, while there is straightforward evidence for the involvement of EFs in simple action planning in infants and children, there is conflicting evidence for the relation between EFs and planning performance on the Tower of London and the Tower of Hanoi task in young children.

There is some evidence that EFs are related to action sequence planning in preschool years. For example, preschoolers with better set shifting abilities showed a more adult-like pattern after disruptions in routine action sequences. This indicated a relationship between action sequence representations and EFs (Yanaoka & Saito, 2019). Moreover, inhibition abilities were associated with the control of scripted action sequences (Yanaoka & Saito, 2017). However, there is no evidence of specific effect of each of the EF core components on planning and control of action sequences.

In summary, this section showed that the three core components of EFs (working memory, set shifting and inhibition) develop greatly over preschool years, making them a strong candidate for explaining the development of action sequence in this age. There is already some evidence for an association between EFs and action sequences in children. The next section explores whether improvements in motor competence might play a role in driving action improvements in action planning in infancy, toddlerhood and preschool years.

1.4.3 Motor competence

Infancy, toddlerhood and early childhood are critical times in the development of fundamental motor skills. These fundamental fine and gross motor skills are the building blocks of more complex movements (Lopes et al., 2020, Malina, 2004). Motor competence, the ability to coordinate and execute different fine and gross motor actions, is essential for action planning, selection and execution. Motor competence or proficiency in movements involves interactions between the neurovascular system and the environment (Lopes et al., 2020).

Motor competence is the term that is used to refer to an individual’s ability to coordinate and execute different motor actions, including both fine and gross motor skills (Lopes et al., 2020). Fine motor skills are the skills that control small movements like reaching and grasping, while gross motor skills are the skills that control less refined, larger movements like crawling, standing and walking (Ali et al., 2017; Matheis & Estabillo, 2018). Gross motor skills involve the coordination of arms, legs, and/or other large body parts, while fine motor skills involve coordination of fingers, hands or feet (Ali et al., 2017; Matheis & Estabillo, 2018). But how do these fine and gross motor skills that support acting develop in the first six years of life?

Although motor development is generally uniform, infants, toddlers and children develop in different rates and different ways. This is influenced by external factors such as environment, experience, and culture, or internal factors such as growth and genetics (Ali et al., 2017; Berk, 2017; Boyd & Bee, 2019; Sundaram & Siddegowda, 2013; Thelen & Smith, 1994; Thelen et al., 2001).

In infancy, motor development is often assessed with gross motor milestones that typically progress in a sequential order within a certain timeframe (Matheis & Estabillo, 2018). However, variations and occasional omissions are possible (Malina, 2004). For example, infants typically sat without support between 4 and 9 months of age, while walking alone developed between 8 and 18 months of age (WHO Multicentre Growth Reference Study Group & de Onis, 2006; Figure 1.7). The motor development usually followed a pattern from head to toe; control over head developed before manual reaching, which in turn developed before walking (Adolph & Joh, 2007).

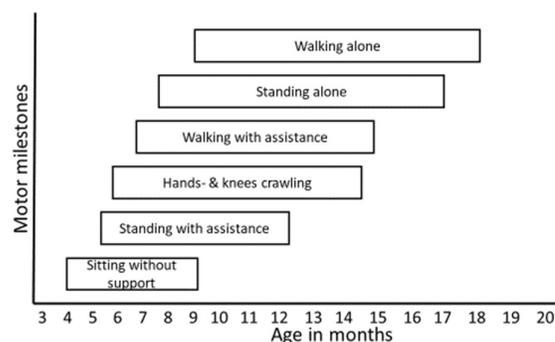


Figure 1.7. Windows of typical achievement from the six gross motor milestones in months over the first 2 years of life. Figure adapted from WHO Motor Development Study: Windows of achievement for six gross motor development milestones (page 92) by WHO Multicentre Growth Reference Study Group & M. de Onis, 2007, *Acta Paediatrica*, 95, 86-95.

The onset of manual actions likewise lies in infancy. The first spontaneous manual behaviours occurred even before birth (de Vries et al., 1986). These spontaneous arm movements continued after birth and in the first year of life (Adolph & Joh, 2007). The first goal-directed reaches appeared around a few months of age, first while lying on the back, and later while sitting (Adolph & Joh, 2007; Boyd & Bee, 2013; Rochat, 1992). Postural control was important in the development of reaching (Bertenthal & von Hofsten, 1998). Around the onset of sitting without support, infants were able to coordinate manual and visual exploration. For example, they can rotate or transfer objects from one hand to another (Rochat, 1989). Sitting abilities even predicted exploration behaviour with objects (Rochat & Goubet, 1995).

If the infant was supported, infants began to reach for stationary objects around 12 to 18 weeks of age (Berthier & Keen, 2006; Clifton et al., 1993) and to moving objects around 18 weeks (von Hofsten, 1980; von Hofsten & Lindhagen, 1979). First reaches often ended in object contact, but not successful capture of the object (Adolph & Joh, 2007) and these early reaches were often jerky and might be corrected. The reaches became smoother and straighter until around 31 weeks of age, when infants' reaches looked like adults' reaches (von Hofsten, 1991). Regarding their fine motor skills, first, infants used a clumsy *ulnar* grasp, in which the fingers close against the palm. Around 9 months of age, infants were able to use their thumb and index finger in a more precise *pincer* grasp (Berk, 2017).

Both fine and gross motor skills continued to develop in toddlerhood (Berk, 2017; Boyd & Bee, 2013; Colson & Dworkin, 1997). Regarding gross motor skills, toddlers improved their walking, running, jumping, climbing and hopping skills (Berk, 2017; Boyd & Bee, 2013; Colson & Dworkin, 1997; Ivanenko et al., 2007). Furthermore, fine motor skills improved over this period (Berk, 2017, Boyd & Bee, 2013; Colson & Dworkin, 1997). For example, toddlers refined their reaching, grasping and manipulating of objects. While 18-month-olds were able to build a tower of four cubes, 24-month-olds could build a tower of six or seven cubes, and 36-month-olds were already able to build a tower of nine or ten blocks (Colson & Dworkin, 1997). Furthermore, toddlers also improved their motor control of drawing with a pencil, starting with spontaneously scribbling around 18 months of age. By 36 months of age, toddlers were able to correctly hold the pencil and draw primitive figures (Berk, 2017; Colson & Dworkin, 1997).

In childhood, children learned more complex movement patterns building on existing motor skills (Ali et al., 2017). Furthermore, this period was important for further development of

stability, gross motor skills like improvements in running, hopping, climbing, catching and throwing skills, and fine motor skills like sewing large stitches, drawing and threading a bead (Berk, 2017; Boyd & Bee, 2013; Cardon et al., 2011; Malina, 2004).

In short, motor competence, the ability to control one's movement, improves dramatically in infancy. In toddlerhood, the motor competence underlying manual actions might still improve, but this motor competence is present in preschool years. Especially in toddlerhood, motor competence might limit or impair toddlers' manual acting. Thus, it is unlikely that improvements in motor competence are a primary driver of improvements in action planning on the preschool years. The subsequent section will change geared a little and ask what brain areas are necessary to support acting and how do these functional systems develop.

1.5 Neural mechanisms of actions

This section will provide a broad overview of the underlying neuroscience of actions, focusing on developmental work. Planning, selecting and executing involves several brain areas connecting underlying actions. It has been hypothesised that these three interconnected processes involve different, but connected underlying networks (Shallice & Cooper, 2011). For example, an fMRI study asked adults to either passively observe a grasp target, plan a grasp movement without executing it, plan and then execute a grasp or immediately executed a grasp. The planning network consisted of the *premotor cortex*, *basal ganglia*, *anterior cingulate*, and *dorsolateral prefrontal cortex*, while the control network involved in execution of actions consisted of the *sensorimotor cortex* including motor cortex, and the *cerebellum* (Glover et al., 2012). This suggests that different networks are involved in planning, selecting, and executing and controlling an action.

The network involved in planning a simple grasp action consisted of *premotor cortex*, *basal ganglia*, *anterior cingulate*, *dorsolateral prefrontal cortex*, *medial parietal area*, *parietal occipital cortex* and *middle intraparietal sulcus* (Glover et al., 2012; Figure 1.8). The dorsolateral prefrontal cortex seems to be especially important in the planning of such actions. Planning impairments were associated with lesions in right dorsolateral prefrontal cortex (Burgess et al., 2000). Furthermore, the dorsolateral prefrontal cortex was activated in an fMRI event-related study during the planning of tool-use actions (Johnson-Frey et al., 2005). All the other areas activated during planning, such as the temporal sulcus, frontal and ventral premotor areas, supramarginal gyrus and angular gyrus, were also activated during the execution of these tool-use actions (Johnson et al., 2005). Lastly, a study involving the Tower of London task in

a PET scanner showed evidence for the involvement of the dorsolateral prefrontal cortex, lateral premotor areas, anterior cingulate and caudate areas in the planning of movement (Dagher et al., 1999).

While this section focuses on the (dorsolateral) prefrontal cortex involvement in action planning, it should be emphasised that this is not the only area considered to be involved in action planning. For example, the premotor cortex was thought to be involved in the integration of target and motor information (Hoshi & Tanji, 2000) and transferring the action plan into motor parameters (Nakayama et al., 2008).

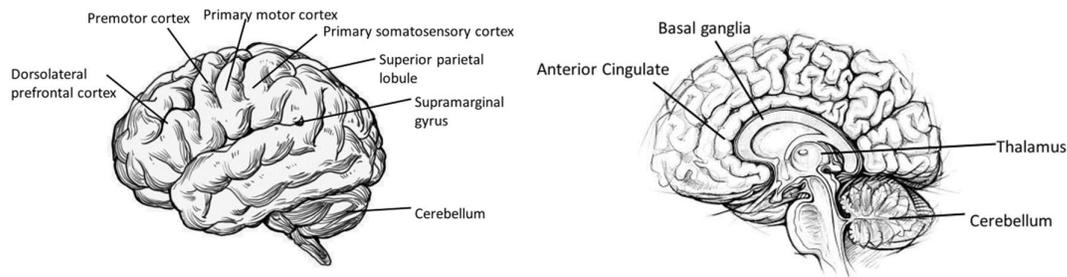


Figure 1.8. Brain areas implicated in action planning, action selection, and action control and execution. Both a whole brain view (left) and a sagittal view of the brain (right) are displayed.

The prefrontal cortex is not only considered to play an essential role in action planning, but also in other higher cognitive function such as reasoning, working memory and inhibition (Diamond, 2013; Tsujimoto, 2008). Importantly, improvements in executive functioning in preschool years have been linked to prefrontal cortex development (e.g. Diamond, 2013; Moriguchi & Hiraki, 2013). While there was behavioural and anatomically evidence, more recently functional near-infrared spectroscopy provided direct evidence for the functional development of the prefrontal cortex and its relation to EFs in childhood (Moriguchi & Hiraki, 2013).

For example, stronger ventrolateral prefrontal cortex activation in children was associated with successful performance in the less-is-more task (i.e. children pointed to the smaller reward to receive the larger reward; Moriguchi & Shinohara, 2019). Furthermore, activation in inferior prefrontal cortex areas was related to successful shifting in the DCCS task (Moriguchi & Hiraki, 2009, 2011). Moreover, activation in the right dorsolateral prefrontal cortex was associated with successful avoidance of goal neglect in the DCCS task, providing evidence that this area was involved in successful goal maintenance (Yanaoka et al., 2020). Lastly, increasing

recruitment of the prefrontal cortex as function of cognitive control demands (i.e. more prefrontal cortex activation if the control demands are high compared to if the control demands are low) improved with age (Chevalier et al., 2019).

Furthermore, there is anatomical evidence for a change in the prefrontal cortex in infancy and early childhood. The dorsolateral prefrontal cortex developed dramatically both in the first year of life in terms of growth in length and extent of dendritic branches of the neurons (Diamond, 2002) as well as between 2 to 7 years of age in terms of neural density (Diamond, 2002). This coincided with a period of rapid development in executive function and could therefore also underpin improvements in action and action sequence planning at these ages. Of course, other functional areas will also be involved in action planning and may show a different developmental timelines.

It has been suggested that the *basal ganglia – prefrontal cortex loops* are involved in action selection (e.g. Chevalier & Deniau, 1990; Haber & Calzavara, 2009; Hazy et al., 2011). The basal ganglia receives input from the neocortex and its output projects back to the frontal cortex via thalamic nuclei (Graybiel, 2000). This basal ganglia-frontal cortex systems consists of multiple parallel loops from the frontal cortex to the striatum, which itself consists of the *caudate nucleus*, *putamen* and *nucleus accumbens*. The projections from the *striatum* continue to the *globus pallidus* (internal segment; *GPI*) to the *substantia nigra* (pars reticulata; *SNr*). From there, these projections move on to the *thalamus*, and finally projecting back to the frontal cortex (Frank et al., 2001; Figure 1.9).

These loops constitute an inhibitory gating mechanisms on the projections from striatum to *GPI* and *SNr* and from *GPI* and *SNr* to *thalamus*. In addition, neurons of the *GPI* and *SNr* are tonically active resulting in that the *thalamus* is inhibited in absence of any other activity. In consequence, striatal neurons fire in order to disinhibit the thalamic neurons (Frank, 2011, Frank et al., 2001; Leisman et al., 2014; Redgrave et al., 2010).

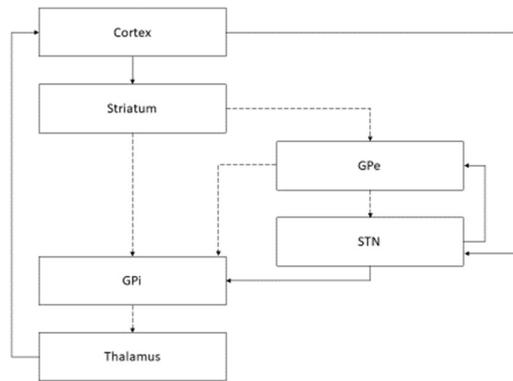


Figure 1.9. Schematic representation of prefrontal cortex - basal ganglia loops. Inhibitory connections are displayed with dotted lines, while excitatory connections are displayed using black lines. Figure adapted from *A computational model of action selection in basal ganglia. I. A new functional anatomy* (page 403) by K. Gurney, T. Prescott, & P. Redgrave, 2001a, *Biological Cybernetics*, 84(6), 401-410.

This disinhibition of the thalamus provides a gating function, enabling other functions to take place but it does not cause them to occur. It has been widely suggested in literature that this gating function is involved in initiating motor movements, while the frontal cortex is involved in motor action planning. The basal ganglia is often seen as releasing the break on the frontal cortex to initiate a movement (Chevalier & Deniau, 1990; Haber & Calzavara, 2009; Hazy et al., 2011). For example, a recent biologically plausible computational model of the basal ganglia has shown that action selection in the Wisconsin Card Sorting Task can be explained by the performance of these basal ganglia – prefrontal cortex loops (Caso & Cooper, 2020).

Very little is known about the development of the basal ganglia in humans (Nelson & Luciana, 2008). One study found a decrease in volume of the basal ganglia with age, providing evidence that this subcortical structure appears not to be fully developed in childhood (Wierenga et al., 2014). In short, the basal ganglia is essential for action selection, however, the influence of its development remains unknown. This point will be revisited more thoroughly in Chapter 5.

The action control network for a simple grasping action involves the *sensorimotor cortex* including the motor cortex, *cerebellum*, *supramarginal gyrus* and *superior parietal lobule* (Glover et al., 2012; Figure 1.8). The primary motor cortex (or M1) has the function of producing a specific movements or to execute actions. It has a precise somatotopic representation of different body parts, which is especially fine-grained for muscle areas that

require fine control such as the hand or the face (e.g. Penfield & Boldrey, 1937; Schellekens et al., 2018).

The primary motor cortex is involved in transferring the neural information of action plans which are generated in other frontal areas to expressions in the muscles. The primary motor cortex is an essential part of the network for action execution, where the primary and secondary motor cortices, and sensory and association areas together result in planning and execution of coordinated actions (Stippich et al., 2017). Activations from the primary motor cortex are transferred via the corticospinal tracts to muscles for execution (von Wittenberghe & Peterson, 2020). There is plasticity in the primary motor cortex; better practiced movements were better represented at the primary motor cortex (Sanes & Donoghue, 2000).

The exact development of the somatotopic representation of the primary motor cortex and the associated connections remains unclear, but it is generally assumed that these are developing or already in place in early infancy. For example, a study using fNIRS reported that by the end of the first year of life, infants showed a shift from diffuse activity to more refined as the action experience increased for actions such as reaching and stepping (Nishiyori et al., 2016). Therefore, by toddlerhood and early childhood, the underlying structures for actions should be in place in the primary motor cortex, although further change is still possible in response to differential experience and changes in body morphology.

The cerebellum is involved in correcting ongoing movement (Allen & Tsukahara, 1974; Paulin, 1993). For example, cerebellar patients showed no correction of movement errors (Therrien & Bastian, 2019). It has been proposed that the cerebellum compares the instructions of the intended movement to actual movement feedback (Therrien & Bastian, 2019). The movement correction information is then forwarded to the thalamus, and then the motor cortex to correct the movement (Pelzer et al., 2017).

In summary, this broad brushed overview of the neuroscience of actions reveals that the dorsolateral prefrontal cortex (among other regions) plays an important role in action planning. In turn, the basal ganglia loops provide a gating function allowing actions to be selected, and the primary motor cortex among other areas is involved in action execution. The cerebellum allows for movement correction. In the next section, a short overview of the methods used in the thesis will be given.

1.6 Overview of the key methods used throughout the dissertation

Several different methods are used in the different chapters of this thesis. These methods are chosen because of their suitability for answering questions asked and their suitability for use with our target age group. This section will give a short overview of behavioural studies (Chapter 2, 3 and 4), motion capture (Chapter 3 and 4), functional near-infrared spectroscopy (Chapter 4) and computational modelling (Chapter 5) with respect to studying action sequences in preschoolers. Specific details relevant to the studies in this thesis are reported in the individual chapters.

1.6.1 Behavioural studies

Behavioural paradigms are an important method to investigate the development of young children's behaviour (Purser & van Herwegen, 2016). Already since the 1950s, behavioural studies play an important role to examine developmental change in cognitive functions (Johnson & de Haan, 2015). However, comparing performance across studies with methodological differences can be difficult. For example, explicit versions of the verbal false belief task showed a different performance pattern than implicit versions of this task, while both were assumed to assess Theory of Mind (Oktay-Gür et al., 2018). Furthermore, the specific link between static laboratory tasks and everyday behaviour is still elusive. One of the key challenges in developmental neuroscience is also to leave behind the traditional laboratory and investigate behaviour in more naturalistic settings (Dahl, 2017).

Behavioural studies in young children can be associated with a number of challenges. Tasks have to be age-appropriate, but avoid floor and ceiling effects (Purser & van Herwegen, 2016), and be suitable for a wide range of cognitive abilities that preschoolers display. In early childhood, children demonstrate large inter-individual difference in all of their cognitive abilities, such as language, working memory, attention, and motor abilities. Furthermore, motivation is an important aspect of the paradigm; behavioural tasks should be designed to be engaging for the child, and task instructions should be easy to comprehend (Purser & van Herwegen, 2016). Unwillingness to continue is generally one of the main drop-out factors in behaviour studies with preschoolers and young children.

Behavioural methods can be combined with other methods such as neuroimaging methods or motion capture to provide answers to additional questions about underlying processes or mechanisms. For the sake that identical behaviour can result from different mechanism, behavioural measures alone do not provide enough evidence for the hypothesised mechanism.

Multiple methods used simultaneously opens the opportunity to answer questions on different levels. In the subsequent Chapters 3 and 4, motion capture and neuroimaging (fNIRS) are used in combination with behavioural methods to investigate action sequence development. This thesis will now provide a short overview of these two methods – motion capture and functional near-infrared spectroscopy.

1.6.2 Optical motion capture

Motion capture is the process of recording live movement and translating the movement data into a 3D construction of the movement (Rahul, 2018; Yahya et al., 2019). There are several types of motion capture: inertial with accelerometers, gyroscope or magnetometer sensors, magnetic using a magnetic field or optical motion capture (Rahul, 2018; Yahya et al., 2019). The current work focuses on optical motion capture.

An optical motion capture system involves several cameras placed in the space. Several synchronised cameras capture the coordinates of the same object (x and y) from different angles, enabling calculation of coordinates (x, y and z) of this object (Rahul, 2018). The motion capture system can involve active or passive markers (Yahya et al., 2019). Passive markers are made of a retro-reflective surface that reflects the (near-)infrared light that the cameras emit, and are used in the studies reported in this thesis (Figure 1.10).

The high resolution data involves a 3D location for each marker over time, enabling to extract kinematic parameters in time and space domain. Optical motion capture system generally record high frequency data, allowing very precise examination of movements in the time-domain. Examples of derived measures can be trajectories deviation, velocity, acceleration and deceleration, but it can also be used to assess time spent in small pauses in movement.

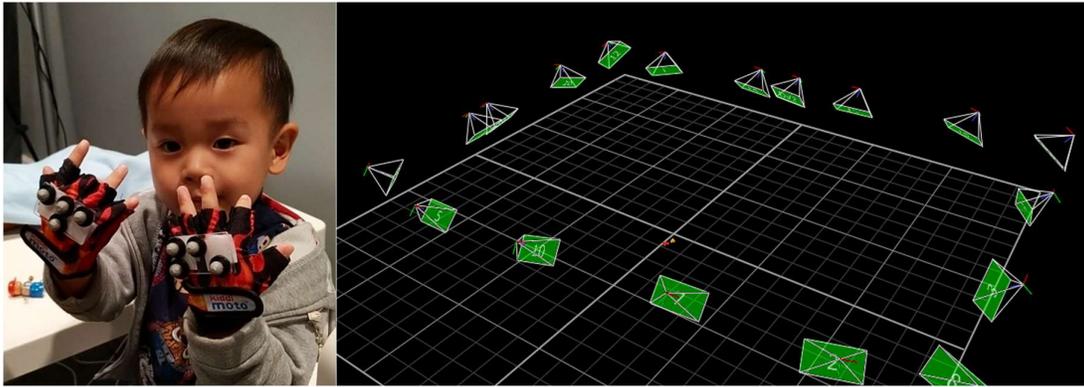


Figure 1.10. Example of optical motion capture gloves used on the left hand side. The right hand shows the gloves markers in red and orange in the 3D motion capture space.

Most of the research using motion capture to investigate development has focused on the development of gait and movement control (e.g. Cowie et al., 2010; Cowie & Pervez, 2016; D'Souza et al., 2017; Gottwald et al., 2016, 2017; Gottwald & Gredebäck, 2015; Kahrs et al., 2014; Möhring et al., 2020; Mowbray et al., 2019; 2020; Mowbray & Cowie, 2020; von Hofsten, 1991; von Hofsten & Rönnqvist, 1988, 1993), or to investigate movement abnormalities in developmental disorders such as cerebral palsy (Davies & Kurz, 2013; Dixon et al., 2016; Klotz et al., 2014; Kurz et al., 2012; Stebbins et al., 2010) or autism spectrum disorder (Crippa et al., 2015; Mari et al., 2013; Taffoni et al., 2019).

Of particular relevance to this thesis is the fact that motion capture techniques can be used to reveal the temporal progression of decisions, which would otherwise remain concealed from the human eye (Freeman et al., 2011; Song & Nakayama, 2009). Reaching kinematics are influenced by dynamic decision processes that occur in parallel both in lower-level (Song & Nakayama, 2006, 2008; Spivey et al., 2005; Welsh & Elliott, 2005) and higher-level processing (Dale et al., 2008; McKinstry et al., 2008) in adults.

Recently, developmental studies have demonstrated the promising prospect to use motion capture to record children's online decision-making processes (Erb et al., 2017, 2018). Magnetic motion capture was used to assess reach curvature and initiation time in the Erikson Flanker task assessing inhibitory control. The results demonstrated that these kinematics were associated with different processes in inhibition (i.e. response threshold adjustment and conflict resolution processes) and that they showed divergent developmental trajectories (Erb et al., 2018). Similarly, motion capture revealed that these two key processes underlying cognitive

control were also demonstrated in initiation time and reach curvature in children's and adult's set shifting (Erb et al., 2017).

In the subsequent Chapters 3 and 4, this approach will be extended by investigating markers in hierarchical action sequences. Optical motion capture can be combined with other methods such as neuroimaging methods. In Chapter 4, a study using optical motion capture and fNIRS simultaneously is described. Next, a short overview of the method fNIRS is given.

1.6.3 Functional near-infrared spectroscopy

Functional near-infrared spectroscopy (fNIRS) is a neuroimaging method that measures changes in haemoglobin concentration in a non-invasive way (Hoshi, 2005). It allows us to measure hemodynamic activation in the neocortex. fNIRS uses near-infrared light (700 to 900 nm) that passes through biological tissue, but it is absorbed by haemoglobin (Hb) (Ferrari & Quaresima, 2012; Hoshi, 2005; Pellicer & del Carmen Bravo, 2011; Pinti et al., 2020). If a specific area of the brain is activated, the blood volume in that specific area changes. Difference in absorption spectra of deoxy-haemoglobin and oxy-haemoglobin (deoxy-Hb or HHb and oxy-Hb or HbO₂ respectively) enables to assess relative change in haemoglobin concentration using two or more wavelengths (Ferrari & Quaresima, 2012; Hoshi, 2005; Pellicer & del Carmen Bravo, 2011; Pinti et al., 2020).

Brain activation changes are characterised by increase in cerebral blood flow resulting in an increase in HbO₂ and an increase in cerebral oxygen metabolic rate resulting in a decrease in HHb. The increase in cerebral blood flow exceeds the increase in cerebral oxygen metabolic rate. Brain activation is characterized by an increase in HbO₂ and a decrease in HHb (Ferrari & Quaresima, 2012; Hoshi, 2005; Pellicer & del Carmen Bravo, 2011; Pinti et al., 2020).

Light emitters and detectors are placed on the skull in the cap (Figure 1.11). fNIRS is the most sensitive to changes in neural activity close to the scalp (Ferrari & Quaresima, 2012; Hoshi, 2005; Pellicer & del Carmen Bravo, 2011; Pinti et al., 2020). The near-infrared light does not penetrate below the neocortex, so this method is unable to detect neural activation in deeper structures of the brain such as the basal ganglia.

fNIRS is easy to use, comfortable to wear and relatively resilient to motion artefacts (Lloyd-Fox et al., 2010; Mehnert et al., 2013; Moriguchi & Hiraki, 2013; Pinti et al., 2020) making it ideal for use with young children. However, traditional systems require the child to be tethered to an amplifier, only able to measure neural activation in static laboratory situations. The arrival

of the state-of-the-art wireless fNIRS systems allows for brain activation to be recorded in more naturalistic situations with freely moving subjects. The new wireless systems are suitable to investigate neural changes in for example action planning.

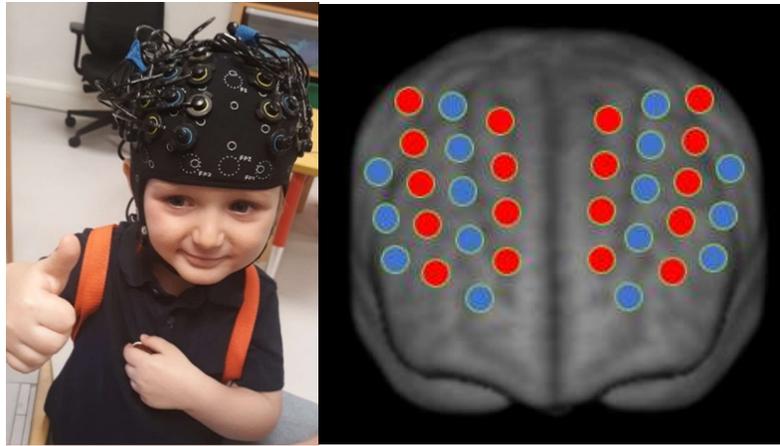


Figure 1.11. Example of a wireless fNIRS cap (left) and the corresponding locations on a brain model (right). The backpack contains the wireless recording device that send the signal by Bluetooth to a computer, allowing the child to move around freely.

fNIRS has been used to investigate a wide range of neural activation in cognitive functions ranging from social cognition to action understand or language in infants, children and adults (for reviews see Butler et al., 2020; Lloyd-Fox et al., 2010; McDonald & Perdue, 2018; Nagamitsu et al., 2012; Pinti et al., 2018, 2020; Quaresima & Ferrari, 2019; Soltanlou et al., 2018; Wang et al., 2020; Yeung, 2021). Furthermore, fNIRS is friendly to use in atypically developing populations, such as autism spectrum disorder (for reviews see Liu et al., 2019; Mazzoni et al., 2019; Zhang & Roeyers, 2019) or in low-resource areas (Lloyd-Fox et al., 2015; Perdue et al., 2019).

Recently, fNIRS has been used to investigate neural changes in prefrontal cortex activation in executive function tasks in preschoolers. For example, (as already described in section 1.5 above) the inferior prefrontal cortex was shown to be involved in successful performance on the DCCS task assessing set shifting in preschoolers and adults (Moriguchi & Hiraki, 2009, 2011). Similarly, multiple studies have used fNIRS to provide evidence for the contribution of prefrontal cortex activation in executive functions in preschoolers (Chevalier et al., 2019; Mehnert et al., 2013; Moriguchi et al., 2018; Moriguchi & Shinoshara, 2019, Tsujimoto et al., 2004).

In Chapter 4, wireless fNIRS will be used to investigate prefrontal cortex activation in action sequences. However, not only experimental methods can give insights into development and mechanisms of actions; computational models provide good opportunities to create testable hypotheses about underlying mechanisms.

1.6.4 Computational models

Computer models can be used to test theories of mental processes and development or create hypotheses about behaviour. Computational modelling is the process of creating and simulating a mathematical model on the computer designed to predict the behaviour or outcome of cognition (Sun, 2008). They have been particularly useful in providing mechanistic explanations of development (e.g. Elman et al., 1997; Mareschal, 2010; Yermolayeva & Rakison, 2014).

Connectionist models such as interactive activation and competition networks (IAC, or also called parallel distributed processing networks) have shown to be of particular use in explaining theories of brain functioning. These IAC networks consist of processing units with a number of different pools. There are excitatory connections among units in the same pool and inhibitory connections among units in different pools. Activation in these units evolves gradually over time (Rumelhart & McClelland, 1989; Thomas & McClelland, 2008). Precise details are discussed in Chapter 5, where a model based on the frontal cortex - basal ganglia neural architecture is described as a possible model of action selection in children during goal-directed action sequencing.

One of the first IAC models was able to explain the context effect of letter perception (McClelland & Rumelhart, 1981). IAC models have also been able to explain other cognitive processes in adults, such as the reaction time difference in the Stroop task (Gilbert & Shallice, 2002), routine action control (Cooper & Shallice, 2000, 2006), and behavioural and neural data in an implicit memory task (Hoffman & Jacobs, 2014). In addition, an IAC model based on the neural architecture of the frontal cortex - basal ganglia loops has recently been proposed to explain behavioural and neural action selection performance of adults and Parkinson's disease patients on the Wisconsin Card Sorting Task (Caso & Cooper, 2020).

1.7 Thesis objectives

This project uses behavioural paradigms, optical motion capture, wireless fNIRS and computational modelling to investigate the development of action sequence planning in

preschoolers. The combination of these methods allows us to investigate the developmental trajectory of action sequences on different levels, ranging from the level of raw movements, to cognitive processes and neural mechanisms involved.

As discussed above, goal-directed action sequences are essential in our daily life, and many of these action sequences have a hierarchical goal structure. While adults are proficient at planning and executing these action sequences (with the occasional lapse), infants, toddlers and children still have to learn how to plan and execute these.

This thesis aims to investigate the development of action sequences in two approaches; (i) by studying action sequences in the simplest form in the youngest age group in Chapter 2, and by (ii) studying action sequences with a hierarchical goal structure in more depth in preschoolers, an age group allowing us to investigate related dynamic markers and the underlying brain areas involved in action sequences in Chapter 3 and 4.

Recent evidence has shown that the planning and control of action sequences develops over the preschool years and might be related to executive function development. Therefore it is also hypothesised that hierarchical action sequence abilities improve over preschool years, and that this is related to executive functions. This project aims to identify which specific core aspects of executive functions (i.e. working memory, inhibition, or set shifting) is related to specific parts of action sequence planning and execution (i.e. not being distracted or ability to keep track of the goal hierarchy).

While studies have shown that toddlers between 2 and 3 years of age can imitate simple action sequence, there are no studies investigating toddlers' ability to plan and control action sequences in this age range. It was hypothesised that the ability to control simple action sequences develops over toddlerhood, such as a simple action sequences with a goal constraint. Furthermore, motor competence, which still develops over toddlerhood, might be related to simple action sequences.

Motion capture can be used to investigate the dynamic processes involved in decision-making and planning. Indeed, adults showed increased action selection time at branch points in action sequences where they would switch from one subgoal to the next subgoal. Therefore, branch points will be specifically explored as event markers that can reveal to us more about the development of hierarchical action sequences using optical motion capture.

The main underlying neural brain areas involved were: (i) dorsolateral prefrontal cortex (among other areas) for action planning, (ii) the basal ganglia for action selection, and (iii) the primary motor cortices for action execution. First, it was hypothesized that involvement of the dorsolateral prefrontal cortex, which develops in early childhood, is important in hierarchical action sequence planning. Second, while the focus of the existing literature has tended to lie on action planning and action execution improvements in development, the novel hypothesis that action selection problems might underlie problems with action sequences in early preschool period was explored. This would could indicate that the deficit in action sequences would be in action selection, and not in planning.

Finally, a the key challenges to the existing research is to leave behind the traditional laboratory studies and to investigate development and brain functioning in more real-world or naturalistic settings (Dahl, 2017; Matusz et al., 2019; Pinti et al., 2018). More naturalistic scenarios will reveal a richer pattern of behaviour and cognition that are suppressed in controlled lab contexts. This project aims to use more ecologically valid paradigms using wireless equipment, allowing children to act like they would in daily life.

This is especially important, since actions are embedded within the context they are planned and executed. Lab settings with only one or a few objects to act upon do not reflect the richness of everyday action opportunities. Furthermore, rigid objects used in these tasks, such as a ball or a button, do not reflect the wide range of objects that infants, toddlers and preschoolers will encounter to act upon. Most of the objects can not only be grasped or transferred somewhere, but can also be acted upon, can be combined and can be broken apart again. A good example here are Duplo blocks, which can be used to construct complex structures by combining several blocks, but structures can be broken down and combined again to new structures.

Thus, the work in this thesis uses Duplo blocks to investigate action sequences in toddlers and preschoolers. This results in children executing in a more naturalistic settings, similar to something they might encounter in a preschool or at home. Furthermore, the use of state-of-the-art methods such as optical motion capture (Chapter 3 and 4) and wireless fNIRS (Chapter 4) allows us to investigate action sequences at different levels.

The studies reported in this thesis were exploratory. Prior to testing, it was assumed that twenty participants per cell would provide enough power to detect a medium effect size. As the studies were exploratory in nature, no type-I error correction was applied, except in follow-up tests where Bonferroni corrections were applied.

The thesis begins with a study investigating toddlers' and young preschoolers' ability to control action sequences using a simple alternating patterns and action sequences with multiple constraints (Chapter 2). This chapter also investigate the relation of action sequences to executive functions and motor competence. Next, the thesis presents a study assessing improvement in hierarchical action sequences in preschool years, and its relationship to specific EF components in a more complex house building task (Chapter 3). Here, optical motion capture is used to examine embodied markers or hierarchical action sequences. Chapter 4 reports on a study replicating the house building task of Chapter 3, while concurrently recording prefrontal cortex activation using fNIRS. Lastly, Chapter 5 describes a computational model explaining action selection in preschoolers in a model based on the neural architecture of the basal ganglia. Together, these four chapters contribute to new insights in the development of planning, selection and execution of action sequences in toddlerhood and preschool period in naturalistic settings.

CHAPTER 2

Goal constraints and alternating action planning in toddlers' tower constructions

2.1 Introduction

2.1.1 Action planning

Action planning is essential for humans to interact with the environment in a strategic way. Actions should be planned ahead taking into account task demands or constraints from the environment (Gottwald et al., 2017; von Hofsten, 1993, 2004). Even young infants are able to plan simple one or two step actions prospectively (Claxton et al., 2003; Lockman et al., 1984; von Hofsten & Rönnqvist, 1988; Zaal & Thelen, 2005). For example, 10-month-old infants reached more slowly to an object when they needed to fit it down a tube as compared to when they needed to throw it (Claxton et al., 2003).

However, the actions we, adults, execute in daily life are more complex than simply reaching for an object and putting it away. Even the cup of coffee we make in the morning involves planning a multistep action sequence. Action sequences that we execute in daily life are often organised in terms of a goal hierarchy (Rosenbaum et al., 2007). The goal hierarchy consists of a main goal, which in turn consists of several subgoal. Each of these subgoals in turn consists of several action steps. When planning these action sequences within a goal hierarchy, adults maintain the main goal, while also keeping track of the subgoals and action steps that have already been carried out as well as those that need to be carried out next (Botvinick, 2008; Cooper et al., 2014; Cooper & Shallice, 2000, 2006; Miller et al., 1960).

The ability to plan action sequences according to a goal hierarchy developed over the preschool period. Five-year-olds were able to plan and execute their action sequences according to a hierarchical goal structure, while 3- and 4-year-olds experienced problems in their action sequence planning, such as maintaining and following the highest level goal (Yanaoka & Saito, 2017, 2019, 2020). Similarly, imitation of action sequence within a goal hierarchy improved over preschool period (Flynn & Whiten, 2008; Freier et al., 2015).

In summary, adults are able to plan and control an abundance of actions and action sequences with different levels of complexity. Planning and controlling simple actions developed in infancy, while planning and controlling complex action sequences with goal hierarchy developed over preschool period. However, how complex action planning develops and what

mechanisms relate to action planning development remain unknown. This chapter investigates action sequence planning in the youngest age group (2 -to 3-year-olds) and focuses on simplest form of action sequence planning: action sequence of tower building with two goal constraints and action sequence with alternating actions.

2.1.1.1 Action sequence with goal constraints

Actions are planned in order to achieve a goal, but achieving a goal can be accompanied by multiple constraints. For example, if we are instructed to build a tower, one of the goal constraints can be that it should be of a certain size. How young children learn to take into account multiple goal constraints and build them into their overarching action plan remains elusive.

One study sheds some light on this question: Freier and colleagues (2017) investigated preschoolers' ability to plan and control sequential actions following multiple levels of goal constraints. Three- and 5-year-olds were asked to colour in six farm animals following the direction of an arrow beneath the animals as lower goal constraint. Furthermore, they were instructed to use each of the three colours provided equally often as a superordinate goal constraint. The results showed that both 3- and 5-year-olds were able to follow the lowest goal constraint of colouring all the farm animals following the direction of the arrow. However, only 5-year-olds were able to take into account the superordinate goal constraint when planning their action sequence, and use each of the three colours provided equally often. Five-year-olds would either cycle between colours (i.e. cycling approach; blue, yellow, red, blue, yellow, red), or showed a grouped approach (i.e. blue, blue, yellow, yellow, red, red) to achieve this superordinate goal constraint. Interestingly, both age-groups had no trouble recalling the task goals, suggesting that the issue was not a memory problem, but rather challenge for cognitive control (Freier et al., 2017).

In short, these results demonstrated that children from about 3 years of age were able to take into account one goal constraint in their action sequence planning. However, whether younger toddlers are able to plan their actions accordingly remains unexplored. Furthermore, the results demonstrated that only by 5 years of age, children were able to coordinate their actions by cycling their colouring between three colours simultaneously. It is possible that the motor demands involved in holding a pencil and colouring were too taxing for these 3-year-olds and that a simpler task with more familiar actions may have allowed them to demonstrate better

planning abilities. Thus, the current study focuses on tower building because it is an easier and highly familiar activity for toddlers and young preschoolers.

2.1.1.2 Alternating actions

Most children that successfully achieved the higher order goal constraint cycling between colours in a cycling approach (Freier et al., 2017). Alternating actions follow a pattern. For example, if we divide marbles equally between ourselves and a friend, we might share them using an alternating action pattern; one for you, one for your friend, one for you, one for your friend etc. These alternating actions follow a repeating pattern (for example: A, B, A, B in the simplest version) that consists of unit of repeat. The pattern is cyclic and can be generated by repeating a smaller proportion of the pattern. In the simplest scenario, the smaller proportion of the pattern is just A B, but this can vary in the number and complexity of items (Papic, 2007). The term *alternating* can be used to refer to patterns that involve two actions that are repeated, while the term *cycling* refers to action patterns that involve more than two actions that are repeated. Preschoolers who were taught to observe the structure of units of repeat in these patterns subsequently showed a better understanding of repeat and spatial structuring in mathematic (Papic, 2007; Papic et al., 2011; Papic & Mulligan, 2007).

Thus, understanding, recognising and planning patterns seems to be an essential skill in mathematic in preschoolers (Papic, 2007; Papic et al., 2011; Papic & Mulligan, 2007). While these patterns are clearly important for mathematic in school, the development of the ability to plan these patterned or alternating action sequences remains unknown. Only Freier and colleagues (2017) shed some light demonstrating that 5-year-olds can cycle between three colour pencils (i.e. cycling approach) in their action sequences. This study is the first to investigate whether toddlers are able to plan a simple pattern in their action sequences, and whether this ability relates to executive functions (EFs) – such as working memory, inhibitory control and task switching – as well as basic motor competence. Previous studies have shown that EFs were related to both simple and complex action planning (Gottwald et al., 2016; McCormack & Atance, 2011; Yanaoka & Saito, 2019).

2.1.2 The mechanisms of action development

This study aimed to investigate the development of planning, selecting and executing alternating actions and actions with goal constraints. But, it also remains unexplored what drives the development of these forms of action planning. It has been suggested that the development of executive functions (EFs) could underlie the development of planning

(McCormack & Atance, 2011). Furthermore, motor competence might be essential for the development of planning, especially in toddlerhood.

2.1.2.1 Executive functions

Executive functions are cognitive control processes that regulate goal-directed behaviours (Barkley, 2012; Diamond, 2013; Miyake & Friedman, 2012). Three components are often considered to be the core aspects of EFs: *working memory*, *inhibition* and *set shifting* (McCormack & Atance, 2011; Miyake & Friedman, 2012). The development of EFs in infancy and childhood were linked to motor behaviour (Livesey et al., 2006) and motor planning (Gottwald et al., 2016; Pennequin et al., 2010). Furthermore, EFs were also related to control and planning of familiar action sequences (Yanaoka & Saito, 2019, 2020). Therefore, it is expected that EF will also play a role in the development of other forms of action planning, such as planning actions with an alternating patterns or planning actions with multiple goal constraints.

2.1.2.2 Motor competence

Infancy, toddlerhood and early childhood is considered a critical time for the development of fundamental movement skills that are the building blocks of more complex movements (Lopes et al., 2020; Malina, 2004). Motor competence involves proficiency in movements with interactions between the neuromuscular system and the environment (Lopes et al., 2020). Motor competence reflect the ability to execute and coordinate different motor actions. It is therefore required for action planning; in order to plan a specific goal-directed action, you should be able to execute and coordinate this motor action.

Gross motor skills and fine motor skills developed rapidly in toddlerhood (Berk, 2017; Boyd & Bee, 2013; Colson & Dworkin, 1997). Fine-motor skills are especially important in action planning involving objects. Regarding fine motor skills, toddlers refined their reaching, grasping and manipulating motor skills. Eighteen-month-olds were able to build a tower of four cubes, while 24-month-olds can already build a tower of six to seven cubes, and 36-month-olds were able to build a tower of 9 to 10 blocks (Colson & Dworkin, 1997). Therefore, improvements in motor competence may underlie or contribute to action planning development in toddlerhood.

2.1.3 The current study

To investigate the emergence of action sequences in toddlers, this study focuses on the simplest forms of action sequences; alternating in a sequence between repeating two actions, and following two goal constraints in action sequences. Furthermore, it is investigated whether this development is related to improvements in executive functions and motor competence. Children were asked to sort coins in alternating pattern between two boxes. To assess whether children are able to take into account multiple goal constraint in their action sequence planning, children were instructed to build a tall tower (goal constraint 1) that was striped – i.e., alternating between colours (goal constraint 2).

It was hypothesised that both planning alternating actions and planning actions according to multiple goal constraints improves over toddlerhood and early childhood. Furthermore, it was predicted that children with better executive function skills would be better at these tasks (McCormack & Atance, 2011).

2.2 Method

2.2.1 Participants

A total of 20 24-month-olds ($M = 24.77$ months, $SD = 12.69$ days, 8 females), 20 30-month-olds ($M = 30.10$ months, $SD = 21.23$ days, 12 females) and 30 36-month-olds ($M = 36.50$ months, $SD = 19.20$ days, 18 females) participated in this study. Participants were drawn from a population of typically developing children with no reported colour blindness. Families were recruited from a database of interested parents by phone or email. Participation was voluntary. Caregivers were informed about the test procedures before giving informed consent. Families were given a present ('a child scientist t-shirt) and a certificate for participation, and travel expenses were reimbursed. The data of 24-month-olds and 30-month-olds was analysed as one group of 2-year-olds, because of similar performance on the planning tasks.

As a result of Covid-19 restrictions, the sample of 36-month-olds was tested with increased distance between experimenter and child, and all adults wore face covering. One 24-month-old, one 30-month-old and two 36-month-olds were excluded from the data-analysis, because the child did not listen to any of the instructions ($n = 1$ 24-month-old), the caregiver influenced the testing session ($n = 2$; 1 30-month-old and 1 36-month-old) or there was no data for the planning task ($n = 1$ 36-month-old).

One 36-month-old had no data for the working memory task. One 30-month-old had no data for the motor competence task. One 24-month-old and one 30-month-old had no data for the alternating task. Five 24-month-olds, one 30-month-old, and three 36-month-olds had no data for the set shifting task. Lastly, three 24-month-olds, two 30-month-olds and one 36-month-old had no data for the zebra task. Reported analysis excluded these participants only if they had missing data for that task, thus the final Ns varied slightly from task to task.

2.2.2 Procedure

All procedures were approved by the local ethics committee and conducted according to the principles of the Declaration of Helsinki. Toddlers and preschoolers were tested in a quiet room with their caregiver present. Each participant was seated in an age-appropriate chair at an age-appropriate table.

Children were presented with the task in the following order: planning task, zebra task, alternating task, working memory task, set shifting task, motor competence task and inhibition task. Children were praised for their performance throughout.

2.2.2.1 The planning task

Children were asked to build a tower out of Duplo blocks for a bunny puppet named ‘Fluffy’ as the primary overarching goal, while taking into account two goal constraints: (i) making a tall tower, as tall as the tower displayed on the wall (20 blocks), and (ii) making it striped by alternating between colour blocks. Fluffy first demonstrated how children should make a striped tower using colours (yellow and green) identical to those in picture of the tower fixed on to the wall, next to their workspace. The picture was placed there both to help explain the task constraints and as a reminder of the goal. Children were then presented with one box of blue blocks, one box of red blocks, and a green building plate (Figure 2.1). The task was considered complete when the child indicated that their tower was finished. The experimenter then checked whether children remembered what Fluffy wanted them to do, and while some did not answer verbally, most participants non-verbally indicated that their tower was identical as the example tower on the wall.



Figure 2.1. The set-up of the Tower task.

2.2.2.2 The zebra task

The Zebra task was developed to ensure the child understand the principle of something being striped. The experimenter showed the child that a stuffed zebra was striped. The child was then asked to identify the tower that was striped like zebra (by pointing to one of three photographs (see Figure 2.2)).



Figure 2.2. The stuffed zebra with the different towers. The correct striped tower was the pink-brown tower.

2.2.2.3 The alternating task

This task was developed from a simple one box coin slot task. To assess children's ability to plan and execute simple alternating actions, the child was asked to sort 11 plastic coins between two small boxes in an alternating pattern following the demonstration of the experimenter (e.g., left, right, left, right... etc.).

2.2.2.4 The working memory task

The spinning pots task (Hughes & Ensor, 2005) was used to assess working memory (WM) capacity. Eight distinct in colour, form, material and size boxes were arranged on a Lazy Susan tray. The experimenter would hide 6 stickers in the boxes together with the child. The child had to find all the stickers opening as little boxes as possible. In between opening a box, the boxes were covered with a small blanket and the Lazy Susan tray was spin.

2.2.2.5 The set shifting task

The trucks game (Hughes & Ensor, 2005) was used to assess set shifting abilities. It consisted of two phases. In the first phase, children had to guess one of the two trucks to consistently get a sticker. The truck the child guessed in the first trial was the truck they needed to pick consistently throughout the first phase. In the second phase, children had to shift to consistently pick the other truck to get a sticker. Each of the phases consisted of eight trials.

2.2.2.6 Motor competence

Motor competence was assessed using a cubes stacking task based on the Mullen Developmental Scale (Mullen, 1995). Children were instructed to stack as many wooden cubes on a tower as possible. The task ended when the tower fell down.

2.2.2.7 The inhibition task

The magic wand task (Friedman et al., 2011) was used to assess response inhibition. Children were instructed to not touch a glitter wand right in front of them. The experimenter looked away for the maximum duration of 30s.

2.2.3 Coding

2.2.3.1 The planning task

Children's performance on the planning task was coded offline. The ability to successfully complete the first goal constraint was coded as the height of the tower in number of blocks. The variable for planning success was binary: 1 for a successful tower between 15 and 25 blocks (i.e. the example tower was 20 blocks), and 0 for a smaller or taller tower. The ability to successfully complete the second goal constraint was coded as the number of colour switches on the tower divided by the total number of blocks minus 1. This resulted in a percentage score between 0 and 1, with 0 indicating only one colour used, and 1 indicating a perfect striped tower. Children who built a tower smaller than 3 blocks (8 toddlers) were

excluded in the secondary constraint analysis. Lastly, the duration of the tower task was coded in seconds.

2.2.3.2 The zebra task

Children's ability to recognise a striped tower or understand when something is striped was given a binary score: 1 if the answer was correct (1; the pink-brown tower) or 0 if incorrect (0; other towers).

2.2.3.3 The alternating task

The ability of the child to plan and execute simple alternating actions was scored as the longest alternating pattern with a maximum of 10. For example if the child executed: left, right, right, left, the longest alternating pattern was 2.

2.2.3.4 The working memory task

As in Hughes and Ensor (2005), the working memory score was calculated as 16 minus the number of boxes opened minus the total stickers. The number of boxes the child opened to find all stickers was recorded with a maximum of 16. Therefore, the minimum score of 6 reflected poor working memory, while the maximum score of 16 reflected good working memory.

2.2.3.5 The set shifting task

Children were only included if they had 5 or more correct trials in the pre-switch phase (Hughes & Ensor, 2005). An additional 17 children were excluded (3 24-months-olds, 3 30-months-olds and 11 36-months-olds). The shifting score was calculated as the proportion of correct trucks picked post-shifting phase minus the proportion of correct trucks picked pre-shifting phase.

2.2.3.6 The motor competence

The number of wooden blocks on the tower when the tower remained standing was taken as measure of motor competence.

2.2.2.7 The inhibition task

The inhibition score was the latency to touch the toy with a maximum of 30s. Due to the bimodal nature of the data (either children touched the wand within the first 7s or waited the entire 30s), this continuous score was transformed into a binary variable with a score of 0

reflecting children that grasped the wand (fail), and a score of 1 reflecting children that waited the entire time (pass).

2.3 Results

Analyses were implemented in RStudio (version 1.2.1335).

2.3.1 Executive function and motor competence development

To investigate the validity of the executive function and motor competence tasks, the scores from each of these tasks (working memory, set shifting and motor competence) were correlated with the child's age in days (Figure 2.3) in planned analyses. As inhibitory control was a binary task score, a binary logistic regression was executed to examine the effect of age as predictor on the inhibition score. It was expected that performance would improve over age.

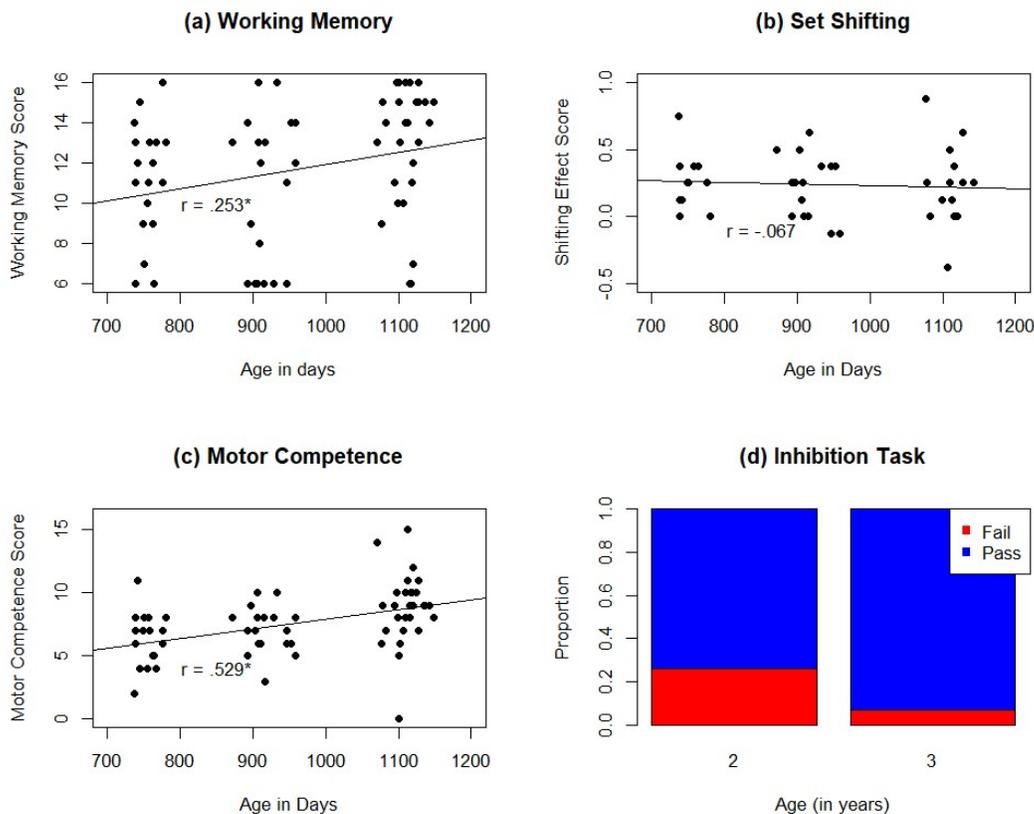


Figure 2.3. The scores for each child on (a) the working memory, (b) set shifting and (c) motor competence as a function of age in days. The proportion of children passing the inhibition task (score = 1, in blue) and failing the inhibition task (score = 0, in red) is shown in (d) for the two age groups (2-year-old toddlers and 3-year-old preschoolers). The * represent a significant correlation at $p < .05$.

Working memory correlated significant with age in days ($r(63) = .25, p = .042$). As predicted, older children had a higher working memory score than younger children. The shifting score did not correlate significantly with age in days ($r(38) = -.07, p = .681$). This suggests a lack of task sensitivity. Motor competence correlated significantly with age in days ($r(63) = .523, p < .001$). Older children showed better motor competence than younger children. The binary logistic regression showed that the model with age in days predicted the binary score of inhibition significant better than a model with no predictors ($\chi^2(1) = 4.36, p = .036, Nagelkerke R^2 = .105$). As shown in the Figure 2.3(d), performance improved over this period, but performance in 2-year-olds was already near ceiling level.

The shifting and working memory scores did not correlate significantly ($r(38) = .19, p = .251$). Nor did they predict the binary score of inhibition in a binary logistic regression (working memory; $\chi^2(1) = 0.41, p = .524$; shifting: $\chi^2(1) = 1.27, p = .261$).

2.3.2 Alternating actions

2.3.2.1 Planning alternating actions

The ability to complete the alternating actions task improved over this period; age in days correlated significantly with alternating abilities ($r(62) = .50, p < .001$; Figure 2.4) in a planned analysis.

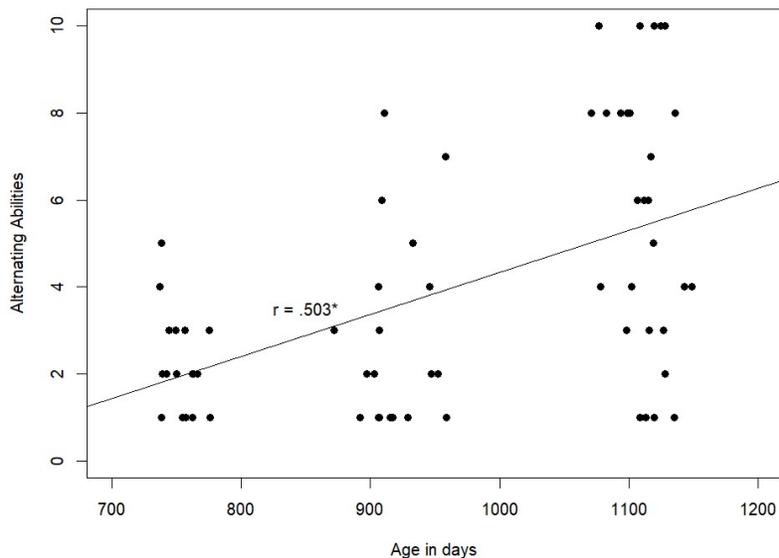


Figure 2.4. The scores for each child on the alternating task as a function of age in days. The * represent a significant correlation at $p < .05$.

A planned stepwise linear regression with predictors of the executive function scores and motor competence score (but not age in days), showed that motor competence and working memory scores significantly predicted alternating abilities ($F(2,59) = 4.71, p = .013$; Table 2.1 and Figure 2.5).

Table 2.1

The stepwise regression model with alternating abilities predicted by motor competence and working memory.

	<i>B</i>	<i>SE</i>	β	<i>t</i>	<i>p</i>
Step 1: Alternating Abilities					.030
Intercept	1.51	1.17		1.28	.203
Motor competence	0.32	0.14	0.27	2.22	.030
$R^2 = .075$					
Step 2 : Alternating Abilities					.013
Intercept	-0.65	1.57		-0.41	.690
Motor competence score	0.31	0.14	0.26	2.17	.034
Working memory score	0.20	0.10	0.24	1.96	.055
$R^2 = .138$					

Interestingly, alternating abilities and working memory scores were still marginally significantly correlated when controlling for motor competence in an exploratory partial correlation analysis ($r(62) = .25, p = .055$). Furthermore, alternating abilities and motor competence correlated significant when controlling for working memory ($r(62) = .27, p = .034$) in an exploratory analysis. However, working memory and motor competence did not correlate with each other ($r(62) = .09, p = .484$).

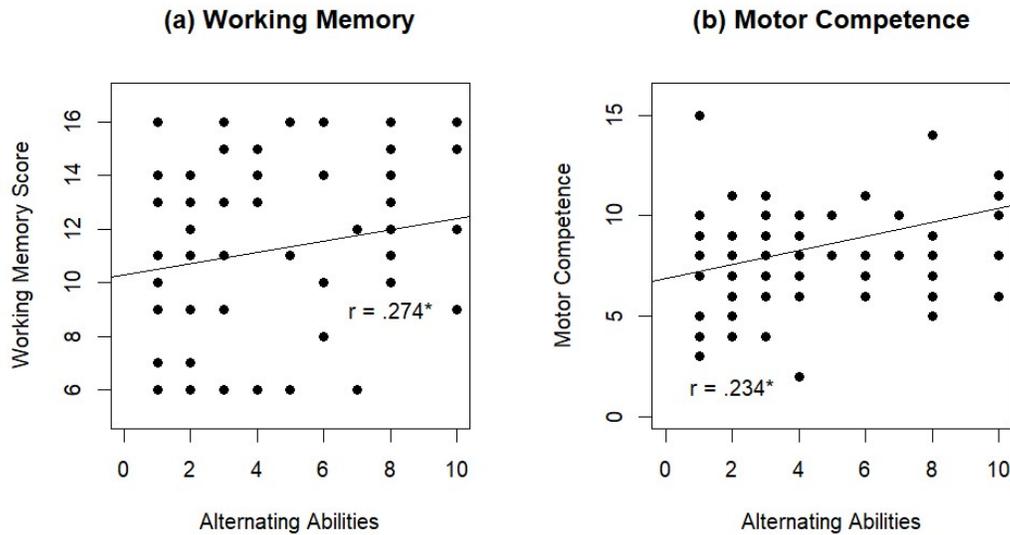


Figure 2.5. The scores for each child on the alternating task as a function of working memory (a) and motor competence (b). The * represent a significant correlation at $p < .05$.

2.3.2.2 Recognising alternating patterns

A chi-square test of association between the binary score on the zebra task and age group (2- or 3-year-olds) showed a marginally significant association ($\chi^2(1) = 3.40, p = .065$, Figure 2.6).

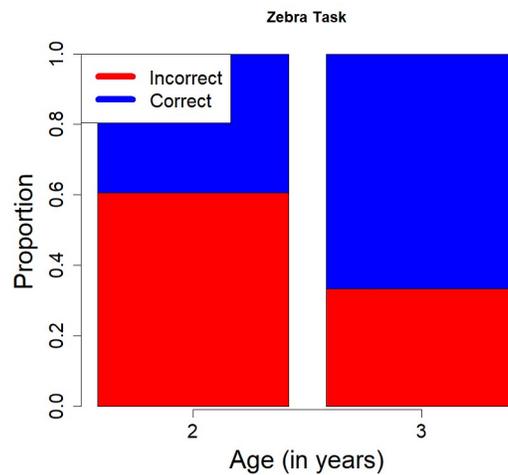


Figure 2.6. The proportion correct responses for the Zebra task (i.e. understanding striped) for 2- and 3-year-old children. A score of 1 indicated children who answered correctly (in blue), while a score of 0 indicated children who answered incorrectly (in red).

A stepwise binary logistic regression with age in days, executive function scores, motor competence and alternating abilities as predictors showed that alternating abilities was the strongest predictor of recognising striped patterns ($\chi^2(1) = 4.36$, $p = .037$, Nagelkerke $R^2 = .16$). On average, children who answered correctly in this task ($M = 4.71$, $SD = 2.85$) showed a higher alternating score than children who answered incorrectly ($M = 3.19$, $SD = 2.68$) (Figure 2.7).

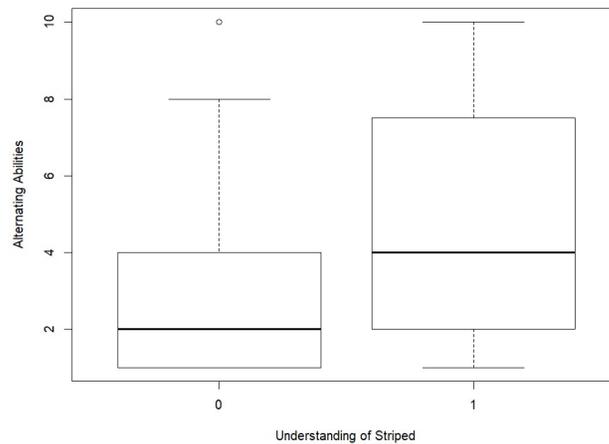


Figure 2.7. The alternating score for children showing understanding of striped by passing the Zebra task (score = 1) and children not showing understanding of striped by failing the Zebra task (score = 0).

As working memory score and motor competence significantly predicted alternating abilities (Section 2.3.2) and alternating abilities significantly predicted understanding of striped in the Zebra task, a binary logistic regression with working memory score and motor competence as predictors was performed. This model was not significant ($\chi^2(2) = 1.69$, $p = .429$), suggesting that a third independent component of alternating action abilities might be related to recognising (or understanding) stripedness.

2.3.3 Completing action sequences with multiple goal constraints

2.3.3.1 Primary constraint

Figure 2.8 shows the percentage of participants in each age group that built the tower to the correct height (between 15 and 25 blocks), built it too low (with too few blocks) or built it too high (with too many blocks). In subsequent analyses, the last two groups are combined into one group of children who fail to align actions accordingly with the primary constraint (i.e.,

building a tower height of 20 blocks). Two- and 2.5-year-olds were demonstrated to have similar performance, and were analysed as one group of 2-year-olds.

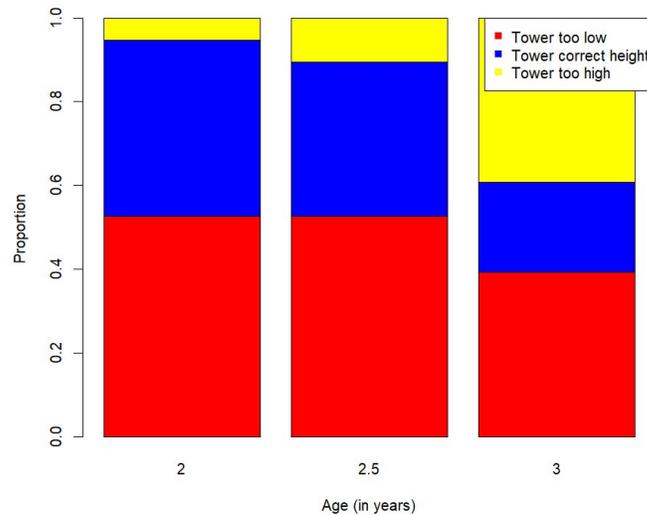


Figure 2.8. The proportion of children for each age group (2, 2.5 and 3 year old) that successfully complete the tower (blue), built a tower too low (red) or built a tower too high (yellow). Given the similarity in performance in 2- and 2.5-year-olds, these groups were analysed as one group of toddlers.

A planned stepwise forward binary logistic regression with age in days, executive function tasks scores, and motor competence score showed no significant predictors better than the null model (age in days: $\chi^2(1) = 2.84$, $p = .092$; working memory score: $\chi^2(1) = 1.70$, $p = .192$; inhibition score: $\chi^2(1) = 1.70$, $p = .192$; set shifting score: $\chi^2(1) = 0.15$, $p = .695$; motor competence: $\chi^2(1) = 0.08$, $p = .783$).

In an exploratory stepwise forward binary logistic regression for 2-year-olds only, working memory was a marginally significant predictor of the ability to successfully complete the primary constraint ($\chi^2(1) = 3.70$, $p = .055$, Nagelkerke $R^2 = .126$). None of the other predictors were significant. No predictors were significant in a stepwise forward binary logistic regression for 3-year-olds only. As shown in Figure 2.9, 2-year-olds were able to complete the primary goal constraint had a lower working memory score than 2-year-olds who were unable ($M = 9.47$, $SD = 3.38$ and $M = 11.57$, $SD = 3.16$ respectively).

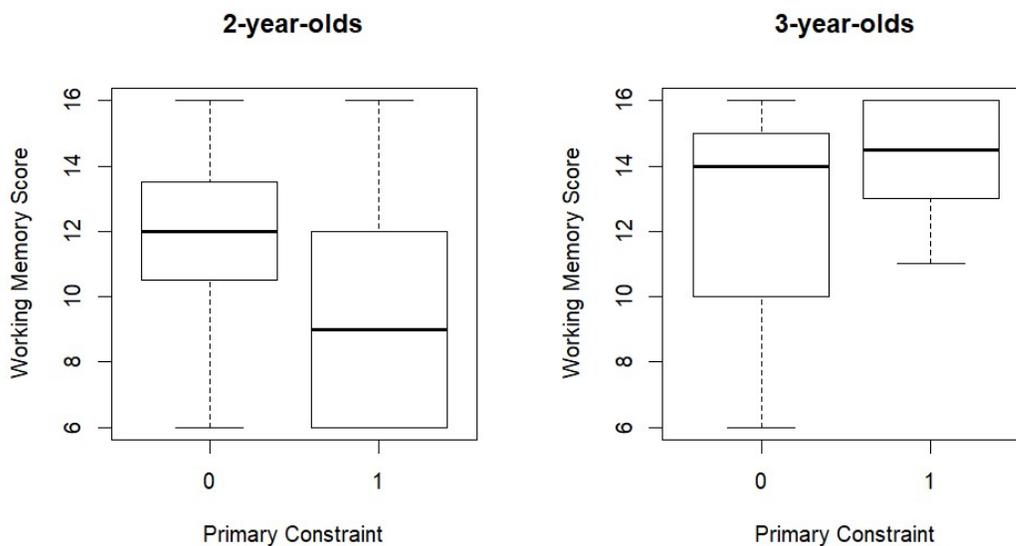


Figure 2.9. Boxplots for the relation between primary constraint (building tower to the correct height) in pass (score = 1) or fail (score = 0) and working memory score in 2-year-olds and 3-year-olds.

2.3.3.1.2 Building the tower too high

Some 2-year-olds and many 3-year-olds build the tower too high (Figure 2.8). An exploratory stepwise binary logistic regression comparing children that build the tower to the correct height and children that build it too high showed that this was significantly predicted by age in days ($\chi^2(1) = 8.64$, $p = .003$, Nagelkerke $R^2 = .30$). Both age in days and inhibition score as independent predictors significantly improved this model ($\chi^2(1) = 4.15$, $p = .042$, Nagelkerke $R^2 = .41$). Older children and children with a low inhibition score are more likely to build the tower too high (Figure 2.10).

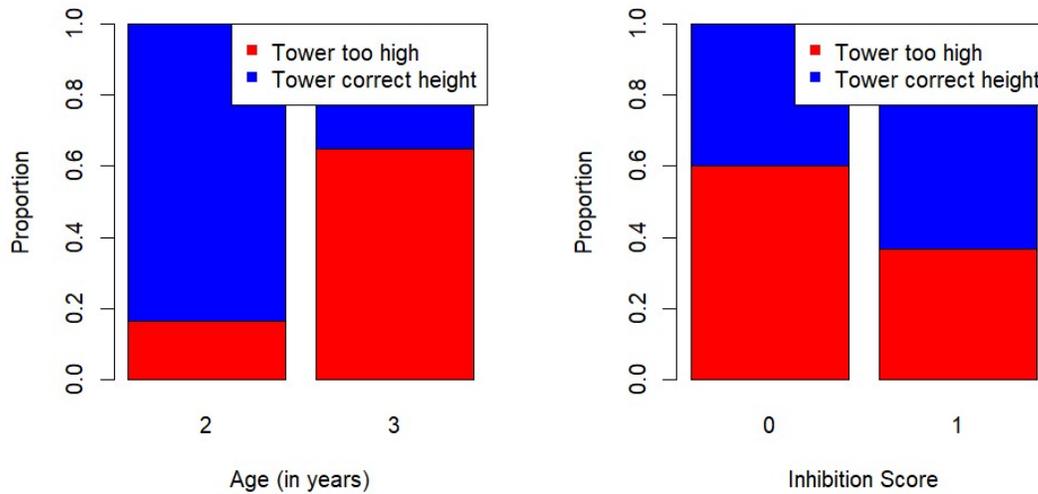


Figure 2.10. The proportion of children that build the tower to the correct height (in blue) and children that build the tower too high (in red) for each age group (a) and the inhibition score with pass (score = 1) and fail (score = 0) (b).

2.3.3.2 Secondary constraint

A planned stepwise forward regression with age in days, executive function scores and motor competence score showed that age in days and working memory score was the significant predictors of the percentage striped score ($F(2,53) = 10.95, p < .001$, Table 2.2 and Figure 2.11).

Table 2.2

The stepwise linear regression model with percentage striped (secondary constraint) predicted by age in days and working memory

	<i>B</i>	<i>SE</i>	β	<i>t</i>	<i>p</i>
Step 1 : Percentage striped					
Intercept	-0.84	0.29		-2.89	.005
Age in days	0.001	0.00	0.49	4.16	< .001
$R^2 = .239$					
Step 2: Percentage striped					
Intercept	-0.96	0.29		-3.24	.002
Age in days	0.001	0.00	0.12	3.43	<.001
Working memory	0.026	0.01	0.23	1.91	.061
$R^2 = .276$					

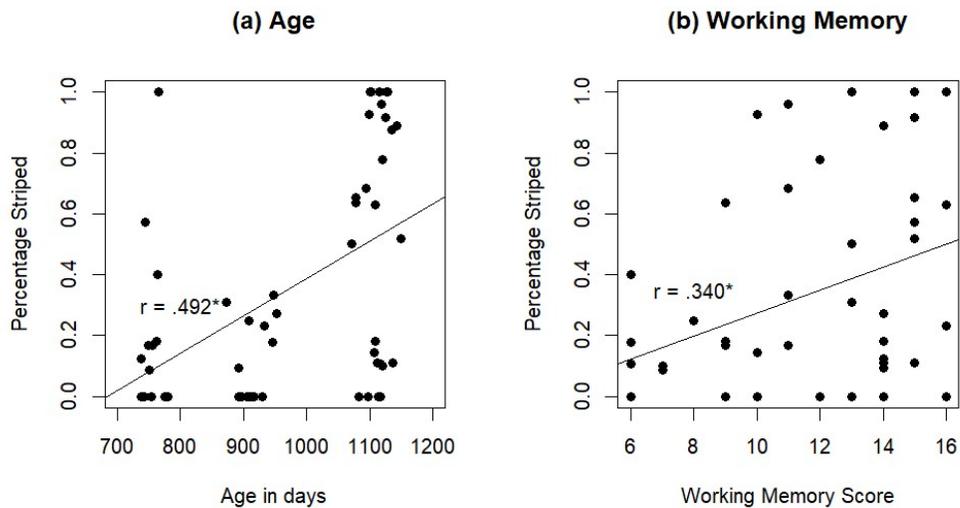


Figure 2.11. The scores for each child on secondary constraint as a function of age in days (a) and working memory (b). The * represent a significant correlation at $p < .05$.

Separate exploratory stepwise linear regressions for the two age groups, showed no significant predictors for 2-year-olds, nor for 3-year-olds.

2.3.3.3 Primary and secondary constraint

To assess the relationship between the primary and secondary constraint, two planned binary logistic regression with performance in the secondary constraint as predictor and performance on the primary constraint as outcome were conducted. For 2-year-olds, it showed that percentage striped is a significant predictor of ability to successfully complete the primary constraint of building a tower to a designated height ($\chi^2(1) = 4.44, p = .035, Nagelkerke R^2 = .18$). For 3-year-olds, percentage striped is a significant predictor of the ability to successfully complete the primary constraint (building the tower to correct height) ($\chi^2(1) = 8.31, p = .004, Nagelkerke R^2 = .40$). Interestingly, an opposite pattern is observed in the effect of success on the secondary constraints on predicting success on the primary constraint the two age groups (Table 2.3, Figure 2.12). For 2-year-olds, those who are successful on the primary constraint are less likely to be successful on the secondary constraint; whereas, for 3-year-olds, children who are successful on the primary constraint are more likely to be successful on the secondary constraint as well (Figure 2.12).

Table 2.3

The regression models with primary constraint ability predicted by secondary constraint ability for the two age groups

	<i>b</i>	<i>SE</i>	β	<i>z</i>	<i>p</i>
Model 1: 2-year-olds					
Intercept	0.61	0.49		1.24	.215
Percentage Striped (secondary constraint)	-4.90	2.88	-2.12	-1.70	.089
$R^2 = .184$					
Model 2: 3-year-olds					
Intercept	-5.61	2.82		-1.98	.047
Percentage Striped (secondary constraint)	5.67	3.14	5.39	1.81	.071
$R^2 = .397$					

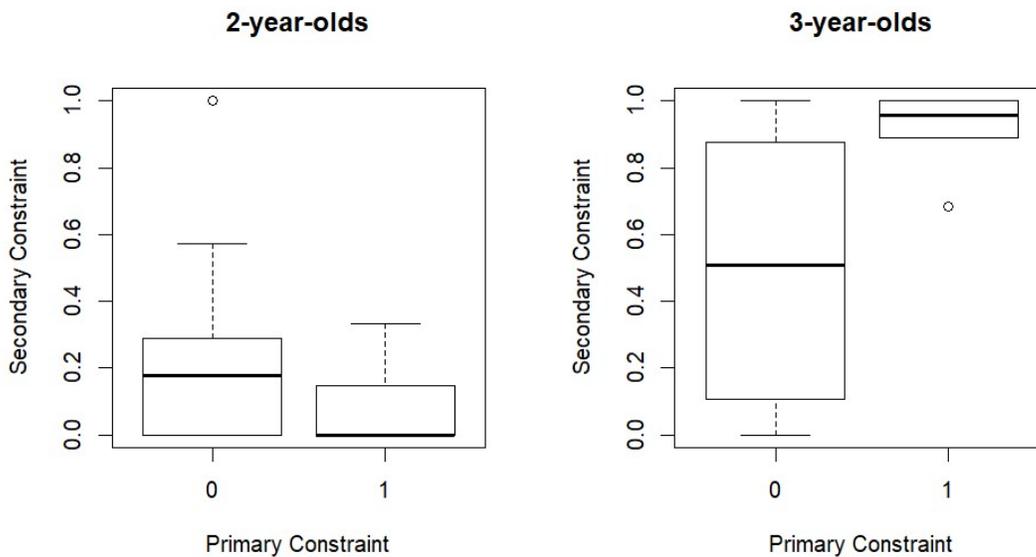


Figure 2.12. Boxplots for the relation between primary constraint (building tower to the correct height) with pass (score = 1) and fail (score = 0) and the secondary constraint (making the tower striped) in the different age groups.

2.3.3.4 Duration of planning task

The duration of the planning task was negatively correlated with age in days ($r(64) = -.31, p = .013$) and negatively correlated with working memory ($r(63) = -.25, p = .048$) in exploratory analysis. Older children and children with a high working memory showed shorter durations on the planning task (Figure 2.13). Furthermore, in an exploratory binary logistic regression,

the duration of the planning task significantly predicted binary outcome of the primary constraint ($\chi^2(1) = 4.39, p = .036, Nagelkerke R^2 = .09$). Children who successfully completed the primary constraint took longer to complete the task than children who did not take into account the primary constraint (Figure 2.13). Duration of the planning task also correlated marginally significantly with the percentage striped associated with completion of the secondary constraint ($r(55) = -.24, p = .072$) in an exploratory analysis.

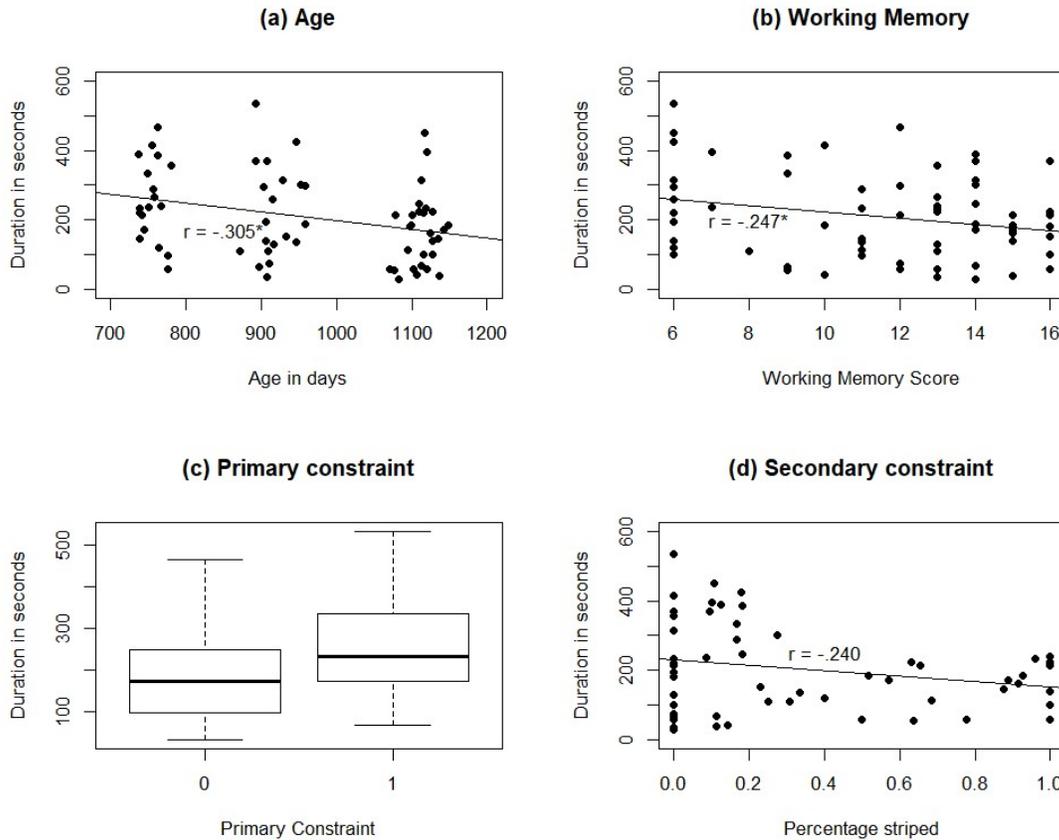


Figure 2.13. The duration of the planning task as function of age in days (a), working memory score (b) and success on secondary constraint (d). The relation between primary constraint and duration of planning is depicted in boxplots (c). The * represent a significant correlation at $p < .05$.

2.3.4. Relations between different action sequence planning tasks

To assess whether the toddlers who were better at the alternating action sequence task were also the toddlers who were better at the action sequence task with multiple goal constraints, a correlation between the secondary constraint success and the alternating abilities was executed

in an exploratory analysis. Furthermore, a binary logistic regression was executed to investigate whether alternating abilities was a significant predictor of the primary constraint success on the action sequence task with multiple goal constraints.

There was a significant correlation between the alternating abilities score and the percentage of striped as measure of success on the secondary constraint ($r(54) = .40, p = .002$). Children with a higher alternating score were also the children with a higher percentage of striped as secondary constraint (Figure 2.14). Alternating abilities did not significant predict the success on the primary constraint (i.e. building the tower to the correct height) ($\chi^2(1) = 1.76, p = .185$).

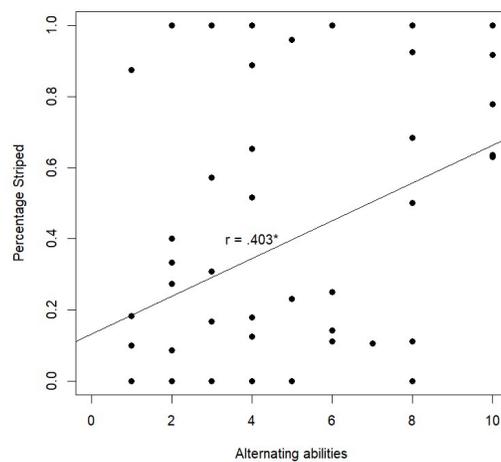


Figure 2.14. The alternating abilities on the coin alternating task as function of success on the secondary constraint (i.e. percentage striped) on the action sequence task with multiple goal constraints.

2.4 Discussion

This study investigated the development of complex planning in toddlerhood, and how it relates to executive function improvements (McCormack & Atance, 2011; Yanaoka & Saito, 2021). It focused on two types of action planning: (i) planning of alternating actions, and (ii) planning of actions with multiple goal constraints.

Toddlers and preschoolers were asked to plan and execute a simple alternating action sequence by sorting coins between two boxes in an alternating pattern. As hypothesised, the results showed that planning and execution of alternating actions improved over toddlerhood. Furthermore, it was found that working memory and motor competence were independent predictors of the ability to alternate actions. In addition, understanding striped was shown to

be predicted by alternating abilities, but not by working memory or motor competence. This suggested that alternating action abilities might be supported by motor competence and working memory, and relates to understanding of patterns.

The ability to align actions with multiple goal constraints was assessed by instructing children to build a Duplo tower taking into account two goal constraints. Interestingly, in 2-year-olds, the ability to successfully complete the primary constraint (of building a tower to a specified height) was negatively related to the ability to complete the secondary constraint (using bricks of alternating colour). One possible explanation for this is that working memory capacity in this age group is not sufficient to keep track of both constraints, or, that cognitive control is not robust enough to align actions according to both constraints. To put it in another way, either the working memory to support the planning and control is inadequate that toddlers are unable to keep track of both constraints or the cognitive control in toddlers is insufficient to support the planning and control of action sequences with two goal constraints.

In 2-year-olds, working memory was shown to be marginally significant in predicting success at taking into account the primary constraint. In contrast to our predictions, children with a higher working memory score were more likely to fail to take into account the primary constraint in their action planning. The negative relation between the two constraints (i.e., success at one but not the other) could reflect a working memory capacity or cognitive control problem. In other words, toddlers with a higher working memory score either attempt to keep track of both goal constraints, but fail because their working memory capacity is not sufficient or toddlers with a higher working memory score might have the working memory capacity to maintain both goal constraints, but have inadequate cognitive control to take them into account when planning and controlling their actions.

Three-year-olds showed a positive relationship between primary and secondary goal constraint in their action sequence planning. This suggests that, by this age, 3-year-olds have improved their ability to keep track of multiple goal constraints and the cognitive control to plan and control their actions according to multiple goal constraints. Furthermore, working memory was the significant predictor of following the secondary constraint. All of this suggests that the ability to align action sequence planning with multiple constraint developed over the preschool years and might be related to working memory capacity development.

In addition, it was shown that many older children built the tower too high and this was related to inhibition skills. Children with better inhibition were less likely to perseverate and build the

tower higher. Therefore, inhibition skills might be essential to stop planning and executing of actions when the goal is achieved.

Lastly, the success on the secondary constraint (i.e. percentage striped) in the tower task was correlated to alternating abilities. This suggests that either children who were better on one action sequence task (for example action sequences with multiple goal constraints) were also better on other action sequence tasks (such as alternating action sequences), or that alternating abilities were important in the secondary constraint of the tower task (i.e. alternate between two colours block to make the tower striped). As there is no relationship between the alternating abilities and success on the primary constraint in the action sequence task with multiple goal constraints, the second hypothesis is more likely, i.e. alternating abilities are essential in this action sequence task, but there is not necessarily a relationship between different types of action sequence planning (at least there is no evidence yet to assume this relationship).

These findings stand in contrast with those of Freier and colleagues (2017), as this study demonstrated that some 3-year-olds were successful at completing both constraints in a simpler task with multiple goal constraints. In an earlier study, 3-year-olds were unable to cycle between three colours (Freier et al., 2017), however, now 3-year-olds were able to alternate in their action sequence planning between two colours in a construction task. This demonstrates that the ability to plan action sequences are embedded within the context these actions are planned. A failure to plan actions accordingly in developmental populations might not indicate an impairment to plan the actions, but instead a difficulty with selecting and executing those actions (e.g., holding and selecting coloured pencils rather than fitting together Duplo blocks). Alternating between two actions seem to be a precursor in development to cycling abilities between more than two actions.

Furthermore, Freier and colleagues (2017) demonstrate that 3-year-olds are able to plan their actions according to one goal constraint. This study extends these findings by demonstrating that about half of toddlers are able to keep track of one constraint and plan their actions accordingly.

Lastly, the results are in line with the hypothesis that executive functions and complex action planning are related (McCormack & Atance, 2011). Executive functions were related to both alternating actions as well as action sequences with goal constraints. However, motor competence was only related to alternating actions, not action sequences with multiple goal constraint in this age group. This could be due to task differences; the alternating task required

fine grasping of small coins, while the action sequence task involved manipulating big Duplo blocks, something toddlers and preschoolers have gained experience with in daily life.

A limitation is that the set shifting was shown to be insensitive to age. This suggested that the shifting task is unsuitable to assess set shifting abilities in toddlerhood. Previous studies (Hughes & Ensor, 2005, 2006) have used it successfully in similar age groups. However, unlike the current study, they used all executive tasks (inclusive working memory and inhibition) to create on task score and this resulting score correlated significantly with age (Hughes & Ensor, 2005, 2006). This might suggest that shifting score might still not have emerged as a dissociable core component of executive functions in toddlerhood (Hendry et al., 2016). There is much conflicting evidence surrounding this question. For example, previous research has found that the best-fitting model of performance in 6-year-olds consisted of an updating factor and a combined inhibition and shifting factor (van der Ven et al., 2013), suggesting that EFs are not fully fractionated into independent components yet by this age.

Furthermore, the inhibition task showed a ceiling effect, more than 75% of the 2-year-olds and more than 90% of the 3-year-olds successfully completed the task. This inhibition task has previously been used to assess response inhibition between 14 and 36 months (Friedman et al., 2011); however, this study shows that it might not be the most sensitive task to assess individual difference in inhibition in toddlers and early preschoolers. Lastly, in this sample, there was no relationship between working memory and inhibition, which is often reported in adults. Similarly, a previous study had also not demonstrated a correlation between working memory and simple inhibition in 18-month-olds (Gottwald et al., 2016).

A second limitation is that this study was unable to confirm whether children successfully remembered both goal constraints at the end of the planning task. In the previous study, children were able to verbally report the goal at the end of the task, despite failing to align their actions accordingly (Freier et al., 2017). However, verbal abilities in toddlers are limited (Colson & Dworkin, 1997). Most toddlers confirmed non-verbally by nodding that they thought their tower was equal to the one indicated on the wall.

A final point is that the child's motivation to plan actions according to the goal constraints might have influenced the results. Some children might have been able to keep track of the goal constraints and would, consequently, be able to plan their actions accordingly, but were not motivated to do so. Motivation is a key component of planning. Without motivation, planned

actions are abandoned before execution (Friedman et al., 1987). Future research should investigate the relationship between motivation and action planning in toddlerhood.

2.4.1 Conclusions

To summarise, this study showed that the ability to execute a simple pattern of alternating actions improved over toddlerhood, and that this ability was related to both improvements in working memory capacity and improvements in motor competence. Furthermore, 2-year-old toddlers were unable to keep track of two goal constraints in an action sequence planning task. However, 3-year-olds were more likely to successfully take both goal constraints into account when planning an action sequence. Furthermore, this emerging ability was suggested to be related to working memory across toddlerhood.

The next chapter will investigate preschoolers' ability to keep track of goal hierarchy in their action sequence planning and how this relates to executive function development. Furthermore, motion capture is employed to investigate implicit markers of hierarchical action sequence planning in preschoolers.

CHAPTER 3

Multilevel goal management in preschoolers' toy house constructions¹

3.1 Introduction

3.1.1 Action sequences

Action planning is crucial for everyday functioning. Planning and selecting an action or action sequence with success involves taking into account task demands or constraints from the environment. Actions should be adjusted with respect to these demands, and therefore planned ahead (Gottwald et al., 2017; von Hofsten, 1993, 2004). In our daily life, we constantly plan action sequences consisting of multiple levels of goals set within a goal hierarchy (Rosenbaum et al., 2007). These goal hierarchies are the foundation of everyday goal-directed behaviour (Cooper et al., 2014). Even something as simple as making a cup of coffee in the morning comprises a hierarchical goal structure. The main goal of making a cup of instant coffee consists of several subgoals such as adding the granules, which in turn consists of several action steps such as picking up the granules package. Depending on the action sequence, specific action steps may have to be selected in a specific order. For example, you cannot pour the milk before picking up the milk package. Furthermore, the executor of the action sequence has to maintain the main goal of the hierarchy throughout the task, while keeping track of which subgoals and which action steps have already been executed, and which subgoals and which action steps should be executed next (Botvinick, 2008; Cooper et al., 2014; Cooper & Shallice, 2000, 2006; Miller et al., 1960).

In adults, action selection within a goal hierarchy was slowed down at decision boundary points (also called 'branch points') where a switch from one subgoal to another was required (Arnold et al., 2017; Ruh et al., 2010). In several action sequence planning task, both in real-life as in a computer-based tasks, action selection took more time at branch points when a switch from one subgoal to the next subgoal was made (Arnold et al., 2017; Ruh et al., 2010). Selecting the next action of the next subgoal at these branch point in hierarchical planning was thought to

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require cognitive control. The resulting increased cognitive load at branch points was reflected in increased selection time (Ruh et al., 2010).

Motion capture techniques can potential be useful to investigate these dynamic markers of hierarchical action planning. Indeed, motion capture can be employed to reveal the temporal progressions of decisions and actions, which would otherwise remain concealed from the human eye (Freeman et al., 2011; Song & Nakayama, 2009). For example, reaching kinematics were influenced by dynamic decision processes that occur in parallel both in lower- (Song & Nakayama, 2006, 2008; Spivey et al., 2005; Welsh & Elliott, 2005) and higher-level processing (Dale et al., 2008; McKinstry et al., 2008). Furthermore, there were promising prospects of using motion capture to investigate the development of online decision-making processes in children (Erb et al., 2017, 2018).

3.1.2 Development of action sequence planning

Recent studies have shown that 5-year-old children were able to align their planning and execution of action sequences to the goals at all levels of the goal hierarchy (Freier et al., 2017; Yanaoka & Saito, 2017, 2019). Three- and 4-year-old children, in contrast, had difficulties to keep track of the main goal in a goal hierarchy while planning and executing an action sequence (Freier et al., 2017; Yanaoka & Saito, 2017, 2019).

For example, when preschoolers were instructed to follow two levels of goals in their colouring of farm animals, both 3- and 5-year-old children showed good abilities to access and follow the lowest level goal (i.e. follow an arrow indicating the order of colouring) in their action sequence planning and execution. However, only 5-year-old children were able to align their actions according to the highest goal (i.e. use each of the three colour pencils equally often) (Freier et al., 2017). Similarly, 5-year-old children were able to accommodate their actions according to the main goal in a doll-dressing task, while 4-year-olds may set subgoals rather than maintaining the main goal (Yanaoka & Saito, 2017). Furthermore, 5-year-old children made more errors after disruptions in the middle of a subtask than after disruptions at the end of the subtask while performing a repeated familiar action sequence (Yanaoka & Saito, 2019), a pattern that is also found in adults' execution of familiar action sequences (Botvinick & Bylsma, 2005). However, 4-year-old children were sensitive to both types of interruptions, showing developmental difference in action sequence representations in preschool period (Yanaoka & Saito, 2019). Moreover, young preschoolers often demonstrated *goal neglect* in

which they show understanding of and remember the main goal, but failed to execute the task according to this goal (Marcovitch et al., 2007, 2010).

Imitation studies have provided more evidence for an improvement in action sequence planning in preschool period. In their second year of life, toddlers were able to imitate simple action sequences that consists of two or three action steps (Bauer & Hertsgaard, 1993; Bauer & Mandler, 1989, 1992; Bauer & Shore, 1997; Bauer & Thal, 1990). The ability to imitate more complex action sequences improved over preschool years.

These imitation studies have shown that memorization for the exact order of action steps in an action sequence was of low cognitive priority in children (Loucks & Price, 2019) and adults (Loucks et al., 2020). Hierarchical goal structures seemed to lead action sequence imitation, already early in life (Flynn & Whiten, 2008; Loucks et al., 2017; Loucks & Meltzoff, 2013; Whiten et al., 2006), potentially because planning action sequences to align the actions according to the hierarchical goal structure decreases cognitive load. For example, 3-year-old children imitated intact goal sequences in a similar way as interleaved sequences, indicating that the representations for these action sequence displays were similar (Loucks et al., 2017; Loucks & Meltzoff, 2013). The ability to follow the hierarchical goal structure in imitation increased between 3 and 5 years of age (Flynn & Whiten, 2008). Lastly, 3-year-old children were more likely to re-enact an action irrelevant to the hierarchical goal structure of that action sequence compared to 5-year-old children (Freier et al., 2015).

In sum, imitation studies have demonstrated a fledging hierarchical goal representation in early preschool period (Loucks et al., 2017; Loucks & Meltzoff, 2013; Whiten et al., 2006), but the ability to plan actions appropriately or these hierarchical goal representation still developed over preschool period (Flynn & Whiten, 2008; Freier et al., 2015; Yanaoka & Saito, 2019). This was consistent with the idea of graded goal representation, suggesting that representations become gradually stronger over development (Munakata, 2001).

3.1.3 Executive functions and action sequence planning

In short, the planning and control of action sequences developed throughout the preschool period. Five-year-old children were able to align their actions to the structure of the goal hierarchy of the action sequence, as do adults, whereas 3- and 4-year-old children experienced difficulties following the highest level goal (Freier et al., 2017; Yanaoka & Saito, 2017, 2019). However, it remains unclear what drives the improvements in planning and control of action sequences over preschool years. Many putative factors have proposed. For example, it has been

suggested that working memory, set shifting and especially inhibition could underlie this complex planning (McCormack & Atance, 2011).

These three abilities are commonly considered to be the core aspects of executive functions (EF). Executive functions can be defined as the cognitive control processes that regulate a person's goal-directed behaviour (Barkley, 2012; Miyake & Friedman, 2012). Planning is often described as a more complex and higher-level executive functions that is likely to be dependent on all three core aspects (working memory, set shifting and inhibition) of executive functions (McCormack & Atance, 2011; Miyake & Friedman, 2012).

Importantly, working memory, set shifting and inhibition are all skills that improve enormously over preschool period (Anderson & Reidy, 2012; Diamond, 2013; Garon et al., 2008). Furthermore, executive functions in both infancy and childhood were linked to motor planning (Gottwald et al., 2016; Pennequin et al., 2010) and motor behaviour (Livesey et al., 2006). Moreover, children with better set shifting skills also showed a more adult-like pattern in errors after disruptions when planning and executing a familiar action sequence. This suggests a relationship between action sequence representations and executive functions (Yanaoka & Saito, 2019). Lastly, here is also evidence for the role of EFs in acquisition of familiar action sequences in preschoolers (Yanaoka & Saito, 2020). Therefore, improvement in these three core components of executive functions may be related to improvements in planning and control of action sequence in preschool period.

3.1.4 Current study

This study aimed to provide a more in-depth understanding of the development of action sequences using optical motion capture. It investigate first how the development of action sequence planning in preschool period relates to the development of their executive functions. Second, this study investigate whether there are dynamic markers of hierarchical planning in preschoolers' action sequences when planning a complex goal-directed action sequence. To investigate this, this study uses a new and fun planning task using Duplo® blocks. Children had to build a house with Duplo blocks following an instruction video. The Duplo house could be built in different ways, investigating whether children plan their actions according to a hierarchical goal structure, and whether they are motivated to follow the hierarchical goal structure in their action sequence planning.

It was hypothesised that children with better executive function skills would be better at the action sequence planning task (McCormack & Atance, 2011). Furthermore, it was predicted

that children with adult-levels of proficiency of action sequence planning, action planning will be slowed down at branch points where a switch from one subgoal to another is required (Arnold et al., 2017; Ruh et al., 2010). These markers of hierarchical action planning are expected in children's reaching movements, because reaching kinematics was already affected in infancy by what to next with an object (Chen et al., 2010; Claxton et al., 2003), and was adjusted to the difficulty of the successive action (Gottwald et al., 2017). Therefore, it is hypothesised that children adjust their reaching at the 'more difficult' branch points.

3.2 Method

3.2.1 Participants

A total of 25 3-year-old ($M = 39.24$ months, $SD = 3.36$, 10 females), 24 4-year-old ($M = 50.71$ months, $SD = 2.79$, 10 females) and 20 5-year-old ($M = 63.05$ months, $SD = 2.19$, 10 females) children participated in this study. Participants were drawn from a population of typically developing children. Families were recruited from a database with interested caregivers, and contacted by phone or email to see whether they and their child would be interested in taking part. Participating in this study was entirely voluntary. Caregivers were informed about the test procedures prior to giving written informed consent, and all children gave verbal assent. Families were given a present and a certificate for participation, and all travel expenses were reimbursed.

Not all participants completed all the task. Four 3-year-olds and one 4-year-old had no data for the working memory task. One 3-year-old and one 4-year-old provided no motion capture data for the planning task, because they were unwilling to wear motion capture gloves. Two 4-year-olds provided no data for the planning task including the motion capture.

3.2.2 Procedure

All procedures were approved by the local ethics committee and conducted according to the principles of the Declaration of Helsinki. Children were tested in a quiet lab room with their caregiver present. Each child was seated in an age-appropriate chair with an age-appropriate table. The caregiver was seated behind the child, and the experimenter was seated at the left side of the child.

Children were presented with the five tasks in the following order: planning task, inhibition task, set shifting task, working memory task, and motor competence task. Children received a sticker as reward after each task and were praised for their performance. Four children executed

the executive function tasks and the motor competence task before the planning task, because they were initially uncomfortable with the motion capture procedure. Four children completed the motor competence task before the working memory task, due to technical problems at that certain moment.

All executive function tasks were programmed using PsychoPy coder interface (version 3.0.2 Peirce, 2008), and were played on a normal (15 inch) laptop with two smiley stickers on the spacebar to indicate the response button.

3.2.2.1 Planning task

Children were asked to wear cycling gloves with distinct small plastic plates of reflective markers on both hands (Figure 3.1). The marker of interest was located on the knuckle of the child's middle finger (3rd metacarpal). Movements were recorded at 100Hz using a 3D optical motion capture system (Vicon, Yarnton, United Kingdom). Six near-infrared cameras mounted on auto-poles were positioned around the table. The planning task was filmed using a synchronized video camera at 50Hz to record the child's behaviour.



Figure 3.1. A child wearing the motion capture gloves with two distinct plates of optical markers for the left and right hand.

The action sequence planning task involved constructing a Duplo house with a hierarchical goal structure for a Duplo man named Bob. Children were instructed to play close attention to a movie of an adult building the house, so that they could build it the exact same way. Children could re-watch the instruction movie until they felt ready to build the house. On average, children saw the movie 1.88 times ($SD = 0.96$, $range = 1 - 6$). It was checked whether the child had paid attention to the movie i.e. whether the child knew the goal of the task (build a house),

and the action sequence subgoal colours (yellow wall, followed by blue wall, followed by green roof). If the child answered incorrectly or was unsure, the experimenter discussed the movie again with the child.

Blocks necessary for building the house were stored in boxes which were mechanically wired to open when the child pressed a start button. This button press was introduced to ensure that each reach movement began from the same location. Boxes were manually closed by the experimenter at the end of each reach and grasp of a block. Each box contained the blocks of one colour that was required to complete one subgoal (Figure 3.2). Several distractor blocks were placed randomly between the boxes. Children were instructed to first build the house, before playing with the other fun blocks. The experimenter encouraged the child to build using the blocks provided, but never mentioned the goal nor the subgoal or the task, nor answered any questions of the child related to the planning task. The task was considered complete when the child indicated that their house was finished. The child was asked whether what they build and whether it was the same as they had seen in the movie.

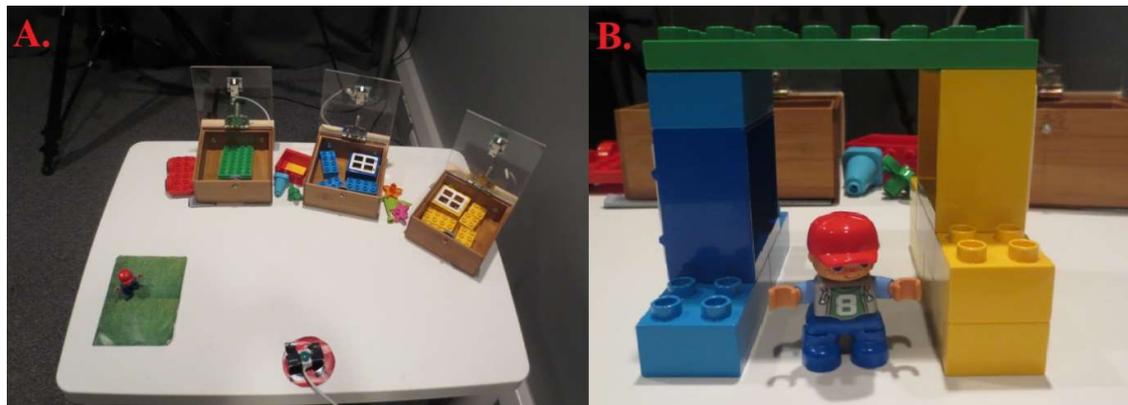


Figure 3.2. A. The set-up of the planning task. Pressing the small green button opens the boxes. B. The house as it should be built according to the instruction video.

3.2.2.2 Inhibition task

Inhibition was measured using the BAT task, a child-friendly version of the go/no-go task (Drechsler et al., 2010; Kaller et al., 2008; Sobeh & Spijkers, 2013). Children were told a story in which there was a small town that had problems with vampires, and were asked to be monster hunters.

If they saw a bat, children were instructed to press the space bar, because bats can change into vampires. If they saw a cat, children were instructed to not press the space bar, because cats

are good. Children were encouraged to press as quickly as possible for the bat (go-trials), but not for the cat (no-go trials). Before the start, children were asked what they had to do when they saw a bat, and what they had to do when they saw a cat. The task always started with two practice trials (one cat and one bat). Initially, there was always five go-trials to ensure that the go-response was the pre-potent response. The remaining trials occurred in a random order. The majority of the trials (74% or 26 out of 35 trials) were go-trials. Children had two seconds to respond, before the cat or bat disappeared from the screen, and the next trial started after an inter-stimulus interval of one second (Figure 3.3).

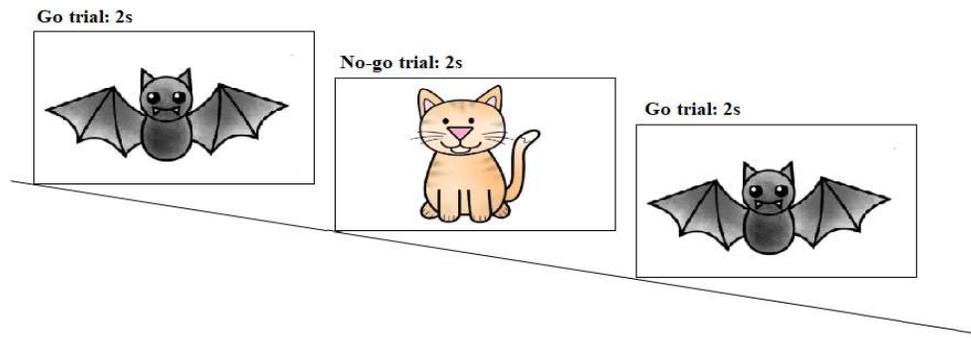


Figure 3.3. Example trials of the BAT inhibition task. Children were required to push the space bar whenever a bat appeared, but not when a cat appeared.

3.2.2.3 Set shifting task

Set shifting was assessed using an adapted shifting task. Children always saw two pictures on the screen at the same time, either a sun or a moon, and a fish or a fox. Half of the children played the moon game first, and the other half played the fish game first, assigned randomly based on participant number. Children were instructed that we are going to play the moon (or fish) game, and that it is really fun and easy. If they saw a moon (or fish), they were instructed to press between the smileys, but only if they see a moon (or fish). If they saw anything else, they were instructed to not press. The task started with three practice trials (two pressing trials, and one no-pressing trials). Each game consisted of 20 trials presented in a random order with 60% go-trials (i.e. requiring a button press).

After the moon (or fish) game, the experimenter instructed the child to forget about the moon (or fish) game, and the game that the child was playing switched. The experimenter continued to repeat exactly the same instructions as in the previous game. There were extra conflict trials

(in which the child did not need to respond before the rule-change) compared to other types of trials.

Children were reminded using an auditory cue ('we are playing the moon/fish game' or 'only press if you see a moon/fish') every four trials by showing a moon/fish surrounded by a red square. Children had three second to respond before the current trial disappeared from the screen, and the next trial started after an inter-stimulus interval of one second (Figure 3.4).

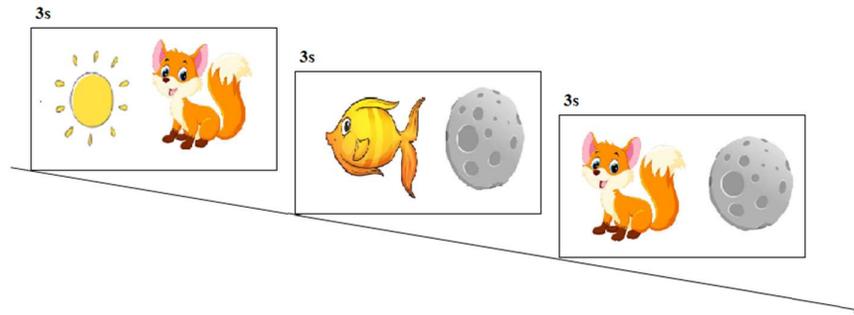


Figure 3.4. Example of three trials in the moon game. Children were required to press the space bar when they saw a moon. The fish game looked identical, except that children were required to respond by pressing the space bar when they saw a fish.

3.2.2.4 Working memory task

Working memory was measured using an auditory reverse digit span task (Carlson et al., 2002; Marcovitch et al., 2010). Children were presented with a silly bunny named Fluffy on the screen who said things backwards (Figure 3.5). Children were instructed to repeat the list of numbers that Fluffy said in the correct order. Fluffy first said 'Carrots like I' to illustrate how Fluffy said things the other way around. The experimenter demonstrated the first set of numbers to the child. There were three sets of two, three and four numbers. Children were reminded that that Fluffy said things the other way around at each trial. The experimenter would ask the child 'what Fluffy said', and 'since Fluffy says things the other way around, what Fluffy meant to say' each trial.

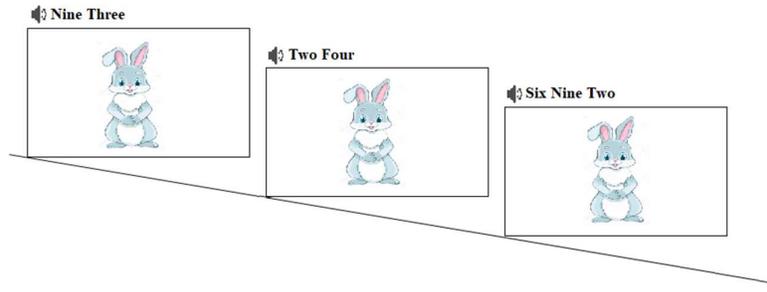


Figure 3.5 Example of three trials of the working memory task.

3.2.2.5 Motor competence task

Motor competence was assessed using a lacing card (Figure 3.6) (Forrester et al., 2019). Children were instructed to weave the lace through the holes in the paper lacing card. Prior to the start of this task, the experimenter demonstrated the child how to lace on a different card. Children had unlimited time to complete the lacing task, but only the first minute and a half were coded.



Figure 3.6. The task materials for the lacing task.

3.2.3 Data-analysis

3.2.3.1 Planning task

Children's performance on the planning task was coded offline. Three main behaviours of the planning task was coded binary; whether the child was able to complete the main goal, whether the child followed the subgoal order, and whether the child used distractors in their building. The main goal score indicated whether the child was able to finish the main goal of building a

house. A building with at least two walls, a roof and in which the Duplo man was able to fit in was counted as a house, and was given a score of 1. Anything else was scored as a fail with a score of 0. The ability to follow subgoal order was calculated as the amount of colour switches that occurred during the building of the house (i.e. each colour of blocks was associated with a different subgoal. The subgoal score was categorized into two groups; the perfect subgoalers were given a score of 1 (with 2 colour switches), and imperfect subgoalers were given a score of 0. Lastly, the number of distractor used in the building was counted. The distractor score was categorized into two groups: the group that was not distracted was given a score 0 and the group that was distracted was given a score of 1. Examples of children’s action sequences and corresponding houses are provided in the Appendix.

Table 3.1

Group sizes of the binary outcome variables of the planning task

	<i>N score = 0</i>	<i>N score = 1</i>
Main goal score	38	29
Colour switches (subgoal score)	29	38
Distractor score	54	13

The start and end of each reaching movement to grasp a Duplo blocks was coded as well. These action steps were divided into branch points (*between* subgoal steps, where the child switched from one subgoal to another) and *within* subgoal steps (where the child remained in the same subgoal as the previous action step). The start of each reaching movement was coded as the moment where the child pressed the button to open the boxes, the end as the moment where the child grasped a Duplo block. For each reaching trajectory, the hand that executed the reach (i.e. left or right) was coded, and kinematic data of this hand was used in further analysis for lingering and pause time. Markers and events were identified in Nexus (version 2.8.2, Vicon, Yarnton, United Kingdom), and data was pre-processed in MATLAB (version R2018b, MathWorks, Inc., Natick, Massachusetts, United States).

Missing knuckle markers were first interpolated using the three other markers on the same hand in Nexus. Steps with one missing marker frame were linearly interpolated in MATLAB. Remaining steps containing two or more consecutive frames with missing marker locations were excluded. Position vectors were padded with 1s (100 frames) before and after each reaching movement, and low-pass filtered using a Butterworth 2nd order filter with a low-pass

of 10Hz. Velocity vectors were calculated as the square root of the sum of squared differentials for the x, y and z vectors. Acceleration and jerk vectors were calculated as the first and second order differentials of the velocity vectors. Pre-processing steps were based on Cook and colleagues (2013). The first reach in this task was always excluded from the motion capture analysis. The following motion capture measures were derived from the data; lingering time, pause time and non-reaching hand movement.

3.2.3.1.1 Lingering time

Lingering time (in frames) was the number of total frames that the child waited to move to reach for a block after they had pressed the start button. It was hypothesised it was a measure of planning time before the next action step. Lingering time was calculated as the number of frames between the start frame pressing the button and the movement onset. The movement onset was calculated in the following three steps. First, the peak velocity of the reaching movement was calculated. Second, the first frame after the button press was determined where the velocity reached above 15% of the peak velocity. Third, the first frame before this 15% peak velocity frame where the acceleration was smaller than 0.1 mm/frame^2 was taken as the movement onset frame.

Steps in which the non-reaching hand pressed the button (branch points steps: 17% of total 169 steps; within subgoal steps: 15% of 378 steps), and steps with two or more consecutive missing frames were excluded (branch point steps: 1 out of 169 steps; within subgoal steps: 0 out of 378 steps). Two additional participants were excluded from this analysis, because they had no valid branch point steps. The final analysis included 63 participants. The hypothesis was that children who would follow the goal hierarchy, would linger longer at branch point steps, reflecting hierarchical action planning. There was no specific hypothesis about age effects on lingering time.

3.2.3.1.2 Pause time

Pause time (in frames) was the time that the child waited to press the button after moving back to the button from the previous action step. An effect of hierarchical action planning was only expected here, if the child considered the button press as the initial part of grasping-a-block movement. This was calculated as the number of frames between the movement offset and the start frame pressing the button. The movement offset frame was calculated in the following three steps. First, the peak velocity for each reach was calculated. Second, the frame in which the velocity reached above 15% of the peak velocity for the last time before the button press

was calculated. Third, the first frame after this velocity frame in which the acceleration was smaller than 0.1 mm/frame^2 was taken as the movement offset frame.

Steps in which the non-reaching hand pressed the button (branch points steps: 17% of total 169 steps; within subgoal steps: 15% of 378 steps), and steps with two or more consecutive missing frames were excluded (branch point steps: 1 out of 169 steps; within subgoal steps: 4 out of 378 steps). Two additional participants were excluded due too few valid steps. The final analysis included 63 participants. Here, the hypothesis was that there would be no evidence of hierarchical action planning in pause time, since it was expected that children would not consider the button press as a part of the grasping-a-block action.

3.2.3.1.3 Non-reaching hand movement

The non-reaching hand movement measure reflected the amount of movement the child made with their non-reaching hand. The hypothesis was that this could reflect hand gestures that would help the child plan. The mean velocity (in mm/frame) between 2s (200 frames) before and 2s (200 frames) after the button press was calculated.

Steps in which the non-reaching hand pressed the button (17% of total 169 steps; within subgoal steps: 15% of 378 steps), and steps with two or more consecutive missing frames (branch point steps: 9% of 169 steps; within subgoal steps: 15% of 378 steps) were excluded. Five additional participants were excluded because they had no valid branch point steps of their non-reaching hand data. The final analysis included 60 participants. The hypothesis was that there would be more non-reaching hand movement at branch points, if the child followed the hierarchical goal structure.

3.2.3.2 Inhibition

The total number of errors (misses and false alarms) divided by the number of trials was taken as the inhibition score.

3.2.3.3 Set shifting

The pre-shift and post-shift error rates of the shifting task was calculated. The error rate was the number of misses and false alarms divided by the number of trials. The shift effect error rate, the set shifting score, was calculated by subtracting the pre-shift error rate from the post-shift error rate.

3.2.3.4 Working memory

The average proportion correct across every set of items (two, three and four) was coded respective of serial order (updating) and irrespective of serial order (working memory). The scores were then averaged to create one average score on updating, and one average score on working memory.

The working memory score was calculated as described in Marcovitch and colleagues (2010), and reflected how many digits the child can successfully keep in their working memory. The updating score was an addition to the original procedure of Marcovitch and colleagues (2010) and reflected whether children are able to update the digit list in the right order in their working memory (i.e. say the list of number backwards). Previous studies have recommended that forward and backward digit span scores should not be combined, because there was evidence that these processes are distinct (Reynolds, 1997; Rosenthal et al., 2006).

3.2.3.5 Motor competence

The number of holes completed and the number of errors made during the first minute and a half were coded. An error was when the lace touched the card, but did not get weaved through the hole. The motor competence score was calculated as the number of correct holes divided by the total number of holes completed plus the number of errors.

3.3 Results

Analyses were implemented in RStudio (version 1.2.1335).

3.3.1 Behavioural results

3.3.1.1 Executive function tasks

To investigate the validity of the executive function tasks, the scores on each of these tasks were correlated with the child's age in months in planned analyses (Figure 3.7). It was expected that performance would improve with age.

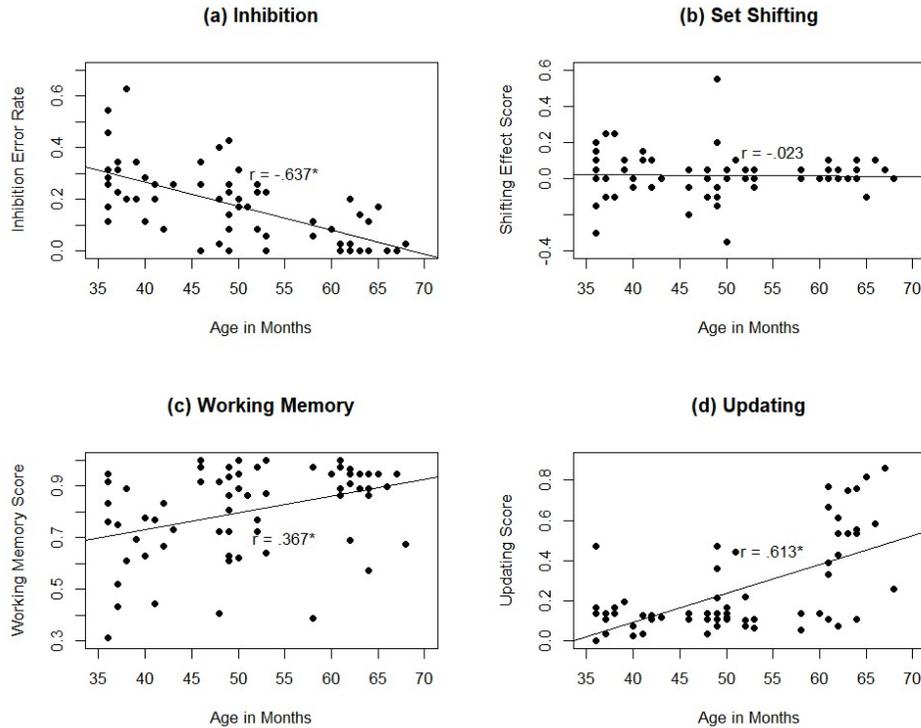


Figure 3.7. The scores for each child on the three executive function tasks (y-axis) and their age in months (x-axis). The * represents a significant correlation at $p < .05$.

Inhibition error rate correlated negatively with age in months ($r(69) = -.64, p < .001$). As predicted, younger children had a higher error rate than older children. The shifting effect score did not correlate with age in months ($r(69) = -.02, p = .853$), in contrast to the hypothesis. This reflects a lack of task sensitivity, suggesting this might not be the appropriate task to investigate set shifting in this age group. The working memory score on the digit span task correlated significantly with age in months ($r(64) = .37, p = .003$). As predicted, younger children had a lower working memory score than older children. The updating score on the backward digit span task correlated significantly with age in months ($r(64) = .61, p < .001$). As in the hypothesis, younger children had a lower updating score than older children.

Inhibition score correlated significantly with set shifting score ($r(69) = -.27, p = .024$), working memory score ($r(64) = -.41, p = .001$) and updating score ($r(64) = -.51, p < .001$). Set shifting score did not correlate with working memory score ($r(64) = -.02, p = .864$), nor with updating score ($r(64) = .07, p = .571$). Working memory score and updating score correlated significantly ($r(64) = .47, p < .001$).

3.3.1.2. Completing the main goal

To investigate whether age and executive function tasks scores were predictor of whether the child was able to keep track of the main goal (i.e. build the house), planned stepwise forward binary logistic regressions were used with the main goal as dependent variable (0 = fail to keep track of main goal, 1 = keep track of main goal), and age in months and EF tasks scores as predictors. Analysis with the sample with data for all tasks were reported ($N = 62$).

The analysis showed that age was a significant predictor of performance ($\chi^2(1) = 7.10, p = .008$, Nagelkerke $R^2 = .14$). Three-year-olds were less likely to keep track of the main goal successfully in the planning task than 5-year-olds (Figure 3.8).

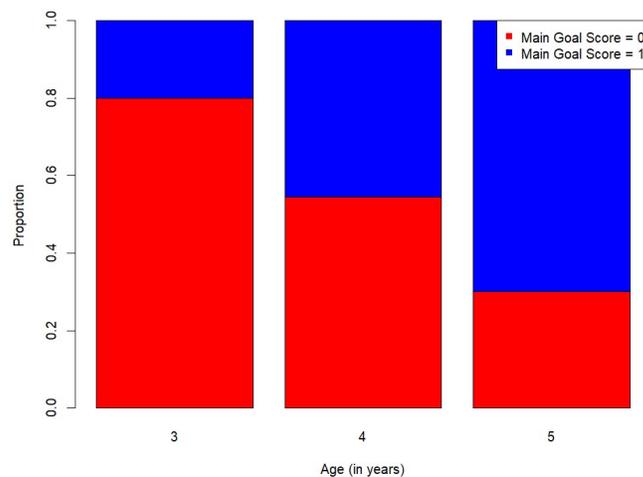


Figure 3.8. The proportion of 3-, 4- and 5-year-olds that were able to keep track of the main goal (blue) in the planning task, or that were unable to keep track of the main goal (red).

None of the executive function scores added anything significant over and above the variance explained by age in months (inhibition: $\chi^2(1) = 0.01, p = .916$; shifting score: $\chi^2(1) = 2.17, p = .141$; updating score: $\chi^2(1) = 1.39, p = .239$; working memory score: $\chi^2(1) = 0.33, p = .567$).

3.3.1.3 Following the subgoals

To investigate whether age and executive function scores were predictors of the child's ability to follow the subgoals, planned stepwise forward binary logistic regressions with subgoal score as dependent variable (0 = imperfect subgoalers, 1 = perfect subgoalers) and age in months and EF scores as predictors were used. Analysis with the sample with data for all tasks were reported ($N = 62$).

Updating score was the strongest predictor ($\chi^2(1) = 4.12, p = .042, \text{Nagelkerke } R^2 = .09$). The other predictors did not improve the model (age in months: $\chi^2(1) = 0.91, p = .292$; inhibition: $\chi^2(1) = 1.03, p = .309$; shifting: $\chi^2(1) = 1.11, p = .392$; working memory: $\chi^2(1) = 0.73, p = .392$). Perfect subgoal followers ($M = 0.30, SD = 0.28$) had a higher updating score than imperfect subgoal followers ($M = 0.19, SD = 0.20$).

3.3.1.4 Distractibility during planning

To investigate whether age and executive function scores were predictors of the child's distractibility, planned stepwise forward binary logistic regression with distractor score as dependent variable (0 = no distractors, 1 = distractor(s) used in the building) and age in months and EF tasks scores as predictors were used. Analysis with the sample with data for all tasks were reported ($N = 62$).

Inhibition score (error rate) was a significant predictor ($\chi^2(1) = 7.18, p = .007, \text{Nagelkerke } R^2 = .18$). Only updating score as predictor in combination with inhibition score improved the model ($\chi^2(1) = 3.89, p = .049, \text{Nagelkerke } R^2 = .26$). The other scores did not significantly improve the model (age in months: $\chi^2(1) = 0.96, p = .327$; shifting: $\chi^2(1) = 1.15, p = .284$; working memory: $\chi^2(1) = 0.36, p = .546$). Children who were not distracted during the planning ($M = 0.15, SD = 0.15$) had a lower error rate on the inhibition task than children who were distracted ($M = 0.27, SD = 0.12$). Furthermore, children who were not distracted during the planning task ($M = 0.29, SD = 0.24$) had a higher updating score than children who were distracted ($M = 0.11, SD = 0.05$).

3.3.1.5 Associations between the different behavioural planning measures

To investigate the associations between the main goal score, the subgoal score and the distractor score, three planned Fisher's Exact tests were executed. There was a significant association between the main goal score and the subgoal score (*odds ratio* = 4.22, $p = .007$), between the subgoal score and distractor score (*odds ratio* = 26.97, $p < .001$)², and between the main goal score and distractor score (*odds ratio* = 0.19, $p = .030$).

² There were no children with a subgoal score of 1 (perfect subgoalers) and distractor score of 1 (distracted). The odds ratio is therefore calculated as infinite. This odds ratio reported here is underestimation of the actual odds ratio.

3.3.2 Kinematics of action planning

3.3.2.1 Lingering time

One outlier with a score three times the standard deviation above the mean was removed from the analysis. All dependent variables were checked for normal distribution and homogeneity of variance. Analyses were planned. Non-parametric tests were reported if these assumptions were violated.

A non-parametric related-sample Wilcoxon Signed Rank test showed a higher lingering time at branch points ($M = 57.78$ frames, $SD = 47.16$, $median = 39.00$) compared to within subgoal steps ($M = 43.68$ frames, $SD = 47.51$, $median = 33.10$) ($z = 4.09$, $p < .001$, $r = .52$). To investigate possible effects between different groups, separate tests were conducted comparing the difference score (i.e. lingering time at within subgoal steps subtracting from lingering time at branch points) between age groups, main goal score and subgoal follower score.

A one-way ANOVA with the difference score of lingering time as dependent variable and age group as the between-subject factor showed no significant effects of age on the difference between lingering time at branch points and within subgoal steps ($F(2,59) = 0.71$, $p = .494$, Figure 3.9a).

A non-parametric independent sample Mann-Whitney U test with the difference score of lingering time as dependent variable and main goal score as between-subject factors showed no significant effect of main goal on the difference in lingering time at branch points and within subgoal steps ($z = 1.12$, $p = .264$, Figure 3.9b).

An independent sample t-test with difference score of lingering time as dependent variable and subgoal follower score as between-subject factors showed no significant effect of subgoal follower score on the difference in lingering time between branch points and within subgoal steps ($t(60) = 0.96$, $p = .342$, Figure 3.9c).

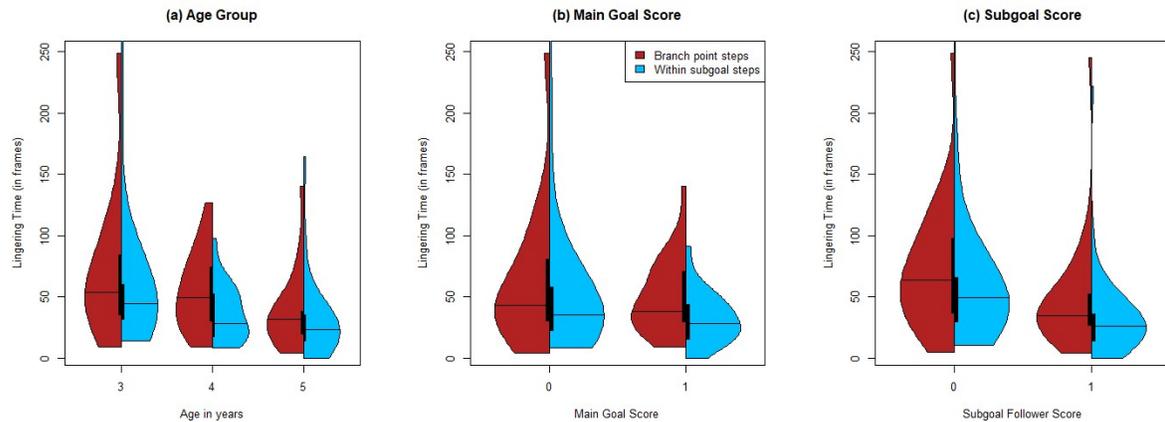


Figure 3.9. Violin plots of lingering time (in frames) for (a) the different age groups, (b) the different main goal scores, and (c) the different subgoal follower scores for both within subgoal steps (blue) and branch points (or between subgoal steps, red). The line represents the median value of each group.

3.3.2.2 Pause time

One outlier with a score three times the standard deviation above the mean was removed from the analysis. All dependent variables were checked for normal distribution and homogeneity of variance. Analyses were planned. Non-parametric tests were reported if assumptions were violated.

A non-parametric related-samples Wilcoxon Signed Rank test showed that pause time was not significantly different between branch points and within subgoal steps ($z = 1.20, p = .229$). To investigate potential effects between different groups, separate tests were executed comparing the difference score (pause time at within subgoal steps subtracted from pause time at branch points) between age groups, main goal score and subgoal follower score.

A non-parametric independent-samples Kruskal-Wallis test with the difference in pause time as dependent variable and age as independent variable showed no significant effect of age group on difference in pause time between branch points and within subgoal steps ($\chi^2(2) = 1.71, p = .426$, Figure 3.10a).

A non-parametric independent-samples Mann-Whitney U test with difference score of pause time as dependent variable and main goal score as between-subject factor showed no significant effect of main goal score on the difference in pause time in branch points and within subgoal steps ($z = 0.20, p = .844$, Figure 3.10b).

A non-parametric independent-samples Mann-Whitney U test with difference score of pause time as dependent variable and subgoal follower score as between-subject factor showed no significant effect of subgoal follower score on difference in pause time at branch points and within subgoal steps ($z = 1.05, p = .296$, Figure 3.10c).

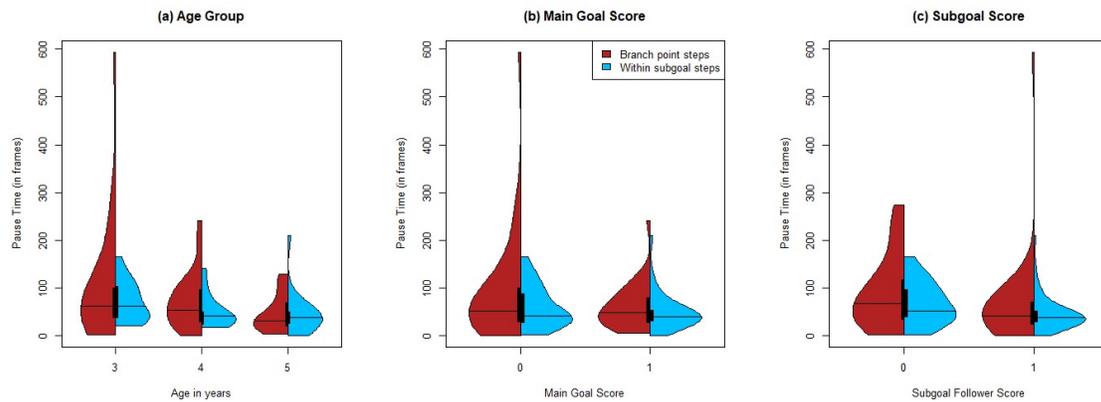


Figure 3.10. Violin plots of pause time (in frames) for (a) the different age groups, (b) the different main goal scores, and (c) the different subgoal follower scores for both within subgoal steps (blue) and branch points (or between subgoal steps, red). The line represents the median.

3.3.2.3 Non-reaching hand movement

One outlier with a score three times the standard deviation above the mean was removed for the analysis. All dependent variables were checked for the normal distribution and homogeneity of variance. Analyses were planned. Non-parametric tests were reported if the assumptions were violated.

A non-parametric related-sample Wilcoxon Signed Rank test showed that children had a higher mean velocity of the non-reaching hand at branch points ($M = 0.94$ mm/frame, $SD = 0.63$, $median = 0.86$) compared to within subgoal steps ($M = 0.78$ mm/frame, $SD = 0.61$, $median = 0.63$) ($z = 2.43, p = .015, r = .32$). To investigate potential effects between different groups, separate tests were conducted comparing differences scores (velocity at within subgoal steps subtracted from velocity at branch points) between age groups, main goal score and subgoal follower score.

A non-parametric independent-samples Kruskal-Wallis test with the difference in mean velocity of non-reaching hand as dependent variable and age as between-subject factor showed a significant effect of age group on difference in mean velocity between branch points and within subgoal steps ($\chi^2(2) = 8.95, p = .011, \epsilon^2 = .15$). Only the contrast between 3- and 5-year-

olds significant in pairwise Mann Whitney U tests ($z = 3.35$, $p = .002$, Bonferroni corrected). Five-year-olds have a higher difference in velocity of in the non-reaching hand between branch points and with subgoal steps ($M = 0.37$ mm/frame, $SD = 0.43$, $median = 0.44$) compared to 3-year-olds ($M = 0.01$ mm/frame, $SD = 0.35$, $median = -0.01$) (Figure 3.11a).

An independent sample t-test with difference score of the mean velocity of the non-reaching hand as dependent variable and main goal score as between-subject factor showed no significant effect of main goal score on the difference in velocity at branch points and within subgoal steps ($t(57) = 0.88$, $p = .382$, Figure 3.11b).

An independent sample t-test with difference score of velocity of non-reaching hand as dependent variable and subgoal follower score as between-subject factor showed that the difference between branch points and within subgoal steps was higher for the group that manage to follow the subgoal structure ($M = 0.26$ mm/frame, $SD = 0.43$) compared to the group that did not ($M = 0.00$ mm/frame, $SD = 0.52$) ($t(57) = 2.07$, $p = .043$, *Cohen's d* = 0.55, Figure 3.11c).

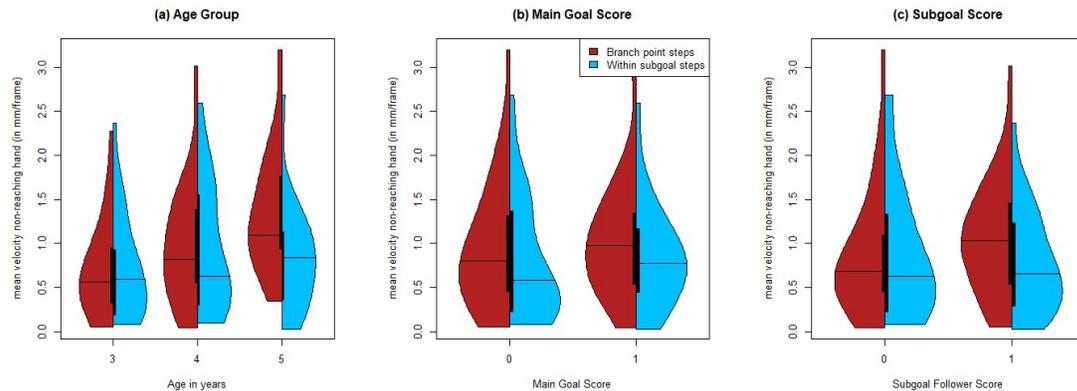


Figure 3.11. Violin plots of the mean velocity of the non-reaching hand (in mm/frame) for (a) the different age groups, (b) the different main goal scores, and (c) the different subgoal follower scores for both within subgoal steps (blue) and branch points (or between subgoal steps, red). The line represents the median value for each group.

3.3.2.4. Relationship between kinematics and EF scores

To investigate the potential relationship between the dynamic markers of action sequence planning measured by motion capture and executive functions, the executive function task scores were correlated with the kinematic scores. The kinematic scores were calculated as the score on the within subgoal steps subtracted from the score on the between subgoal steps

(branch points). Difference between classes of steps reflected evidence of hierarchical action planning of action sequence for that participants. For each of the kinematic scores, one outlier with a difference score three times the standard deviations above the mean was removed. Analyses were planned.

3.3.2.4.1 Lingering time

Non-parametric Spearman correlations were used for lingering time, because its distribution deviated significantly from a normal distribution ($W = .96, p = .029$). Lingering time difference did not correlate with the inhibition score ($r_s(62) = .02, p = .869$), the shifting score ($r_s(62) = -.18, p = .153$), the working memory score ($r_s(57) = -.07, p = .599$) or the updating score ($r_s(57) = -.13, p = .351$).

3.3.2.4.2 Pause time

Non-parametric Spearman correlations were used for pause time, because its distribution deviated significantly from a normal distribution ($W = .94, p = .003$). Pause time difference did not correlate with the inhibition score ($r_s(62) = -.05, p = .690$), the shifting score ($r_s(62) = -.23, p = .073$), the working memory score ($r_s(57) = .15, p = .267$) or the updating score ($r_s(57) = -.03, p = .804$).

3.3.2.4.3 Non-reaching hand movement

Non-reaching hand movement difference correlated significantly with inhibition score ($r(59) = -.33, p = .011$). This indicates that children who were better at inhibition (i.e. with a lower error rate), showed a bigger difference in their non-reaching hand movement at branch points compared to within subgoal steps. The non-reaching hand movement difference did not correlate significantly with shifting score ($r(59) = -.17, p = .187$), the working memory score ($r(54) = .07, p = .604$) or the updating score ($r(54) = .18, p = .194$).

3.3.2.5 Other movement parameters

This paragraph described the motor competence score and age-dependent effects on movement parameters incidental to the aims of this study. The motor competence score correlated significantly with age ($r(69) = .29, p = .026$) and was related to inhibition score ($r(69) = -.32, p = .007$) in planned correlation analyses, but not any of the other EF scores. The motor competence score did not correlate with any motion capture measure, therefore it was decided to exclude the motor competence score from further analyses.

The remaining exploratory motion capture measures are reported here. These variables were not taken into account in the hierarchical action planning analyses, because it was assumed that they reflect age-dependent effects in motor control. The straight path ratio was calculated as the distance travelled divided by the shortest path between start and end point. The shortest distance (in mm) was calculated with the Euclidean distance using the square root of the squared differences of x, y, and z values of the end- and start-point. The duration (in frames) was taken as the number of frames between the coded start and end frame of the reaching movement.

A repeated-measures ANOVA with age group as between-subject factor and type of action step (branch point step, within subgoal step) as within-subject factor and straight path ratio as dependent variable only showed a significant effect of age ($F(2,62) = 4.09, p = .021, \eta_p^2 = .12$) (Figure 3.12b). A similar analysis with duration as dependent variable showed also a significant effect of age ($F(2,62) = 8.29, p = .001, \eta_p^2 = .21$) (Figure 3.12a). Both straight-path ratio and duration decreased over preschool period. Furthermore, duration also showed a main effect of type of action step ($F(2,62) = 6.00, p = .017, \eta_p^2 = .09$), providing evidence for an increased duration at branch point steps when reaching for a new location compared to reaching to the previous box in within subgoal steps.

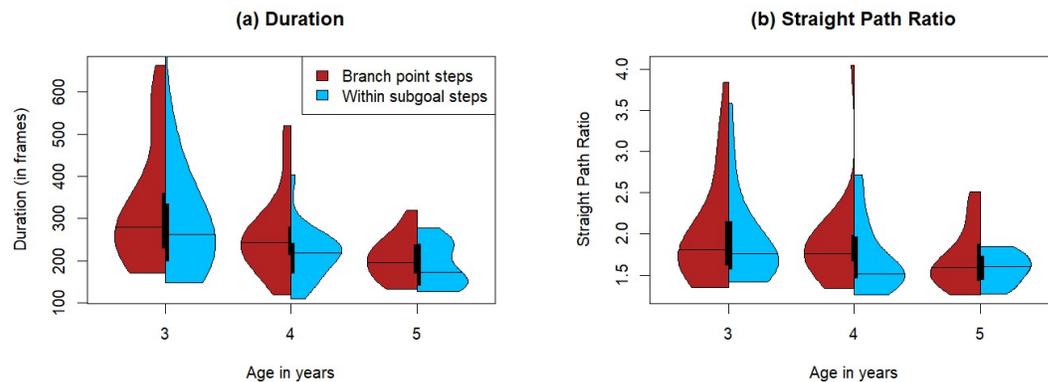


Figure 3.12. Violin plots of (a) duration (in frames) and (b) the straight path ratio for the different age groups for both within subgoal steps (blue), and branch points (or between subgoal steps, red). The line represents the median value for each group.

3.4 Discussion

The planning and execution of action sequences with a hierarchical goal structure improved over the preschool period (Freier et al., 2017; Yanaoka & Saito, 2017, 2019, 2020). This study

examined preschoolers' action sequence planning abilities, such as the ability to keep track of the key goal, follow the subgoals in action execution, and avoid actions irrelevant to the goal hierarchy. Furthermore, potential relationship between improvements in planning abilities and improvements in executive functions were assessed. Lastly, dynamic markers of hierarchical action planning in preschoolers' reaching were investigated using motion capture.

Results demonstrated that 5-year-old children were more often successful at planning and executing their actions according to the key goal compared to 3-year-old children. Furthermore, children who managed to follow the subgoal structure of the goal hierarchy displayed a better updating skills than children who mixed up the action steps. Good updating skills might be beneficial, because they support the ability to maintain which subgoal and action steps have been executed and which should be executed next. Moreover, inhibition skills were related to be less distracted when planning and executing the action sequence. Inhibitory skills are fundamental to overcome distractors or avoid executing actions irrelevant to the goal hierarchy. These results continued to highlight the importance of executive functions in the development of action sequence planning in preschool period (McCormack & Atance, 2011; Yanaoka & Saito, 2019, 2020).

The kinematic data showed structuring of subgoals in the velocity profiles of the non-reaching hand, especially in those older children who followed the subgoal order. Inspection of the video data showed that this effect was not explained by gesturing to support the planning, but instead by increased task focus while executing actions within a subgoal. This resulted in relative freezing of the non-reaching hand during the completion of the current subgoal. Conversely, at a branch point, the non-reaching hand would relax, resulting in more movement, taking time to plan and explore the next subgoal actions. The difference in the movement of the non-reaching hand observed between branch points and within subgoal steps was related to individual difference in inhibition. Children with better inhibitory skills showed less non-reaching hand movement during action steps within a subgoal. This suggests that inhibitory skills support a great ability to focus on executing the current subgoal and decreased susceptibility to distraction.

In infancy, a gradual decrease in movements of the non-acting hand or limb during actions such as reaching has been reported (D'Souza et al., 2017). Here, there was a gradual decrease in visible movements such as wiggling or twisting. These irrelevant non-acting limb movements might further decrease from toddlerhood through to childhood, resulting in small movements

only visible by fine-grained techniques such as motion capture. Moreover, these small movements in the non-acting hand might decrease while the child is concentrating on executing their actions, helping the child to improve cognitive focus on executing these actions with the acting hand, for example when executing the current subgoal. This can be seen as a form of *freezing* of degrees of freedoms to make up cognitive load for the action planning when the next reach is difficult to plan (Blanchard et al., 2005).

In contrast to the hypothesis, the lingering time after pressing the button did not show evidence of hierarchical planning. The original hypothesis was that lingering time would reflect the increased load when planning at branch points (Arnold et al., 2017; Ruh et al., 2010). However, the results suggest that lingering time here reflected the fact that reaching towards a new box at a branch point takes more time to plan compared to re-reaching to an exact identical location box as before in a within subgoal step. This could indicate that lingering time is either insensitive to whether children followed the goal hierarchy of the action sequence, or that the effect of a new reaching location at branch points dominated the lingering results. Pause time did not show any effect of hierarchical action planning, suggesting that children considered the button press as a distinct action, and not part of the grasping-a-block movement.

A limitation of the current study is that the shifting task was shown to be insensitive to age (as it was in Chapter 2), suggesting that the task was inappropriate to investigate set shifting abilities in the preschool period. Consequently, this study was unable to draw conclusions about set shifting and its link to planning abilities. Furthermore, the motivation of the child to plan their actions according to the goal hierarchy as displayed in the instruction video might have influenced the results. Perhaps some children managed to keep track of the subgoals and key goal, but were not motivated to execute their actions accordingly. Indeed, motivation is an important component of planning. Planned actions are abandoned before the execution phase without the motivation to reach a particular goal (Friedman et al., 1987). Future research should investigate the relationship between motivation and planning in preschool years to understand whether young children are unable to plan action sequence or are simply unmotivated. Moreover, a related limitation is that some children might not have remembered the goals, because they were uninterested in the instruction video. However, most children, if they were not too shy answer the questions of the experimenter, provided correct answers for all or most questions. This indicated that the children have paid attention to the instruction videos.

Furthermore in the kinematic analysis, it might be that wearing the gloves impact children's movement kinematics. However, there are some indication that these effects are small or even absent. The gloves were fine-fitted with different sizes. Moreover, the gloves were more likely to impact the grasp component of the movement, but this analysis only looks at the reaching components. Any interference due to wearing the gloves would be the same at branch points as well as within subgoal steps, so this could not be the cause of any observed differences between the two conditions.

3.4.1 Conclusions

To conclude, this study showed that maintaining the key goal when planning and executing an action sequence improves with age over preschool period. Two key executive functions were shown to be linked to improvements in action sequence planning. Inhibition was related to the ability to avoid actions irrelevant to the goal hierarchy of the action sequence. Updating was related to the ability to execute the actions according to subgoals. These results were consistent with the suggestion that executive function could underlie complex action sequence planning (McCormack & Atance, 2011). Executive functions are the key developmental factors linked to improvements in action sequence planning in preschool period.

Furthermore, this study demonstrated that children freeze their non-reaching hand during execution of a subgoal when following the goal hierarchy in action sequence planning. This showed further evidence of maturation of hierarchical goal representation over preschool years.

The next chapter will replicate and extend these findings by investigating whether the prefrontal cortex is involved in planning of action sequences with a hierarchical goal structure. Motion capture and wireless fNIRS are combined to investigate the freezing of the non-reaching hand during subgoals and the prefrontal cortex activation during branch points.

CHAPTER 4

Prefrontal cortex activation in preschoolers' multilevel goal management of toy house constructions.

4.1 Introduction

4.1.1 Development of action sequence planning

Action sequences are important in everyday life. As discussed throughout this thesis, many things we do are planned and controlled by action sequences with a hierarchical goal structure (Cooper et al., 2014; Rosenbaum et al., 2007). For example, the hierarchical goal structure of the action sequence 'making a cup of coffee' consists of the main goal of making a cup of coffee, and several subgoals such as adding the coffee granules. Each subgoal in turn consists of several action steps such as picking up a package or pouring. The actor has to keep track of both the main goal as well as which subgoals and action steps have already been executed, and which should be executed next (Botvinick, 2008; Cooper et al., 2014; Cooper & Shallice, 2000; 2006; Miller et al., 1960).

Recent studies have shown that planning and executing action sequences with a goal hierarchy developed in preschool period, with 5-year-olds showing mature abilities to plan and execute their action sequences, while 3- and 4-year-olds often struggled with keeping track of the main goal (Chapter 3; Freier et al., 2017; Yanaoka & Saito, 2017, 2019).

For instance, 5-year-olds showed good abilities to align their actions according to two levels of goals in their colouring of farm animals. However, 3-year-olds were only able to follow the lowest level goal (i.e. follow the arrow indicating the order of colouring), but not the highest level goal (i.e. use each of the three colours equally often) in their action sequence planning and execution (Freier et al., 2017). Furthermore, 4-year-olds would set subgoals rather than maintaining the main goal in a doll-dressing task, while 5-year-olds were able to plan and execute their actions according to the main goal (Yanaoka & Saito, 2017). In addition, 5-year-olds showed a pattern of errors similar to that of adults after disruptions in familiar action sequences, while 4-year-olds showed different sensitivity to errors, indicating a developmental difference in action sequence representation (Yanaoka & Saito, 2019). Lastly, in Chapter 3, the ability to keep track of the main goal in an action sequence with a goal hierarchy of building a Duplo house was related to age. Five-year-olds were more likely to build a house successfully as compared to 3-year-olds.

Moreover, imitation studies have demonstrated an improvement in execution of action sequences in the preschool period. For example, there was an improvement in the ability to follow the hierarchical goal structure in imitation between 3 and 5 years of age (Flynn & Whiten, 2008). In addition, 5-year-olds were less likely to re-enact an action irrelevant to the hierarchical goal structure compared to 3-year-olds (Freier et al., 2015). Hierarchical goal structures were already important in action sequence imitation early in life (Flynn & Whiten, 2008; Loucks et al., 2017; Loucks & Meltzoff, 2013; Whiten et al., 2013).

To summarise, early in preschool period, there seems to be a fledging hierarchical goal representation to support action sequence planning (Loucks et al., 2017; Loucks & Meltzoff, 2013; Whiten et al., 2006). However, the ability to plan and execute actions according to these hierarchical goal representations (or perhaps the hierarchical goal representations themselves) still develops over the preschool period (Flynn & Whiten, 2008; Freier et al., 2015, 2017; Yanaoka & Saito, 2017; 2019).

In adults, the selection of action sequences within a goal hierarchy was slowed down at branch points where a switch from one subgoal to another is required (Arnold et al., 2017; Ruh et al., 2010). Likewise, preschoolers who planned their action sequence according to the goal hierarchy showed more freezing of their non-reaching hand when they were executing the current subgoal, while they relaxed their non-reaching hand resulting in more movement at branch points (Chapter 3). The freezing of the non-reaching hand was suggested to reflect an increased task focus while executing the current subgoal.

4.1.2 Executive functions and action planning development

It has been suggested that improvement in the planning and execution of action sequences are related to improvement in executive functions in preschool period. Indeed, the core aspects of executive functions (i.e. working memory, set shifting and inhibition) all showed exceptional improvement over preschool period (Anderson & Reidy, 2012; Diamond, 2013; Garon et al., 2008).

Executive functions are linked to motor behaviour (Livesey et al., 2006) and motor planning (Gottwald et al., 2016; Pennequin et al., 2010) both in infancy and childhood. Moreover, the fact that children with better set shifting skills show a more adult-like pattern in errors after disruptions in familiar action sequences suggests a relationship between action sequence representations and executive functions (Yanaoka & Saito, 2019). Furthermore, executive functions was also related to the familiar action sequence of doll-dressing in preschoolers

(Yanaoka & Saito, 2017). Lastly, as shown in Chapter 3, two core aspects of executive functions were related to improvements in two distinct parts of action sequence planning. Inhibition was related to the ability to avoid executing action irrelevant to the goal hierarchy, and updating was related to the ability to execute actions according to subgoals. Therefore, executive functions could underlie complex action sequence planning improvements in preschoolers.

4.1.3 Neural mechanisms of action planning

But how does the brain support planning of action sequences, and how does this functional system develop? It has been hypothesised that action planning, selection and execution involves different, but connected underlying networks (Shallice & Cooper, 2011). For examples, in an fMRI grasping study, the planning network involved the *premotor cortex*, *basal ganglia*, *anterior cingulate*, and *dorsolateral prefrontal cortex* (Glover et al., 2012). The dorsolateral prefrontal cortex seems to be especially important in action planning; lesions in the right dorsolateral prefrontal cortex in adult patients were associated with planning impairments (Burgess et al., 2000). In addition, the dorsolateral prefrontal cortex was the only area that was only activated during the planning of tool-use actions, but not during the execution of these actions (Johnson-Frey et al., 2005). Furthermore, the dorsolateral prefrontal cortex was involved in preparing a future sequential action based on information stored in short-term working memory in an fMRI study (Pochon et al., 2001). Lastly, the dorsolateral prefrontal cortex was involved in planning in a Tower of London task assessed in a PET scanner (Dagher et al., 1999; Owen, 2005). Therefore, it has been suggested that dorsolateral prefrontal cortex plays a critical role in the network involved in planning of action sequences (Kaller et al., 2011; Tanji et al., 2007). For example, in a monkey study, the neuronal activity in the dorsolateral prefrontal cortex reflected future movements in multistep actions (Mushiake et al., 2006).

However, none of these studies have investigated neural areas involved in action sequences in preschoolers. Brain imaging patterns from preschoolers are difficult to investigate as they rarely comply with the restrictions of neuroimaging testing (i.e. sitting still, many trials). This chapter aimed to overcome this issues and filling the gap using wearable fNIRS.

This chapter focused on the dorsolateral prefrontal cortex and its involvement in action sequence planning in pre-schoolers. It should be emphasised that this is not the only area considered to be involved in action planning. However, given the anatomical evidence for a

change in the neural density in this area in early childhood (between 2 and 7 years of age; Diamond, 2002), it is a strong candidate for potentially being linked to improvements in action and action sequence planning that occur in this preschool. Furthermore, its location on the neocortex allows to use fNIRS to investigate brain activation patterns in children while they act.

Recently, the arrival of light-weighted fNIRS systems allows to measure brain activation patterns in more naturalistic situations (Pinti et al., 2018). However, real life situations do not follow a ‘block-design’, so new protocols must be developed as well as novel analysis approaches to deal with these less well-controlled experimental contexts with as small number of trials (Pinti et al., 2018). However, this can be done. For example, Pinti and colleagues (2015) examined brain activity using fNIRS in adults during a real-world prospective memory task. Similarly, the feasibility of using fNIRS to image brain function in naturalistic situations was shown in adults playing table tennis or a musical instrument, as well as other everyday activities (Balardin et al., 2017). The current study will extend this approach to a younger age group by using wireless fNIRS to investigate prefrontal cortex activation in planning of action sequence while preschoolers are able to freely move and construct their Duplo house.

4.1.4 Current study

The current study aims to extend the previous chapter to investigate neural areas supporting action sequence planning. This study builds on the previous study and has a secondary aim to replicate that the ability to plan and execute action sequences with a hierarchical goal structure develops over preschool years, and that improvements are linked to improvement in executive functions. Once again, this study instructed children to build a house with Duplo blocks following an instruction movie. It was hypothesised that children with better executive functions skills would be better at the action sequence planning task (Chapter 3; McCormack & Atance, 2011).

Furthermore, Chapter 3 used optical motion capture to demonstrate that children freeze their non-reaching hand during the execution of a subgoal when following a goal hierarchy in the action sequence. The current study has a further aim of replicating these results in a new sample. The hypothesis is that children that are able to follow the goal hierarchy will freeze their non-reaching hand more (i.e. showing less movement) when they execute the current subgoal, while relaxing their non-reaching hand more (i.e. showing more movement) at branch points when they plan the next subgoal.

The most important aim of this study is to investigate the involvement of the prefrontal cortex in action sequence planning. To do this, a wireless fNIRS system is used measuring brain activation over the frontal and motor cortices simultaneously with motion capture in the action sequence planning task. It was hypothesised that older children who are able to follow the goal hierarchy (i.e. good planners) will show more recruitment of the prefrontal cortex (especially the dorsolateral prefrontal cortex) at branch points where the switch from one subgoal to another has to be made.

4.2 Method

4.2.1 Participants

Fifteen 3-year-olds ($M = 40.34$ months, $SD = 3.02$ months, 8 females) and 16 5-year-olds ($M = 64.41$ months, $SD = 3.41$ months, 4 females) participated in this study. Families were recruited from a database of interested caregivers and were a population of typically developing children. Caregivers were contacted by phone or email to see whether their family would be interested in participating. Participation was entirely voluntary. Prior to giving informed consent, caregivers were informed about all test procedures. All children gave verbal assent. Families were given a small present ('child-scientist t-shirt') and a certificate for participation. Travel expenses were also reimbursed.

Participants were tested on four tasks. Not all participants completed all tasks. One 3-year-old child did not provide any data for any of the executive function tasks, while one additional 3-year-old provided no data for the digit span task (working memory and updating). One 3-year-old refused to wear the NIRS cap and provide no fNIRS data for the inhibition as well as the planning task.

4.2.2 Procedure

All procedures were conducted according to the principles of the Declaration of Helsinki and approved by the local ethics committee. All adults wore a face covering to account for restrictions because of COVID-19 pandemic. Children were tested in a quiet lab ('Preschool Lab in ToddlerLab') with their caregiver present. The lab was designed to look like a naturalistic preschool environment. Children were seated in an age-appropriate chair at an age-appropriate table.

Children were presented with the four tasks in the following order: planning task, inhibition block-design task, set shifting task and working memory task. Motion capture and fNIRS data

was recorded during the planning task, and fNIRS data was recorded during the inhibition task. Children were praised for their performance after each task, and received a sticker as a reward. The executive function tasks were programmed using PsychoPy coder interface (version 3.0.2 Peirce, 2008). The tasks were played on a normal (15 inch) laptop with two smileys on the spacebar to indicate the response button for the inhibition task, and two smileys on the left and right arrow to indicate the response buttons for the set shifting task.

4.2.2.1 Planning task

The planning task was similar to the planning task described in Chapter 3. Children were asked to wear cycling gloves with distinct small plates of reflective markers on both hands (Figure 4.1). The marker of interest was located on the knuckle of the child's middle finger (3rd metacarpal). Movements were recorded at 120 Hz using with 16 near-infrared cameras using a 3D optical motion capture system (Vicon, Yarnton, United Kingdom). The near-infrared cameras were mounted to the walls surrounding the whole room. Two synchronised video cameras were used to record the child's behaviour in the planning task at 60 Hz.



Figure 4.1. A child wearing the motion capture gloves and the fNIRS cap.

Concentration changes of oxygenated haemoglobin (HbO₂) and deoxygenated haemoglobin (HHb) were recorded using a 46-channel wireless fNIRS system (Figure 4.1; 2 x Brite24, Artinis Medical Systems, Elst, the Netherlands). Channels were located bilaterally over prefrontal cortex and motor areas (Figure 4.2), operating at wavelengths of 760nm and 850nm with a 25-Hz sampling rate. The NIRS probe consisted of 34 optodes; 18 sources and 16

detectors equally divided over both hemispheres. Channel distances was 25 mm. The circumferences of the cap was 54 cm.

Participant's head circumference, distance from inion to nasion, and distance from left to right were measured. To ensure correct cap placement, pictures of the cap were taken to check placement prior the data-analysis.

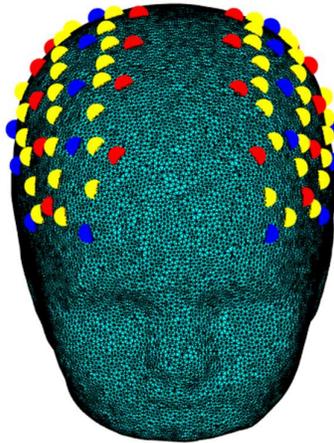


Figure 4.2. The optode arrangement with sources in red, detectors in blue and channels in yellow on head mesh computed from an MRI template of a 5-year-old (Brain Development Cooperative Group & Evans, 2006; Sanchez et al., 2010, 2012; Richards & Xie, 2015; Richards et al., 2016).

Motion capture data was temporally synchronised with the fNIRS data. A server computer sent a marker signal to both the motion capture and fNIRS acquisitions PCs (Clients) over the network creating a start marker in the data file and starting acquisition of the motion capture data. An end marker at the end of the task was transferred in the same way, resulting in an end marker in the fNIRS data file and the motion capture computer stopping data acquisition. Data was temporally aligned offline by including only the fNIRS data between these markers. Events identified from the video data frames (in 60 Hz) were adapted to the fNIRS frame rate (25 Hz) and kinematic data frame rate (120 Hz).

The action sequence planning task consisted of constructing a Duplo house with a hierarchical goal structure for a Duplo man named Bob (similar to Chapter 3). Children were instructed to be attentive to a movie of an adult building the house, and were instructed to build it the exact same way. Children could re-watch the instruction movies until they felt confident to build the house. The children saw the movie on average 2.03 times ($SD = 0.66$, $range = 1 - 4$). The main

difference in this task as compared to Chapter 3 was that the goal hierarchy was more nested; i.e., it consisted of more subgoals than the original task (5 instead of 3), and each of these subgoals in turn consisted of fewer action steps (ranging between 1 and 4) than in the original task.

Before the child started building, it was checked whether children knew the goal of the task (build a house), and the action sequence subgoal colours (yellow wall, followed by blue wall, followed by red wall, followed by pink wall, followed by green roof). The movie with main goal and subgoals were discussed again if the child answered incorrectly or was unsure.

Blocks to build the house were stored in five boxes which were mechanically wired to open when the child pressed a start button (similar to Chapter 3). This was to ensure that each reach movement began from approximately the same location. The experimenter manually closed the boxes at the end of each reach and grasp of a block. Each block contained the blocks of one colour required to complete one subgoal (Figure 4.3). Several distractor Duplo blocks (car, flowers, and flag) were placed randomly between the boxes, and children were instructed to first build the house before playing with these blocks. The experimenter encouraged the child to build, but never mentioned the goal or subgoals of the task, nor did she answer any questions related to the task. The task was considered complete when the child indicated their house was finished. What the child had built and whether it was the same as in the movie was then checked.



Figure 4.3 A. The set-up of the planning task. Pressing the white button opens the boxes. B. The house as it should be built according to instruction video.

4.2.2.2 Inhibition task

As in Chapter 3, inhibition was measured using the BAT task, a child friendly version of the go/no-go task (Chapter 3; Drechsler et al., 2010; Kaller et al., 2008; Sobeh & Spijkers, 2013). However, the inhibition task now followed a block design to ensure that the set-up could be used to measure prefrontal cortex activation in executive functions and planning.

Concentrations changes of oxygenated haemoglobin (HbO₂) and deoxygenated haemoglobin (HHb) were assessed using fNIRS as described in paragraph 4.2.2.1.

Children were told a story in which they were asked to be monster hunters for a little town. Children had to press the space bar if they saw a bat (go-trials), but not if they saw a cat (no-go trials). The task always started with two practice trials to ensure that the children knew what to do. The inhibition task consisted of 12 blocks (6 go-blocks and 6 mixed-blocks). Each go-block consisted of a number of between 9 and 11 trials (total number of go-trials in go-blocks = 60), and would only show bats. The mixed blocks consists of 10 trials each, 5 go-trials and 5 no-go trials (total number of trials in mixed blocks = 60), that appeared in a random order. After each block, there was a random period of rest between 8 and 12 seconds (Figure 4.4). Children had two seconds to respond, and the next trial appeared after an inter-stimulus interval of 1.5 seconds. In total, there were 90 go-trials and 30 no-go-trials (75% go-trials).

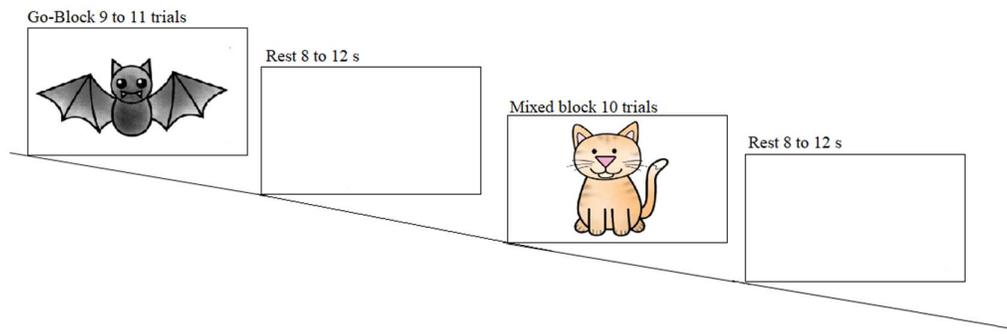


Figure 4.4. Example blocks of the BAT inhibition task.

3.2.2.4 Set shifting task

Set shifting was assessed with the land/food task (Carteron et al., in preparation). First, children would see an animal on the screen, with “land” on the right and “sea” on the left. After instructions and 4 practice trials with feedback, the Land game started. Children were asked to respond with whether the animal should live on the land (‘right arrow’) or in the sea (‘left arrow’). There were 6 different animals (giraffe, sheep, squirrel, whale, shark and dolphin) and each occurred twice in a random order. Children had 15 seconds to respond, but usually responded within 5 seconds. After this, the Food game started, and children were asked to respond with whether the object in the middle could be used to eat (‘right arrow’) or play sports (‘left arrow’). There were 6 different objects (tomato, hamburger, cheese, tennis racket, football and shoe), and each occurred twice in a random order. Lastly, children played a Mixed blocks

in which the land game and food game were intermixed. In this condition, the trials would always occur in a set order; one land game, and food game, one land game, etc. All objects or animals occurred twice, and there was a total of 24 trials in this block. The inter-stimulus interval was 1 second.

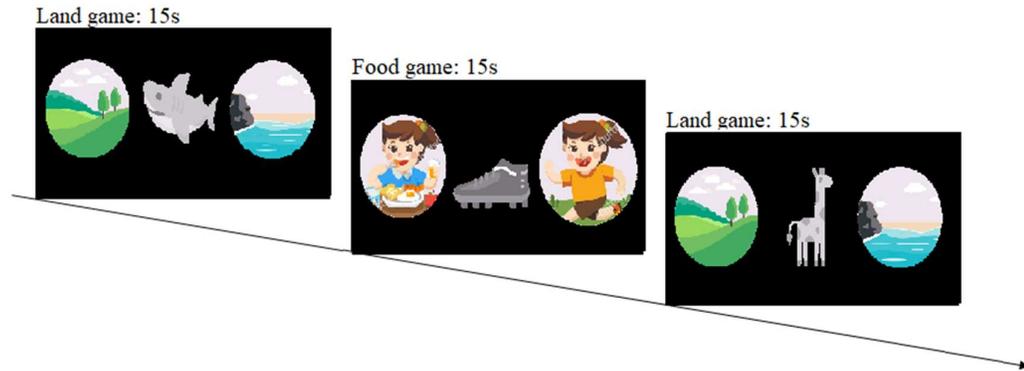


Figure 4.5. Example of three trials in the Mixed game to assess set shifting. Children had to press the left arrow to respond 'left', and the right arrow to respond 'right'.

4.2.2.4 Working memory task

The working memory task (identical to Chapter 3, Figure 4.6) was used to assess working memory and updating. It was an auditory reverse digit span task (Carlson et al., 2002; Marcovitch et al., 2010). Children were shown a bunny named Fluffy who said things backwards. After two examples, children were to repeat the numbers that Fluffy said the other way around. There were three sets of two, three and four numbers. The experimenter asked the child after each trial 'what Fluffy said', and 'Fluffy says things the other way around, what did Fluffy meant to say'.

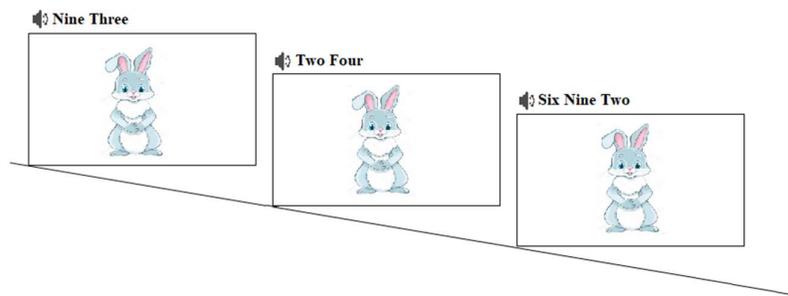


Figure 4.6. Example of three trials of the working memory task.

4.2.3 Data-analysis

Hypotheses and analyses were preregistered on AsPredicted (number 67098) prior to the start of testing.

4.2.3.1 Planning task

Children's performance was coded offline. As in Chapter 3, three main behaviours were coded using a binary score: (i) whether the child was able to complete the main goal, (ii) whether the child followed the subgoal order, and (iii) whether the child used distractors in their building. The main goal score indicated whether the child were able to finish the key goal of building a house. A building with four walls and a roof was coded as a house, with a main goal score of 1. Anything else was given a score of 0 and coded as a fail of building according to the main goal. The ability to follow the subgoal order was scored based on the number of colour switches that occurred during the building of the house. Each colour of blocks was associated with a different subgoal. The subgoal score was based on the categorisation of two groups: perfect subgoalers were given the score of 1 (with 4 colour switches) and imperfect subgoalers (with more colour switches) were given a score of 0. Lastly, the number of distractors that were used when building the house was counted. Children who used distractors in their building were given the score of 1, and children who were not distracted were given a score of 0.

Table 4.1

Group sizes of the binary outcome variables of the planning task

	<i>N score = 0</i>	<i>N score = 1</i>
Main goal score	16	15
Colour switches (subgoal score)	18	13
Distractor score	26	5

The start and end of each reaching movement to grasp a block was coded. These action steps were divided into branch points (*between* subgoals steps, where children switched from building one subgoal to building another subgoal), and *within* subgoal steps (where children remained building the same subgoal). The start was coded as the moment when the child pressed the button to open the boxes. The end was coded as the moment when the child grasped the Duplo block. For each reach, the hand that executed the reach (left or right) was coded.

4.3.3.1.1 Motion capture processing

Pre-processing was performed identical to that in Chapter 3. Markers and events were identified in Nexus (version 2.12.0, Vicon, Yarnton, United Kingdom). The data was pre-processed in MATLAB (version R2018b, Mathworks, Inc., Natick, Massachusetts, United States). Missing knuckle marker locations were first interpolated using the other three markers of the same hand in Nexus. One missing marker frame were linearly interpolated in MATLAB. Remaining steps that were missing knuckle marker location for two or more consecutive frames were excluded.

Positions vectors were padded with 100 frames (0.8s) before and after each reach movement, and low-pass filtered using a Butterworth 2nd order filter with a low-pass frequency of 10Hz. The square root of the sum of square differentials of the x, y and z vectors was used to calculate velocity vectors. Acceleration vectors were calculated as the first order differential of velocity vectors. The first reach in the task was excluded from the motion capture analysis.

As in Chapter 3, the mean velocity of the non-reaching hand between the 2s (220 frames) before and 2s (220 frames) after the button press was taken as a measure of relative freezing. Steps in which the participant used the non-reaching hand to press the button were excluded. Twenty-two branch point steps (13.4% of total 164 steps) and 17 within-subgoal steps (10.7% of total 159 steps) were excluded because the non-reaching hand pressed the button. Eleven branch point steps (7.6% of 164 steps) and 9 within-subgoal steps (5.7% of 159 steps) were excluded because of missing data. The hypothesis was that there is more freezing (i.e. less movement with non-reaching hand) at within-subgoal steps as compared to branch points, in children that followed the subgoal structure of the task.

Lingering time and pause time (in frames) were also calculated. It was expected that lingering time would be larger at branch points compared to within-subgoal steps, but this would be independent of the child's ability to plan hierarchical action sequences. No effects in pause time were expected. Steps for which the non-reaching hand pressed the button were excluded for both lingering and pause time (as above 22 branch point steps and 17 within subgoal steps). Furthermore, twenty additional branch point steps (12.2% of total 164 steps) and 18 within-subgoal steps (11.3% of total 159 steps) were excluded in lingering time because of missing data. In pause time, 16 branch points steps (9.7%) and 6 within-subgoal steps (3.8%) were excluded because of missing data.

Lingering time was calculated as the time between the frame corresponding to pressing the button and the reach movement onset, while pause time was the time between the frame corresponding to reach movement offset and the frame corresponding to pressing the button. Both the movement onset frame as well as the movement offset frame were calculated in three steps. First, the peak velocity of the reaching movement was calculated. Second, for lingering time the first frame after the button press was determined where the velocity reached above 15% of peak velocity, while for pause time this was the last frame before the button press. Third, for lingering time the first frame before this 15% peak velocity frame where the acceleration was smaller than 0.1mm/frame^2 was taken as movement onset frame, while the first frame after this 15% peak velocity with the acceleration smaller than 0.1mm/frame^2 was taken as the movement offset frame for pause time.

4.2.3.1.2 fNIRS pre-processing and analysis

Pre-processing and analysis was done in MATLAB (version R2018b). Channels' quality was assessed using QT-NIRS (Quality Testing NIRS; Montero Hernandez & Polloni, 2020) in order to identify noisy channels to be excluded from further analyses. This automatic quality assessment of noisy channels was shown to be as competent as visual coding by experts (Montero Hernandez et al., in preparation). Pre-processing steps were based on Pinti and colleagues (in preparation). Raw intensity signal at both wavelengths were analysed in 5 seconds time windows to identify the heart beat rate, expected to be between 1.5 Hz and 3.4 Hz in this age group. An SCI (scalp coupling index) of 0.7 and PSP (peak spectral power) of 0.1 were used to identify the presence and power of the heart rate component. Channels with $\text{SCI} > 0.7$ and $\text{PSP} > 0.1$ in at least 65% of the length of the signal were marked as good quality and included in the subsequent analysis.

Pre-processing of the data was done in Homer2 (Huppert et al., 2009). Raw data was converted from intensity to optical density measurements. Motion artefacts were detected channel by channel with a standard deviation threshold of 20 absorbance units and amplitude threshold of 5 μMol over 1s intervals. Artefacts were corrected using a spline motion correct with a parameter of .99 and wavelet-based correction method with an iqr parameter of 0.80 (Di Lorenzo et al., 2019). Data was band pass filtered between 0.01 and 0.50 Hz to minimise slow trends and high frequency physiological noise. Optical density data was converted to concentration data with age-dependent and wavelength-dependent differential path length

factors (3-year-olds: 5.4 μ M for 760nm and 4.6 μ M and 850nm; 5-year-olds: 5.5 μ M and 4.4 μ M respectively; Scholkmann & Wolf, 2013).

Subsequent analysis for the planning task was executed in SPM-fNIRS (Tak et al., 2016). HbO₂ and HHb time courses of each channel were fitted using a general linear model (GLM) approach using a hemodynamic response function (HRF) with time derivative to account for changes in the HRF shape and dynamics in preschoolers. The design matrix consisted of branch points and within subgoal steps for each participant identified from the video data. Beta values were then estimated and used to compare the branch points versus within-subgoal steps. Group level channel-wise one-sample t-tests (or corresponding non-parametric tests) were used to localise where within the PFC significantly higher changes in HbO₂ (oxygenated haemoglobin) and HHb (deoxygenated haemoglobin) occurred for branch points as compared to within-subgoals time points.

Noisy channels per participants were excluded, so each channel analysis consisted of a different number of participants; on average there were 2.96 participants per channel for 3-year-olds ($SD = 3.01$, $range = 0 - 11$; out of 14 participants) and 4.67 for 5-year-olds ($SD = 2.79$, $range = 0 - 10$; out of 16 participants). Channels were only included in the analysis if there were at least 2 participants.

4.2.3.1.3 fNIRS and motion capture interference

As motion capture and fNIRS both use near-infrared light, this could be a source of interference in the fNIRS data. To investigate potential interferences, the motion capture system was turned off in the inhibition task, and discrete Fourier Transform of both the inhibition fNIRS data and the planning fNIRS data was compared for each participant. Results demonstrated a frequency peak around 5Hz only observed in the planning data. In short, the interference of the motion capture occurred in frequencies much higher than the hemodynamic component (0.01-0.50 Hz), and is filtered out using a band pass filter in the pre-processing steps.

4.2.3.2 Inhibition

To calculate the inhibition score, the total number of correct trials was divided by the number of trials. The accuracy was also calculated for each block, and blocks with less than 50% accuracy were not included in the fNIRS analysis.

4.2.3.2.1 fNIRS pre-processing and analysis

Pre-processing steps were identical to that described in the pre-processing of the fNIRS planning data (*section 4.2.3.1.2*). First, the pre-processed data was converted into concentration data. Next, the data was segmented into segments from 5s pre-block onset to 30s post-block onset for each experimental condition (Go and Mixed Blocks). The segmented blocks were averaged over condition (Go blocks or Mixed blocks). The mean amplitude change (area under the curve) of HbO₂ (oxygenated haemoglobin) and HHb (deoxygenated haemoglobin) of each type of block was analysed. Group-level channel-wise paired sample t-tests were used to compare the amplitude changes in response to the Mixed Blocks versus Go blocks, for each chromophore individually.

Channels were excluded per participant if they were noisy. On average there were 3.85 participants per channel for 3-year-olds ($SD = 3.37$, $range = 0 - 14$; out of 14 participants) and 6.87 for 5-year-olds ($SD = 3.67$, $range = 0 - 13$; out of 16 participants). Channels were only included in the analysis if there were at least 2 participants.

4.2.3.3 Set Shifting

The pre-shift and post-shift error rate and average reaction times were calculated. Two scores were calculated. The shift error score was calculated as the total error rate post-shift (Mixed block) minus the total error rate pre-shift (Land and Food block). Furthermore, the reaction time post-shift (Mixed block) minus the reaction time pre-shift (Land and Food block) was calculated as the reaction time shift score.

4.2.3.4 Working memory

For each set (two, three or four digits), the average proportion correct was coded respective of serial order (updating) and irrespective of serial order (working memory). As in Chapter 3, the scores were averaged across sets to create an average score on updating and an average score on working memory.

4.3 Results

Analyses were implemented in RStudio (version 1.2.1335).

4.3.1 Behavioural results

4.3.1.1 Executive function tasks

To assess the validity of the executive functions tasks, the scores were correlated with the child's age in months (Figure 4.7) in planned analyses. Performance was expected to improve with age.

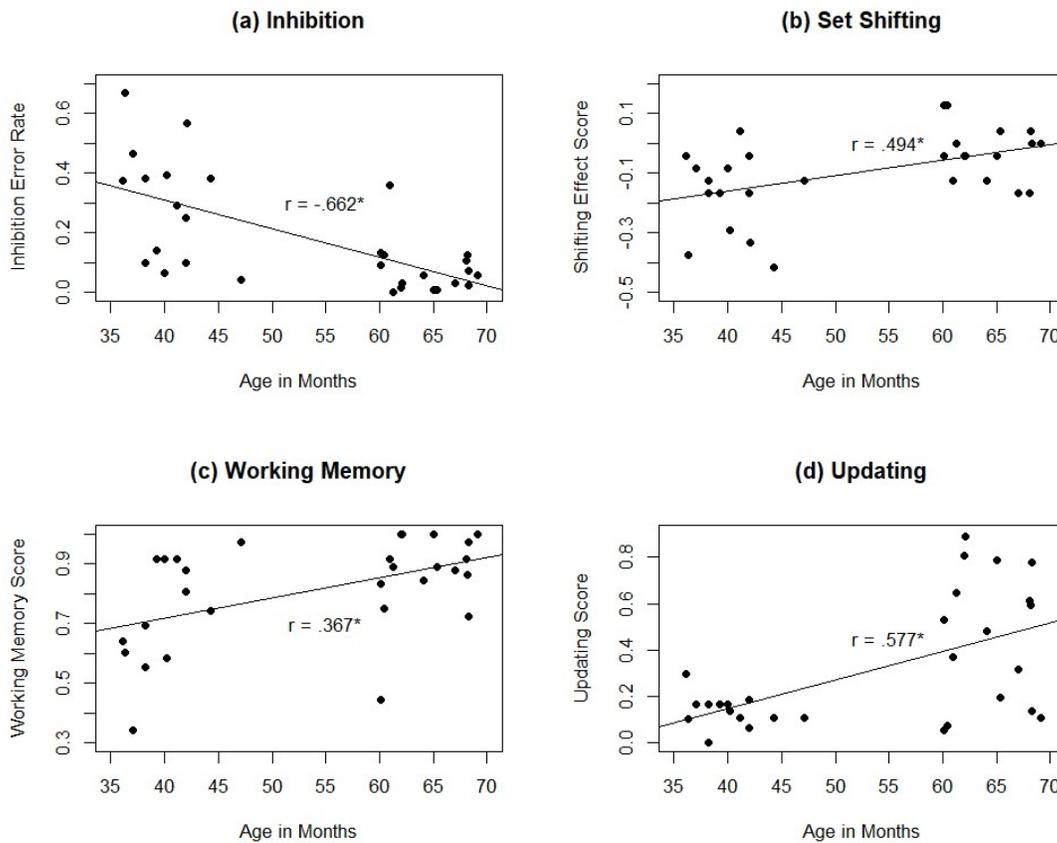


Figure 4.7. The scores for each child on the three executive function tasks (y-axis) and their age in months (x-axis). The * represents a significant correlation at $p < .05$.

Inhibition error rate correlated negatively with age in months ($r(30) = -.66$, $p < .001$; Figure 4.7a). As predicted, and similar to Chapter 3 (despite the task design changed to a block-design), younger children showed a higher error rate than older children. The shifting effect score on accuracy correlated with age in months ($r(30) = .49$, $p = .006$; Figure 4.7b), but the shifting effect score on reaction time did not ($r(30) = .25$, $p = .192$). Older children demonstrated a smaller loss in accuracy on Mixed trials as compared to younger children. The

working memory score in the digit span task correlated significantly with age in months ($r(29) = .37, p = .007$; Figure 4.7c). Similar to Chapter 3 and our hypothesis, younger children showed a lower working memory score than older children. Lastly, the updating score on the backward digit span task correlated significantly with age in months ($r(29) = .58, p = .001$; Figure 4.7d). Younger children had a lower updating score than older children, similar to Chapter 3 and our predictions.

Inhibition score correlated significantly with set shifting score ($r(31) = -.58, p = .001$), working memory score ($r(31) = -.66, p < .001$) and updating score ($r(31) = -.49, p = .005$). Set shifting score did not correlate with working memory score ($r(31) = .31, p = .086$) nor with updating score ($r(31) = .30, p = .100$). Working memory and updating scores correlated significantly ($r(31) = .44, p = .013$).

4.3.1.2 Behavioural scores of planning task

Three planned binary logistic regressions were executed to investigate whether the effects of Chapter 3 were replicated in this planning dataset. Specifically, they investigated whether age in months was a significant predictor of the child's ability to keep track of the main goal, whether updating score was a significant predictor of the child's ability to follow the subgoals, and whether the inhibition score was a significant predictor of the child's distractibility.

Like in Chapter 3, age was a significant predictor of whether a child kept track of the main goal (i.e. build the house) ($\chi^2(1) = 17.28, p < .001, Nagelkerke R^2 = .57$). Three-year-olds were less likely to keep track of the main goal successfully in the planning task than 5-year-olds (Figure 4.8). Note that, while in Chapter 3 about 80% of the 3-year-olds and 30% of the 5-year-olds were unable to keep track of the main goal (Figure 3.8), in this study, about 87% of the 3-year-olds and only 19% of the 5-year-olds is unable to keep track of the main goal.

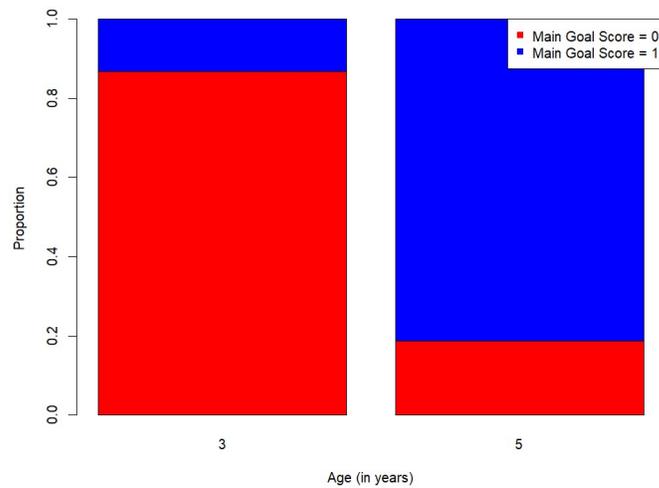


Figure 4.8. The proportion of 3- and 5-year-olds that were able to keep track of the main goal (blue) in the planning task, or that were unable to keep track of the main goal (red).

None of the executive function scores added anything significant over and above the variance explained by age in months (inhibition: $\chi^2(1) = 1.28, p = .311$; shifting score: $\chi^2(1) = 0.58, p = .448$; updating score: $\chi^2(1) = 0.75, p = .387$; working memory score: $\chi^2(1) = 0.96, p = .328$).

As age correlates significantly with all executive functions score, a forward binary logistic regression was executed with the four executive function scores as predictors. If age is not included in the model, inhibition score was the strongest predictor of the ability to complete the main goal ($\chi^2(1) = 11.54, p = .001, Nagelkerke R^2 = .42$) in an exploratory analysis.

Updating score was not a significant predictor of the child's ability to follow the subgoals ($\chi^2(1) = 2.37, p = .124$), in contrast to Chapter 3. None of the other executive function scores, nor age were significant predictors (inhibition: $\chi^2(1) = 3.30, p = .069$, shifting score: $\chi^2(1) = 1.17, p = .280$; working memory score: $\chi^2(1) = 2.38, p = .124$; age in months: $\chi^2(1) = 3.41, p = .065$).

As found in in Chapter 3, inhibition score was a significant predictor of whether the child was distracted ($\chi^2(1) = 8.21, p = .004, Nagelkerke R^2 = .400$). The other scores did not significantly improve the model (age in months: $\chi^2(1) = 0.18, p = .676$; shifting: $\chi^2(1) = 0.09, p = .761$; working memory: $\chi^2(1) = 1.79, p = .181$; updating score: $\chi^2(1) = 1.69, p = .184$). Children who were not distracted during the planning ($M = 0.15, SD = 0.15$) had a lower error rate on the inhibition task than children who were distracted ($M = 0.37, SD = 0.25$).

To investigate the associations between the main goal score, the subgoal score and the distractor score, three planned Fisher's Exact tests were executed. There was a significant association between the main goal score and the subgoal score (*odds ratio* = 16.92, $p < .001$), between significant association between main goal score and distractor score (*odds ratio* = 0.16, $p = .043$)³ and a marginal significant association between subgoal score and distractor score (*odds ratio* = 4.78, $p = .058$)⁴.

4.3.2 Kinematics of action planning

4.3.2.1 Linger time

One outlier with a score of more than three times the standard deviation above the mean was removed from the analysis. One participant was excluded because there were no valid within subgoal steps. All dependent variables were checked for assumptions. Analyses were planned. Non-parametric tests were reported if violated.

A non-parametric related-sample Wilcoxon Signed Rank test showed that, in contrast to the findings in Chapter 3, there were no significant difference between lingering time at branch points or within-subgoal steps ($z = 0.94$, $p = .347$). Separate tests were conducted comparing the difference score (i.e. lingering time at within subgoal steps subtracted from lingering time at branch points) between age groups, main goal score and subgoal follower score.

A non-parametric independent samples Mann-Whitney U test with the difference score of lingering time as dependent variable and age group as between-subject factor showed no significant effect of age group on difference in lingering time between branch points and within subgoal steps ($z = 1.64$, $p = .101$; Figure 4.9a).

A non-parametric independent sample Mann-Whitney U test with difference score of lingering time as dependent variable and main goal score as between-subject factor showed no significant effect of main goal score on difference in lingering time between branch points and within subgoal steps ($z = 0.97$, $p = .331$; Figure 4.9b).

³ There were no children with a main score of 1 (keep track of the goal) and distractor score of 1 (distracted). The odds ratio is therefore calculated as infinite. This odds ratio reported here is underestimation of the actual odds ratio.

⁴ There were no children with a subgoal score of 1 (perfect subgoalers) and distractor score of 1 (distracted). The odds ratio is therefore calculated as infinite. This odds ratio reported here is underestimation of the actual odds ratio.

An independent sample t-test with difference score of lingering time as dependent variable and subgoal follower score as between-subject factor showed no significant effect of subgoal follower score on difference in lingering time between branch points and within subgoal steps ($t(27) = 0.85, p = .404$; Figure 4.9c). In short, as in Chapter 3, none of these between-subject contrasts demonstrated that lingering time is sensitive to hierarchical planning.

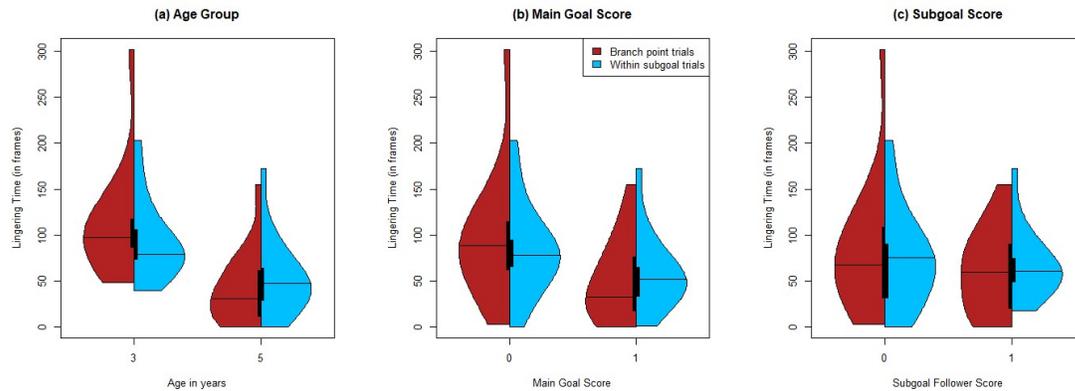


Figure 4.9. Violin plots of lingering time (in frames) for (a) the different age groups, (b) the different main goal scores, and (c) the different subgoal follower scores for both within subgoal steps (blue) and branch points (or between subgoal steps, red). The line represent the median value of each group.

4.3.2.2 Pause time

No scores were more than three times the standard deviations above or below the mean, so no outliers were removed. One participant with no valid within-subgoal steps was removed from the analysis. All dependent variables were checked for the normal distribution and homogeneity of variance. Analyses were planned. Non-parametric tests were reported if assumptions were violated.

A non-parametric related-sample Wilcoxon Signed Rank test showed that pause time was not significantly different between branch points and within-subgoal steps (as in Chapter 3) ($z = 0.21, p = .836$). Separate tests were conducted comparing the difference score (i.e. pause time at within-subgoal steps subtracted from pause time at branch points) between age groups, main goal score and subgoal follower score.

An independent sample t-test with difference score of pause time as dependent variable and age group as between-subject factor showed no significant effect of age ($t(29) = 0.50, p = .622$; Figure 4.10a).

An independent sample t-test with difference score of pause time as dependent variable and main goal score as between-subject factor showed no significant effect of main goal score ($t(29) = 0.18, p = .856$; Figure 4.10b).

An independent sample t-test with difference score of pause time as dependent variable and subgoal follower score as between-subject factor showed no significant effect of subgoal following ($t(29) = 0.02, p = .988$; Figure 4.10c). As reported in Chapter 3, pause time does not reflect hierarchical planning nor taking longer to plan before moving a new box.

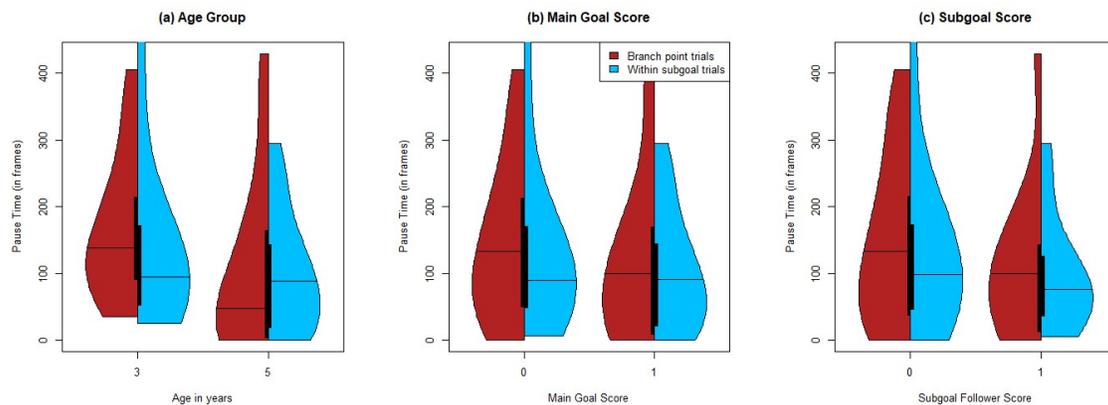


Figure 4.10. Violin plots of pause time (in frames) for (a) the different age groups, (b) the different main goal scores, and (c) the different subgoal follower scores for both within subgoal steps (blue) and branch points (or between subgoal steps, red). The line represents the median.

4.3.2.3 Non-reaching hand movement

No scores were more than three times the standard deviations above or below the mean, so no outliers were removed. Two participants with no valid within-subgoal steps were removed from the analysis. All dependent variables were checked for assumptions. Non-parametric tests were reported if assumptions were violated. Analyses were planned. One-tailed tests were run if the effect was significant in Chapter 3.

A non-parametric related-sample Wilcoxon Signed Rank test showed no significant differences in velocity of non-reaching hand at branch points and at within-subgoal steps ($z = 0.75, p = .455$). Separate tests were conducted comparing differences scores (velocity at within subgoal steps subtracted from velocity at branch points) between age groups, main goal score and subgoal follower score to investigate potential effects between different groups.

An independent sample t-test with difference score of velocity of non-reaching hand as dependent variable and age as between-subject factor showed no significant effect ($t(27) = 1.31, p = .101$, one-tailed; Figure 4.11a).

An independent sample t-test with difference score of velocity of non-reaching hand as dependent variable and main goal score as between-subject factor showed no significant effect ($t(27) = 1.08, p = .291$; Figure 4.11b).

An independent sample t-test with difference score of velocity of non-reaching hand as dependent variable and subgoal follower score as between-subject factor showed a marginal significant effect ($t(27) = 1.50, p = .072$, one-tailed, *Cohen's d* = 0.57; Figure 4.11c). The difference between branch points and within subgoal steps was higher for the group that manage to follow the subgoal structure ($M = 0.24$ mm/frame, $SD = 0.72$) compared to the group that did not ($M = -0.05$ mm/frame, $SD = 0.31$). Please note that although these effect were only marginally significant, they go in the expected direction (i.e., as seen in Chapter 3) but in a smaller sample size ($n = 29$ vs. $n = 58$) and showed similar effect sizes (*Cohen's d* Chapter 3 = 0.55 vs. *Cohen's d* Chapter 4 = 0.57).

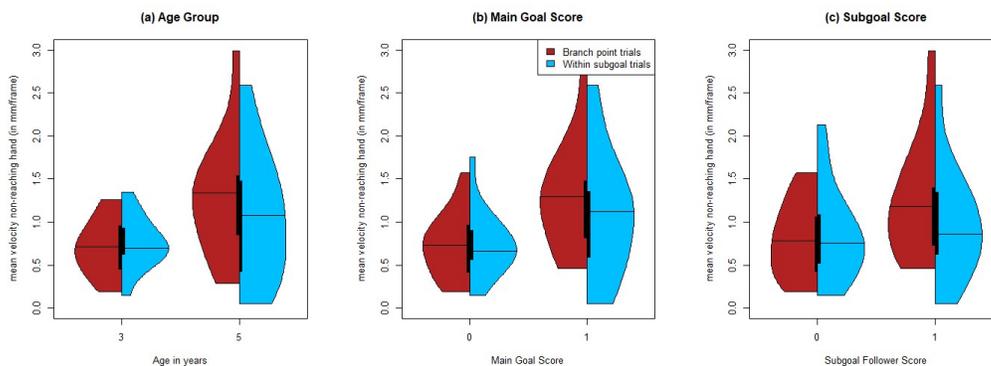


Figure 4.11. Violin plots of the mean velocity of the non-reaching hand (in mm/frame) for (a) the different age groups, (b) the different main goal scores, and (c) the different subgoal follower scores for both within subgoal steps (blue) and branch points (or between subgoal steps, red). The line represents the median value for each group.

Some children pressed the button using both of their hands, something that was not observed in the original study in Chapter 3. To explore the effect of freezing the non-reaching hand when not using it (i.e. not pressing the button with it), the trials in which children used both hands to press the button were excluded. This resulted in an additional 12 participants were excluded because they did not have enough valid trials (at least 1 for branch point steps and 1 for within-

subgoal steps) because they pressed the button with both hands; an additional 65 branch point steps (39%) and 75 within-subgoal steps (47%) were excluded. The remaining sample for this exploratory analysis was 18 participants.

A non-parametric related-sample Wilcoxon Signed Rank test showed that these children demonstrated a higher velocity in non-reaching hand at branch points ($M = 0.91$ mm/frame, $SD = 0.71$, $median = 0.80$) compared to within-subgoal steps ($M = 0.58$ mm/frame, $SD = 0.38$, $median = 0.60$) ($z = 1.98$, $p = .048$, $r = 0.47$).

An independent sample t-test with difference score of velocity of non-reaching hand as dependent variable and age as between-subject factor showed that 5-year-olds ($M = 0.65$ mm/frame, $SD = 0.70$) showed a higher difference of mean velocity of non-reaching hand compared to 3-year-olds ($M = 0.02$ mm/frame, $SD = 0.30$) ($t(17) = 2.49$, $p = .024$, $Cohen's d = 1.17$; Figure 4.12a).

A non-parametric Mann Whitney U test with score of velocity of non-reaching hand as dependent variable and main goal score as between-subject factor showed that who followed the main goal ($M = 0.65$ mm/frame, $SD = 0.71$, $median = 0.28$) showed a higher difference in mean velocity of the non-reaching hand compared to children who did not complete the main goal ($M = 0.13$ mm/frame, $SD = 0.47$, $median = -0.02$) ($z = 2.01$, $p = .044$, $r = 0.47$; Figure 4.12b).

An non-parametric Mann Whitney U test with difference score of velocity of non-reaching hand as dependent variable and subgoal follower group as between-subject factor showed a marginally significant effect that children who followed the subgoals ($M = 0.68$ mm/frame, $SD = 0.70$, $median = 0.56$) showed a higher difference of mean velocity of non-reaching hand compared to children who mixed up all actions ($M = 0.11$ mm/frame, $SD = 0.45$, $median = 0.01$) ($z = 1.92$, $p = .056$, $r = 0.45$; Figure 4.12c).

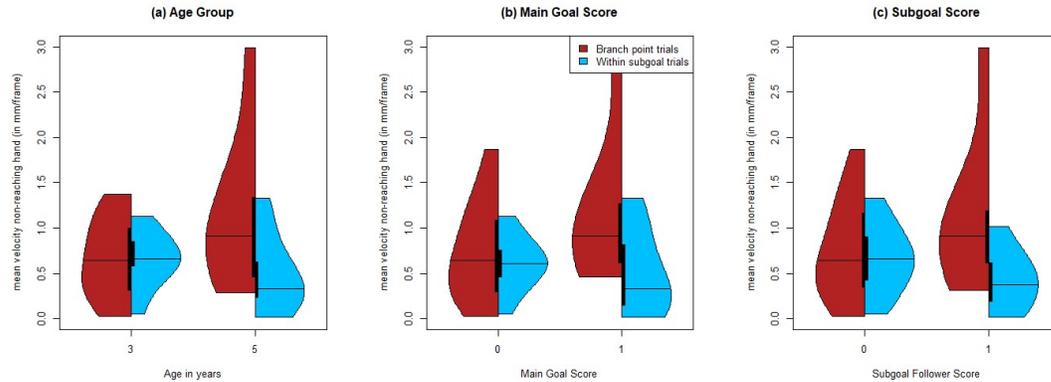


Figure 4.12. Violin plots of the mean velocity of the non-reaching hand (in mm/frame) excluding all trials that children pressed with both hands for (a) the different age groups, (b) the different main goal scores, and (c) the different subgoal follower scores for both within subgoal steps (blue) and branch points (or between subgoal steps, red). The line represents the median value for each group.

4.3.2.4 Relationship between kinematics and EF scores

To investigate the potential relation between executive functions and dynamic markers of action sequence planning measured by motion capture, the executive function tasks scores were correlated with kinematics scores. The kinematics scores were calculated as the score on within-subgoal step subtracted from score on branch points (between subgoal steps). Difference between classes of steps reflected evidence of hierarchical action planning of action sequence for that participants. Outliers were removed as described for other measures above. Analyses were planned.

4.3.2.4.1 Lingering time

Non-parametric Spearman correlations were used for lingering time, because its distribution deviated significantly from a normal distribution ($W = .92, p = .031$). Lingering time difference did not correlate with the inhibition score ($r_s(28) = .25, p = .196$), the shifting score ($r_s(28) = .12, p = .531$), the working memory score ($r_s(27) = -.28, p = .155$) or the updating score ($r_s(27) = -.30, p = .120$).

4.3.2.4.2 Pause time

Pause time difference did not correlate with the inhibition score ($r(29) = -.03, p = .890$), the shifting score ($r(29) = -.05, p = .796$), the working memory score ($r(28) = -.02, p = .930$) or the updating score ($r(28) = .02, p = .919$).

4.4.2.4.3 Non-reaching hand movement

Non-parametric Spearman correlations were used for non-reaching hand movement, because its distribution deviated significantly from a normal distribution ($W = .91, p = .018$). Unlike in Chapter 3, the non-reaching hand difference did not correlate significantly with inhibition score ($r_s(27) = -.18, p = .357$). The difference in non-reaching hand movement did not correlate with shifting score ($r_s(27) = .04, p = .834$), nor working memory score ($r_s(26) = .24, p = .227$). The non-reaching hand score did correlate marginally with updating score ($r_s(26) = .36, p = .063$). This indicated that children who were better at updating (i.e. higher updating score) showed a bigger difference in their non-reaching hand movement at branch points compared to within subgoal steps.

4.3.3 Brain activation patterns of inhibition and action planning

4.3.3.1 Inhibition

The sample sizes in the current analysis were very small ranging from 2 to 10 or 11 participants per channel, and the results described in this paragraph were based on exploratory analysis with small degrees of freedom.

In 5-year-olds, there was a significant amplitude change in oxygenated haemoglobin (HbO₂) in Mixed blocks compared to Go blocks in channel 47 ($t(3) = 12.72, p = .001$, Figure 4.13). There were no significant channels in deoxygenated haemoglobin (HHb). There were no significant differences in 3-year-olds in oxygenated haemoglobin (HbO₂), nor in deoxygenated haemoglobin (HHb). The anatomical locations recovered from the corresponding brain template demonstrated that channel 47 covered the left dorsolateral prefrontal cortex.

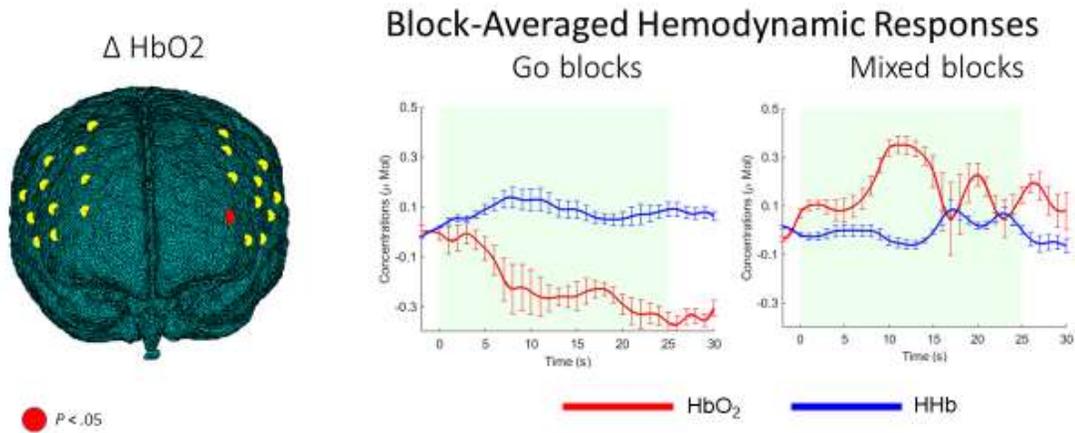


Figure 4.13. In-group level results for the 5-year-old group for oxygenated haemoglobin. The block-averaged hemodynamic response for go blocks and mixed blocks in 5-year-olds is plotted on the right side. Red is oxy, Blue is deoxy haemoglobin.

4.3.3.2 Planning task

Our hypothesis was that the prefrontal cortex would be more active at branch points in older children that follow the goal hierarchy. The sample sizes in the current analysis were very small ranging from 2 to 13 or 14 participants per channel, and the results described in this paragraph were based on exploratory analysis with small degrees of freedom. This analysis is meant as a proof of principle, demonstrating that this set-up allows us to investigate corresponding brain areas to action sequence planning in preschoolers, and providing some first evidence whether the prefrontal cortex is involved in action sequence planning. Corresponding non-parametric tests (One-Sample Wilcoxon Signed Rank Tests) were executed if the channel was non-normal distributed.

In 5-year-old children, the contrast for oxygenated haemoglobin (HbO₂) was significant for channel 14 ($z = -2.02$, $p = .043$, $n = 5$) and marginal significant in channel 22 ($z = 1.83$, $p = .068$, $n = 4$) in a One-Sample Wilcoxon Signed Rank Test. The anatomical locations recovered from the corresponding brain template demonstrated that channel 14 covered the right homolog of Broca's area and channel 22 the right primary motor cortex. Broca's area and its right homolog is considered to not only be involved in language, but also hierarchically structured goal-directed behaviours such as action sequences (e.g. Koechlin & Jubault, 2006). These contrast were not significant in oxygenated haemoglobin (HbO₂) in 3-year-olds (channel 14: z

= -1.60, $p = .109$, $n = 3$; channel 22: $z = -0.45$, $p = .655$, $n = 2$), nor were any other contrast in oxygenated haemoglobin in this age group significant.

In 5-year-old children, the contrast for deoxygenated haemoglobin (HHb) was significant for channel 10 ($z = -2.02$, $p = .043$, $n = 5$) and marginally significant for channel 13 ($z = -1.86$, $p = .063$, $n = 7$). Both areas covered the right dorsolateral prefrontal cortex. In 3-year-olds, there was a significant contrast for deoxygenated haemoglobin (HHb) in channel 16 ($z = 2.20$, $p = .028$, $n = 6$) which covered the premotor and supplementary motor cortex.

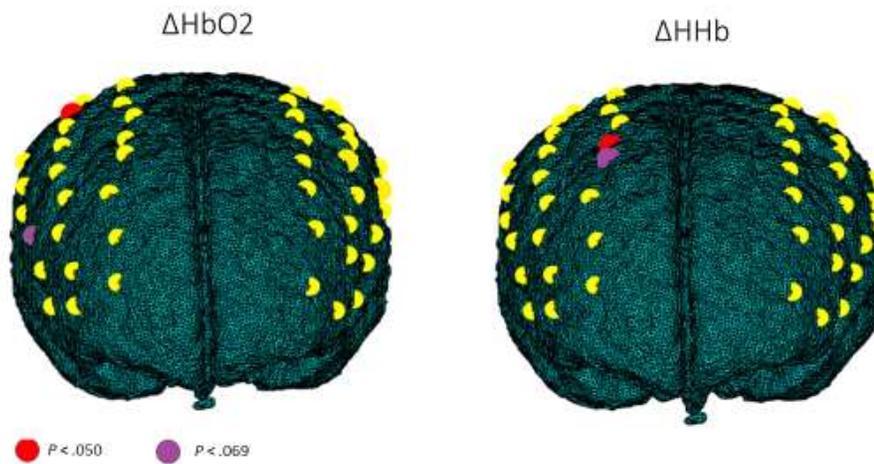


Figure 4.14. The significant and marginal significant contrasts in 5-year-olds between branch points and within subgoal action steps with oxygenated haemoglobin on the left and deoxygenated haemoglobin on the right.

Therefore, branch points, in children who were successfully planning their action sequences, seem to be associated with an increase in oxygenated haemoglobin (HbO_2) in the right primary motor cortex, and a decrease in oxygenated haemoglobin (HbO_2) in the right homolog to Broca's area, and a decrease in deoxygenated haemoglobin (HHb) in the right dorsolateral prefrontal cortex compared to within subgoal steps.

4.4 Discussion

Previously, it was demonstrated that the ability to plan and execute action sequences with a hierarchical goal structure improved over the preschool period, and that these improvements were related to executive function development (Chapter 3; Yanaoka & Saito, 2017; 2019). Furthermore, children who were good planners showed freezing of their non-reaching hand

during the execution of a subgoal (Chapter 3). This chapter aimed to replicate these results, and assessed the involvement of the prefrontal cortex, especially the dorsolateral prefrontal cortex, in action sequence planning using fNIRS.

In this study, children were instructed to build a Duplo house following a given goal hierarchy in a construction video while wearing motion capture gloves to assess movement kinematics of the hands and wireless fNIRS to assess hemodynamic changes in the prefrontal cortex. The main variables of interest in the house task were whether children were able to keep track of the main goal (build a house), whether they followed the subgoals or mixed up the actions (number of colour switches as each colour was a different subgoals) and whether they were sensitive to distractors. Furthermore, the core aspects of executive functions - working memory, inhibition and set shifting – were assessed using standardized computer tasks.

As in Chapter 3, the results demonstrated that age in months predicted whether children were able to keep track of the main goal. Both studies showed a similar improvement in keeping track of the main goal from 3 to 5 years of age. In Chapter 3 20% of the 3-year-olds and 70% of the 5-year-olds were successful, whereas in this Chapter it was 13% and 81% respectively. This suggested that a more nested hierarchical goal structure (with more subgoals but fewer action steps in each subgoal) was beneficial in terms of the likelihood of achieving the main goal for (older) children, who plan and execute their actions according to the subgoal structure. However, for (younger) children, who mixed up all the action steps, a more nested hierarchical goal structure with more Duplo blocks (12 vs. 10) presented a greater challenge for them to keep track of the main goal and align their actions accordingly. Future research should investigate this.

In contrast to Chapter 3, updating skills did not relate to children's ability to follow the subgoal. However, this finding was already weak in the previous chapter and, given the smaller sample size in this study, it is likely that the current analysis did not have enough power to detect these weak effects. Future research should investigate this conflicting evidence. As reported previously, inhibition was the predictor of whether children were distracted by the distractor objects. Inhibitory skills are essential to avoid executing action irrelevant to the goal hierarchy or overcome distractors in action sequence planning. Again, these results demonstrated the importance of executive functions to the improvement of action sequence planning in preschool years (Chapter 3; McCormack & Atance, 2011; Yanaoka & Saito, 2019; 2020).

The motion capture data demonstrated that good planners who followed the subgoals showed freezing (i.e. less movement) with their non-reaching hand when executing a subgoal, and this resulted in more movement at branch points. This was especially evident if all trials in which children pressed the button with both hands were excluded. In Chapter 3, this difference in movement of the non-reaching hand that was observed between branch points and within-subgoals steps was related to individual difference in inhibition. However, in this study, individual difference in updating skills were related to this difference. Better updating skills might support a greater ability to keep track of the subgoals and action steps resulting that children are better able to focus on the current subgoal.

A few previous studies have shown evidence of freezing behaviour in children. For example, Blanchard and colleagues (2005) demonstrated that children freeze more (i.e. less postural sway) in tasks with greater cognitive demands. Furthermore, there was a gradual decrease in movements of the non-acting limb in infancy (D'Souza et al., 2017). This suggests that freezing helps the child to improve cognitive focus on executing the actions with the acting hand, for example when executing the current subgoal in action sequence planning.

Both lingering time and pause time were not sensitive to hierarchical planning. As in Chapter 3, no effect in pause time suggested that children considered the button press as a distinct action, and not part of the grasping-a-block action. In the previous chapter, lingering time reflected that reaching towards a new box at branch points takes more time to plan compared to re-reaching to the exact location as before in a within subgoal step. This effect was absent in the current study. This might have been due to the influence of the set-up: five boxes instead of three with a shorter reaching distance.

The hemodynamic results showed greater oxy-haemoglobin (HbO₂) activation in dorsolateral prefrontal cortex in mixed (go and no-go trials) blocks compared to go blocks in 5-year-olds, but not in 3-year-olds, demonstrating that the current set-up is able to measure brain activation changes related to improvements in executive functions and planning in preschoolers. In 5-year-olds, the age group in which most children were able to successfully plan action sequences according to the goal hierarchy, showed differential brain activation patterns at branch points, when a switch from one subgoal to another was made, compared to within-subgoal steps. These brain activation patterns consisted of an increase in oxygenated blood in right premotor cortex and a decrease in oxygenated blood (HbO₂) in right homolog to Broca's area. Furthermore, a decrease in deoxygenated haemoglobin (HHb) in the right dorsolateral prefrontal cortex was

associated with branch points in 5-year-olds, when successfully planning action sequences. The effect in the dorsolateral prefrontal cortex was only observed in deoxygenated haemoglobin (HHb). This might be because these signal in deoxygenated haemoglobin are less contaminated by processes outside of the brain (Tachtsidis & Scholkmann, 2016). All of these activation patterns were absent in 3-year-olds, an age group who showed difficulties in planning action sequences according a hierarchical goal structure.

This analysis suggest that the dorsolateral prefrontal cortex might be involved in planning subgoals at branch points in action sequences in preschoolers. The dorsolateral prefrontal cortex has already been suggested to be essential in action planning, and especially action sequences (Kaller et al., 2011; Tanji et al., 2007). In monkeys, the neural activity in the dorsolateral prefrontal cortex reflected forthcoming movement in multistep actions (Mushiake et al., 2006). Furthermore, patients with lesions in the right dorsolateral prefrontal cortex showed planning impairments (Burgess et al., 2000). Lastly, the dorsolateral prefrontal cortex was activated during planning of actions in adults in the fMRI scanner (Glover et al., 2012; Johnson-Frey et al., 2005). The results of the current study extended these findings suggesting that the dorsolateral prefrontal cortex is involved in action planning already in preschool period.

Furthermore, the results also suggested an involvement in Broca's area and its right homolog in the planning of action sequences, especially when planning and executing a subgoal (i.e. decrease of oxy-haemoglobin at branch points compared to within subgoal steps). While Broca's area is famous for its involvement in speech production (e.g. Lazar & Mohr, 2011), more recent studies have suggested that Broca's area and its right homolog is also involved in hierarchical action plans (Koechlin & Jubault, 2006), processing of observed hierarchical actions (Wakita, 2014), motor sequence learning (Clerget et al., 2012) and tool-use (Higuchi et al., 2009). It has even been proposed that Broca's area and its right homolog was involved in organising and/or storing of the individual components of action sequence before execution (Clerget et al., 2011) or that Broca's area and its right homolog represented action hierarchy (Wakita, 2014). Future research should investigate this area in preschoolers to understand its involvement in the development of action sequence planning.

One of the main limitations of this current study is its small sample size ($n = 31$). Due to the global COVID pandemic, testing was restricted and delayed, resulting in a relatively small sample size. The small sample size caused issues with power in the analyses. For example, the

number of participants with valid data is in the prefrontal activation analysis was extremely low. Future studies should confirm these findings in a large sample size. Furthermore, the GLM analysis used a HRF response function with time derivative based on adult profiles. However, haemodynamic response functions might change over infancy, toddlerhood and preschool period, as the vascular system, neurons and glia cells underlying the hemodynamic responses still undergo maturation throughout this period (Issard & Gervain, 2018). Future naturalistic studies could use a standardised task (such as the go/no-go task) to create an individualised HRF function for each participant to use in the corresponding GLM analysis.

This study was the first to use wireless fNIRS in a naturalistic task to investigate neurodevelopment in preschoolers. It builds on the approach taken in using behaviour controlled event-related designs in naturalistic situations in adults (Balardin et al., 2017; Pinti et al., 2015). It therefore demonstrated the feasibility of using wireless fNIRS to investigate neurodevelopment in naturalistic setting and showed that good quality fNIRS data can be recorded from freely moving preschoolers. Future research can extend this approach to investigate neural changes in the development of other cognitive functions in more naturalistic settings.

Furthermore, this study was the first to use a combination of optical motion capture and fNIRS to investigate brain development in preschoolers. Only a few studies have combined fNIRS and sensor-based motion capture in adults, providing promising aspects in combining both methods (Hamilton et al., 2018; Kubota et al., 2015; Lin & Lin, 2016). The current study used optical motion capture to demonstrate a development in within-subgoal freezing behaviour during action sequence planning, and used fNIRS to provide evidence for dorsolateral prefrontal cortex involvement in action planning at branch points in preschoolers. Thus, this study showed that multimodal set-up in naturalistic studies provides opportunities to investigate the development of the brain and its cognitive functions.

4.4.1 Conclusions

In short, this study confirms that the ability to plan and execute action sequences with a hierarchical goal structure improved over preschool period. Executive functions were related to improvements in action sequence planning. Inhibition was important to avoid executing actions irrelevant to the goal hierarchy. Again this study provided more evidence that executive functions are the key developmental factors linked to improvements in action sequence planning.

Furthermore, this study confirmed earlier findings that good planners freeze their non-reaching hand when executing a subgoal in an action sequence. This freezing was suggested to provide increased cognitive focus on executing that current subgoal, and was related to individual differences in executive functions.

Lastly, our fNIRS results suggested that the dorsolateral prefrontal cortex might be involved in planning of the next subgoal at branch points when a switch from one subgoal to another is required. This effect was absent in 3-year-olds, and at this age, preschoolers were also struggling to align their actions according to the goal hierarchy. This proposed that development in dorsolateral prefrontal cortex might be related to action sequence improvements in preschool years.

This study used both wireless fNIRS and motion capture in a naturalistic situation, parting from rigid laboratory-based block design studies to ecologically-valid situation with richer patterns of behaviour allowing children to act like they would do in daily life. This study was the first to demonstrate the feasibility of using multi-modal wearables to investigate cognitive development in freely moving preschoolers.

However, action planning in the prefrontal cortex is not the only process contributing to the development successful action sequencing. The next chapter will investigate the contribution of the development of action selection. As mentioned in Chapter 1, action selection is the process of selecting which action sequence plans should be executed with the ultimate aim to achieve the goal. Computational modelling will be used to investigate the hypothesis that immature basal ganglia loops can at least partially explain the development of action sequences observed in the preschool years.'

CHAPTER 5

Computational modelling of toddlers' and preschoolers' action sequence performance

5.1 Introduction

As has been found repeatedly, young children often are able to remember a task goal when prompted verbally, but fail to execute their actions appropriately in goal-directed action sequences when asked to complete the task (e.g. Chapter 3; Chapter 4; Freier et al., 2017; Marcovitch et al., 2007, 2010; Zelazo et al., 1996). For example, 3-year-olds struggled to colour all farm animals using each of three colours equally often, despite being verbally able to recall the task goal (Freier et al., 2017). Similarly, in Chapters 3 and 4, when preschool children were instructed to build a Duplo house following a hierarchically constrained action sequence, they showed an understanding of the goal of the task. However, most of the 3-year-olds were not able to successfully complete this task goal. In contrast, most 5-year-olds were able to successfully complete the task goal of building a house. The discrepancy in young children's verbal understanding and remembering of a task goal, and their ability to execute their actions according to this task goal has been referred to as *goal neglect* (Duncan et al., 1996). Goal neglect was also reported in the *Dimensional Change Card Sorting* (DCCS) task with preschoolers. For example, the majority of 3-year-olds would continue to use the pre-switch rule in sorting their cards in the post-switching phase, despite the fact that they were able to explain the post-switching rule when asked (Zelazo et al., 1996). In contrast, 4-year-olds were able to switch flexibility in sorting rules in their actions (Zelazo et al., 1996). Goal neglect seemed to be related to working memory, with better working memory capacity decreasing the chance of goal neglect occurring in young children (Marcovitch et al., 2010). Goal neglect has also been reported in adult participants with frontal lobe impairments (e.g. Duncan et al., 1997) and in neuro-typical adults when there was an absence of feedback about errors or when multiple simultaneous task constraints have to be organised (Duncan et al., 1996).

In summary, in several tasks involving planning and executing actions or action sequences, young preschoolers demonstrated an inability to execute their actions according to the task goal, despite having the ability to verbally report this goal.

As has been argued and shown throughout this thesis, the preschool years make up an important period in the *development* of complex action behaviours. For example, Chapter 2 reported that 3-year-olds were better than 2-year-olds in both planning simple alternating actions, as well as action sequences with multiple goal constraints. The development of the ability to plan action sequences continues into the subsequent years. For example, 5-year-olds are able to follow both a superordinate goal constraint as well as a lower-level goal constraint when planning goal-directed action sequences, whereas 3-year-olds only took into consideration the lower-level goal constraint in a colouring task (Freier et al., 2017). Likewise, performance on action sequences with a goal hierarchy improved over the preschool period. Three- and 4-year-olds made errors in their action sequences (such as failing to execute the highest goal) while 5-year-olds demonstrated the ability to align their actions according to the goal hierarchy (Chapter 3; Chapter 4; Yanaoka & Saito, 2017, 2019, 2020).

Typically, the errors observed in young children's performance are explained as arising from problems with action *planning* or *goal representations* (e.g., Munakata, 2001). However, actions arise from the connected processes of action *planning*, action *selection* and action *execution*. Therefore, action selection deficits, possibly resulting from immature subcortical action selection circuits could also be contributing to the appearance of these errors. Indeed, this hypothesis is consistent with the idea of goal neglect, in which the goal representation is maintained appropriately, but it is the selection and execution of that goal that has failed.

This chapter uses computational modelling to investigate whether immature subcortical action selection could underlie goal-directed action deficits (including goal neglect) found in young children and, more specifically, whether changes in basal ganglia functioning could explain the observed development of action sequence competence. First, the literature on the neural evidence of basal ganglia processing in action selection will be reviewed, before providing a short overview of computational models of the adult's basal ganglia functioning.

5.1.1 Action selection in the basal ganglia

The *basal ganglia – frontal cortex loops* are believed to be involved in action selection by resolving conflicts between different action programs that can be executed (Chevalier & Deniau, 1990; Haber & Calzavera, 2009; Hazy et al., 2011; Redgrave et al., 1999). The basal ganglia receives input projecting from the neocortex, while its output travels back to the frontal cortex via the thalamus (Graybiel, 2000; Figure 5.1 for an illustration of this circuit). This basal ganglia system consists of multiple parallel loops from the frontal cortex to the striatum. The

projections from the striatum move to the globus pallidus (internal segment; GPi). These projections from the GPi continue to the thalamus, and eventually project back to the frontal cortex (Frank et al., 2001).

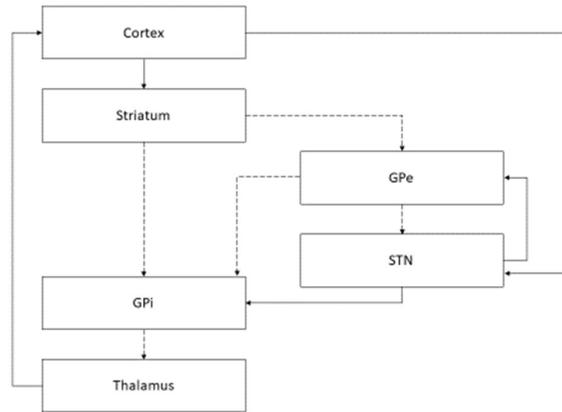


Figure 5.1. Schematic representation of prefrontal cortex - basal ganglia loops. Inhibitory connections are displayed with dotted lines, while excitatory connections are displayed using solid lines. Figure adapted from A computational model of action selection in basal ganglia. I. A new functional anatomy (page 403) by K. Gurney, T. Prescott, & P. Redgrave, 2001a, Biological Cybernetics, 84(6), 401-410.

There is inhibitory gating in the projections from the striatum to the GPi, and from the GPi to the thalamus. Furthermore, the GPi neurons are tonically active, resulting in an inhibited thalamus in the absence of other activity. Importantly, striatal neurons fire to disinhibit the thalamic neurons – thereby “releasing the brake” on the thalamus (Frank et al., 2001; Frank, 2011; Leisman et al., 2014; Redgrave et al., 2010). These functions are mediated by dopamine. There are two types of dopamine receptors in the striatum; one which projects to GPi with excitatory effects (also named D1 or dopamine 1), and one which excites the striatal neurons in the globus pallidus external segment (GPe) (also named D2 or dopamine 2) resulting indirectly in suppression of the GPi (Gurney et al., 1998). Thus, disinhibition of the thalamus acts as a gating function. It enables other functions to take place, but it does not cause them to occur. It has been suggested that thalamic disinhibition is involved in initiating motor movements, while the frontal cortex itself is involved in motor action planning. In other words, the function of the basal ganglia is to release a brake on the frontal cortex allowing it to initiate a movement (Chevalier & Deniau, 1990; Gurney et al., 2001a; Haber & Calzavara, 2009; Hazy et al., 2011).

Computational models have provided support for this account of the basal ganglia functioning. Gurney and colleagues (2001b) used a leaky integrator-type computational model to explain adult's action selection using the functional architecture described above for the basal ganglia. The activation levels of nodes in the model, during action selection, in the key functional areas involved (i.e., the GPe, GPi, and SNr) showed a good match with the firing rate patterns in the neurophysiological data in adults (Gurney et al., 2001b). This model of the basal ganglia was subsequently extended into a neural network model that could explain response selection data (Frank, 2006; Frank & Claus, 2006; Frank et al., 2007), working memory effects (Frank et al., 2001; O'Reilly & Frank, 2006) and reinforcement learning in adults (e.g. Suri & Schultz, 1998).

More recently, Caso and Cooper (2020) describe an interactive activation model, extending the earlier contention scheduling model (Cooper & Shallice, 2000; see *section 1.2*), whose architecture is constrained by the neural architecture of the basal ganglia – frontal cortex loops. This model demonstrated how action selection in the *Wisconsin Card Sorting Task* (WCST) can be explained in terms of a hierarchically organised set of action schemas and the natural functioning of the basal ganglia. Specifically, it was able to explain behavioural and neural performance on the WCST observed in normal adults and Parkinson's disease patients (Caso & Cooper, 2020).

5.1.2 Aims of the current chapter

The existing literature has shown that the preschool years are a period of drastic improvement in children's ability to organise their actions and action sequences in accordance with task goal. The predominant view in the existing literature is that errors observed in how preschoolers' carry out goal-directed action sequences arise because of deficits in action *planning* or immature *goal representation*. This chapter used computational modelling to investigate the novel hypothesis that children's performance errors are at least partially caused by immature subcortical-basal ganglia loops and therefore arise from problems *selecting* the correct steps in action sequences, rather than planning or goal representation issues. In the current chapter, Caso and Cooper's (2020) neural architecture of the basal ganglia was adapted to model developmental profiles on several tasks assessing preschoolers' action sequence performance. Specifically, computational models were used to examine immature action selection in the development on the *Tower task* (Chapter 2), the *House task* (Chapter 3 and 4), the *Colouring task* (Freier et al., 2017) and the *DCCS task* (Zelazo et al., 1996).

In the Tower task, 2- and 3-year-olds were asked to build a tower taking into account two goal constraints: (i) build the tower to the correct height indicated on the wall, and (ii) build a striped tower by alternating between blocks of two colours. The results showed that, in 2-year-olds, there was a negative relation between the two goal constraints; 2-year-olds were less likely to successfully complete the secondary goal constraint if they had completed the primary goal constraint. This effect was reversed in 3-year-olds; the 3-year-olds who completed the primary goal constraint were more likely to successfully complete the secondary goal constraint (Chapter 2).

In the House task, preschoolers between 3 and 5 years of age were instructed to build a Duplo house following an action sequence with a goal hierarchy. The results demonstrated that preschoolers improved over age; older children were more likely to successfully complete the task goal (building a house) and showed fewer colour switches between the different subgoals than younger children, indicating that the older children followed the subgoal structure better (Chapter 3 and 4).

In the Colouring task, 3- and 5-year-olds were instructed to colour six farm animals following two goal constraints: (i) colour the animals following the direction of the arrow, and (ii) use each of the three colours given equally often. Results demonstrated that both 3- and 5-year-olds were able to colour the animals following the direction of the arrow. However, only 5-year-olds were able to simultaneously take into account the higher goal constraint; using each of the three colours equally often (Freier et al., 2017).

The DCCS task involves cards that can be sorted according to two dimensions, for example colour and shape (e.g. Zelazo et al., 1996). In the pre-switching phase, children were instructed to sort the cards according to one dimension, for example colour. Then, a rule change occurred and in the post-switching phase, children were instructed to sort the cards according to the other dimension, for example shape. Three-year-olds continued to sort their cards in the post-switching phase according to the pre-switching rule. However, 4-year-olds were able to switch their sorting rules flexibly, and sorted their cards according to the post-switching rule.

5.2 Overview of the model architecture

Figure 5.2 shows a schematic outline of the general model architecture and is based on the neural architecture of the basal ganglia. It draws substantially on Caso & Cooper's (2020) model of action selection in the Wisconsin Card Sorting Task. The code was implemented in MATLAB (version R2018b). The general model consists of (cortical) schema nodes

representing selection options of critical dimensions of the task; each ensemble of schema nodes is linked to a separate parallel basal ganglia circuit (described in more detail below) thereby implementing the parallel loop architecture of the cortical-basal ganglia connections. In short, each schema node has its own parallel basal ganglia loop as in Figure 5.2. The number of schema nodes differs for each of the four tasks modelled, and will be described in more detail in each task section. Each node has a corresponding activation value which varies as a function of excitation and inhibition received from other nodes in the model as a function of time. The schema nodes compete for selection, but do not have lateral inhibition between the different schema nodes.

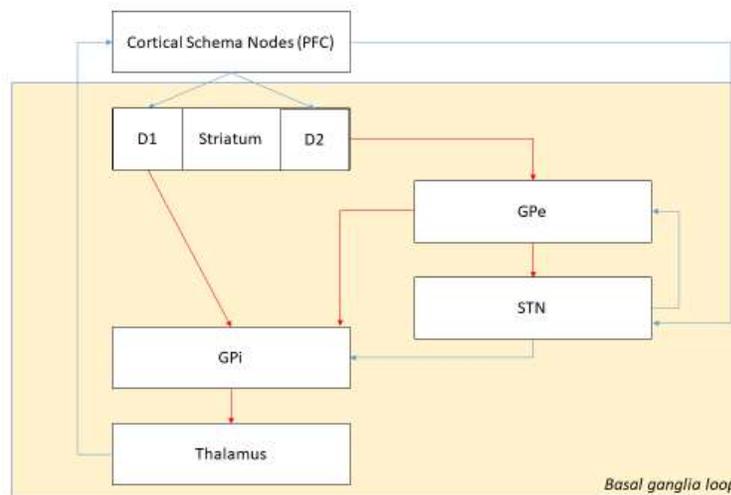


Figure 5.2. Basal ganglia loop associated with each ensemble of schema nodes. Each node has a parallel basal ganglia loop. For example, if there are two nodes (red blocks and blue blocks), there are two parallel basal ganglia loops connected to their node. The red connections reflect an inhibitory connection, while the blue connections reflect an excitatory connections. GPi means globus pallidus internal segment; GPe is globus pallidus external segment, STN is subthalamic nucleus, D1 is Dopamine 1, and D2 is Dopamine 2.

Each set of schema nodes makes up the content of the PFC box in Figure 5.2 and feeds into and receives output from the corresponding basal ganglia loop. An example is shown in Figure 5.3. Each schema node has its own parallel basal ganglia cortical loop. The cortical-basal ganglia loops are parallel loops implementing different action options that are competing for selection (Gurney et al., 2001a).

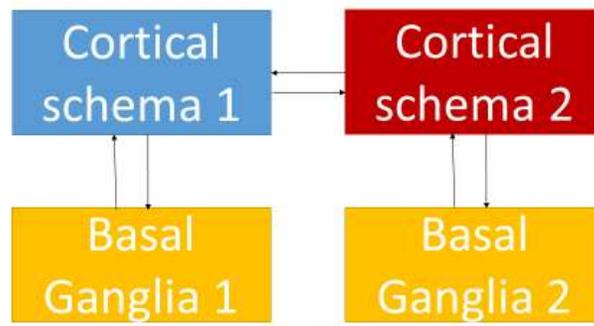


Figure 5.3. Schematic of the connections between the cortical schema nodes and the basal ganglia. All schema nodes have analogous independent parallel connections with the basal ganglia. The cortical schema nodes compete for selection.

5.2.1 Input to the model

There are three things that impact the model's behaviour: noise, external input and local input. Each simulation reported below uses a similar amount of potential random noise. *External input* is activation into the PFC that is extrinsic to the cortical-basal ganglia circuitry, such as information from the visual system. In contrast, *local input* is activation into the PFC or the GPi that is intrinsic to the current circuit, such as modulation of the baseline firing threshold. A key hypothesis of the model is that there are developmental changes in the local input that influence the PFC and/or the GPi.

5.2.2 Activation calculations

For all schemas, activation is calculated at each successive step according to the following three equations based on Caso and Cooper (2020):

- 1.) Calculate the input for each node based on the external input and local input, and a weighting factor: $\text{input}(t+1) = \text{input_node} * w_input$
- 2.) Smooth the input to even out the signal over time: $\text{smoothing}(t+1) = \text{delta} * \text{nodes}(t) + (1-\text{delta}) * \text{input}(t+1)$
- 3.) Apply a logistic function (hyperbolic tangent) to constrain activations to between -1 and 1: $\text{nodes}(t+1) = \tanh(\text{smoothing}(t+1) + \text{nodes}(t) + \text{noise})$.

A more detailed description of the three equations determining the activation in each node follows in the next paragraph. An action (i.e. the corresponding cortical node) is selected if the corresponding schema reaches an activation value above a threshold Θ . To avoid

indecisiveness in the model, this model included that the threshold Θ is reduced by 0.001 every 10 cycles. Similarly, the input decreases every cycle by multiplying it by 0.992 to simulate gradually forgetting the goal.

For each schema node, the activation was calculated according to three equations at each cycle with (t) reflecting time. The cortical schemas receive input from the extrinsic input or intrinsic local input and input from the thalamus. The activations are calculated as follows for the cortical PFC nodes:

- 1.) $PFC_{input}(t) = input_local * W_{input} + thalamus_{node}(t-1) * W_{thalamus, prefrontal\ cortex}$ ⁵
- 2.) $PFC_{activation}(t) = \delta * PFC_{node}(t-1) + (1 - \delta) * PFC_{input}(t)$
- 3.) $PFC_{node}(t) = \tanh(PFC_{activation}(t) + PFC_{nodes}(t-1) + noise)$

The activation of each node of the basal ganglia is calculated using the same equations. The striatal nodes (STR; both D1 and D2) receive excitatory input from the cortical prefrontal cortex nodes:

- 1.) $Striatum_{input}(t) = W_{prefrontal\ cortex, striatum} * PFC_{node}(t-1)$
- 2.) $Striatum_{activation}(t) = \delta * Striatum_{node}(t-1) + (1 - \delta) * Striatum_{input}(t)$
- 3.) $Striatum_{node}(t) = \tanh(Striatum_{activation}(t) + Striatum_{nodes}(t-1) + noise)$

The subthalamic nucleus (STN) nodes receive excitatory input from the cortical nodes and inhibitory input from the GPe (globus pallidus external segment) nodes:

- 1.) $STN_{input}(t) = W_{prefrontal\ cortex, subthalamic\ nucleus} * PFC_{node}(t-1) + W_{globus\ pallidus\ external\ segment, subthalamic\ nucleus} * GPe_{node}(t-1)$
- 2.) $STN_{activation}(t) = \delta * STN_{node}(t-1) + (1 - \delta) * STN_{input}(t)$
- 3.) $STN_{node}(t) = \tanh(STN_{activation}(t) + STN_{nodes}(t-1) + noise)$

The globus pallidus external segment (GPe) nodes receive excitatory input from the subthalamic nucleus (STN) nodes and inhibitory input from dopamine 2 of the striatal (STR2) nodes:

- 1.) $GPe_{input}(t) = W_{dopamine\ 2\ striatum, globus\ pallidus\ external\ segment} * STR2_{node}(t-1) + W_{subthalamic\ nucleus, global\ pallidus\ external\ segment} * GPe_{node}(t-1)$
- 2.) $GPe_{activation}(t) = \delta * GPe_{node}(t-1) + (1 - \delta) * GPe_{input}(t)$
- 3.) $GPe_{node}(t) = \tanh(GPe_{activation}(t) + GPe_{nodes}(t-1) + noise)$

⁵ $W_{x,y}$ means that this is the weight for the activation from structure X to structure Y.

The globus pallidus internal segment (GPi) nodes receive excitatory input from the subthalamic nucleus (STN) nodes and inhibitory input from the globus pallidus external segment (GPe) nodes and dopamine 1 of the striatum (STR1) nodes. The GPi nodes also receive an intrinsic local input depending on the version of the model:

- 1.)
$$GPi_{input}(t) = W_{\text{subthalamic nucleus, globus pallidus internal segment}} * STN_{node}(t-1) + W_{\text{dopamine 1 striatum, globus pallidus internal segment}} * STR1_{node}(t-1) + W_{\text{globus pallidus external segment, globus pallidus internal segment}} * GPe_{node}(t-1) + W_{input} * location_local$$
- 2.)
$$GPi_{activation}(t) = \delta * GPi_{node}(t-1) + (1 - \delta) * GPi_{input}(t)$$
- 3.)
$$GPi_{node}(t) = \tanh(GPi_{activation}(t) + GPi_{nodes}(t-1) + noise)$$

The thalamic nodes receives inhibitory input from the GPi:

- 1.)
$$Thalamus_{input}(t) = W_{\text{globus pallidus internal segment, thalamus}} * GPi_{node}(t-1)$$
- 2.)
$$Thalamus_{activation}(t) = \delta * Thalamus_{node}(t-1) + (1 - \delta) * Thalamus_{input}(t)$$
- 3.)
$$Thalamus_{node}(t) = \tanh(Thalamus_{activation}(t) + Thalamus_{nodes}(t-1) + noise)$$

The full set of parameters of the models and default values for each of the tasks are shown in Table 5.1. Parameters are based on Caso & Cooper (2021) and adapted to the specific task constraints. The parameters specify the strength of the extrinsic input or intrinsic local input, the strength of connections between nodes (W), the threshold for schema selection (Θ), the smoothing constant (δ), the noise level, and the number of trials.

The simulations described below all investigate the main developmental hypothesis that the (full) model and parameters described above capture performance of older children, while the reduction or absence of local input at key subcortical structures or prefrontal cortex (the reduced models) captures younger children's performance. In what follows, all comparisons of reduced model performance are made against the full model performance.

Table 5.1

The complete list of parameters in the model and their default values.

Parameter	Description	Default value	Default value	Default value	Default value
		Tower	House	Colouring	DCCS
δ	Smoothing constant	0.22	0.22	0.22	0.22
μ, σ	Mean and standard deviation of Gaussian normal distribution to model variability in number of trials	18, 10	- ⁶	-	-
max_trials	Maximum numbers of trails in each simulation	Selected from Gaussian distribution (μ, σ)	8	6	17
Noise _{input}	Random noise in PFC input	-0.01 - 0.01	0.01 - 0.01	0.01 - 0.01	-0.01 - 0.01
Input-↓	Input decrease per cycle	0.992	0.992	0.992	0.992
Θ	Selection threshold	0.865	0.865	0.865	0.865
Θ -↓	The model decreases Θ every 10 cycles to solve indecisiveness	0.001	0.001	0.001	0.001

⁶ Note: - means that this parameter is absent in that version of the model.

Θ_{box}	Selection threshold to build Tower too low	0.0650	-	-	-
W_{input}	Weight from input to PFC/GPi	0.3	0.3	0.3	0.3
$W_{\text{pfc, stn}}^7$	Weight from PFC to STN	1.2	1.2	1.2	1.2
$W_{\text{pfc, str1}}$	Weight from PFC to STR1	1.0	1.0	1.0	1.0
$W_{\text{pfc, str2}}$	Weight from PFC to STR2	1.0	1.0	1.0	1.0
$W_{\text{pfc, gpe}}$	Weight from PFC to GPe	-0.3	-0.3	-0.3	-0.3
$W_{\text{stn, gpe}}$	Weight from STN to GPe	0.9	0.9	0.9	0.9
$W_{\text{str2, gpe}}$	Weight from STR2 to GPe	-1.0	-1.0	-1.0	-1.0
$W_{\text{stn, gpi}}$	Weight from STN to GPi	0.9	0.9	0.9	0.9
$W_{\text{gpe, gpi}}$	Weight from GPe to GPi	-0.3	-0.3	-0.3	-0.3
$W_{\text{str1, gpi}}$	Weight from STR1 to GPi	-1.0	-1.0	-1.0	-1.0
$W_{\text{gpi, thalamus}}$	Weight from GPi to Thalamus	-1.0	-1.0	-1.0	-1.0
$W_{\text{thalamus, pfc}}$	Weight from Thalamus to PFC	1.0	1.0	1.0	1.0

⁷ Abbreviations in this table: PFC is prefrontal cortex, STN is subthalamic nucleus, STR1 is dopamine 1 in striatum, STR2 is dopamine 2 in striatum, GPi is globus pallidus internal segment, and GPe is globus pallidus external segment.

Noise _{nodes}	Noise in each node added each cycle	-0.001 – 0.001	-0.001 – 0.001	-0.001 – 0.001	-0.001 – 0.001
Input _{Rule}	Input after each trial based on a rule	0.19 (local input box)	0.2 (external input rule)	<i>Cycling</i> : -0.12 first option, -0.06 for option two back <i>Grouped</i> : 0.10 if first time that option is selected, -0.10 if second time that option selected	0.7 (local input rule)
Input _{Location}	Input after each trial based on location	0.18 (local input location)	0.13 (local input location)	<i>Cycling</i> : 0.06 <i>Grouped</i> : 0.05	0.0757 (local input location)

5.3 Specific models and model performance

5.3.1 Simulation 1: The Tower Task

In Chapter 2, toddlers' ability to take multiple constraints into account in their action sequences was investigated. Toddlers (2- and 2.5-year-olds) and young preschoolers (3-year-olds) were asked to build a tower using Duplo blocks, taking into account two constraints: (i) build the tower to the correct height; 20 blocks, and (ii) build the tower striped by alternating between colours (Figure 5.4).

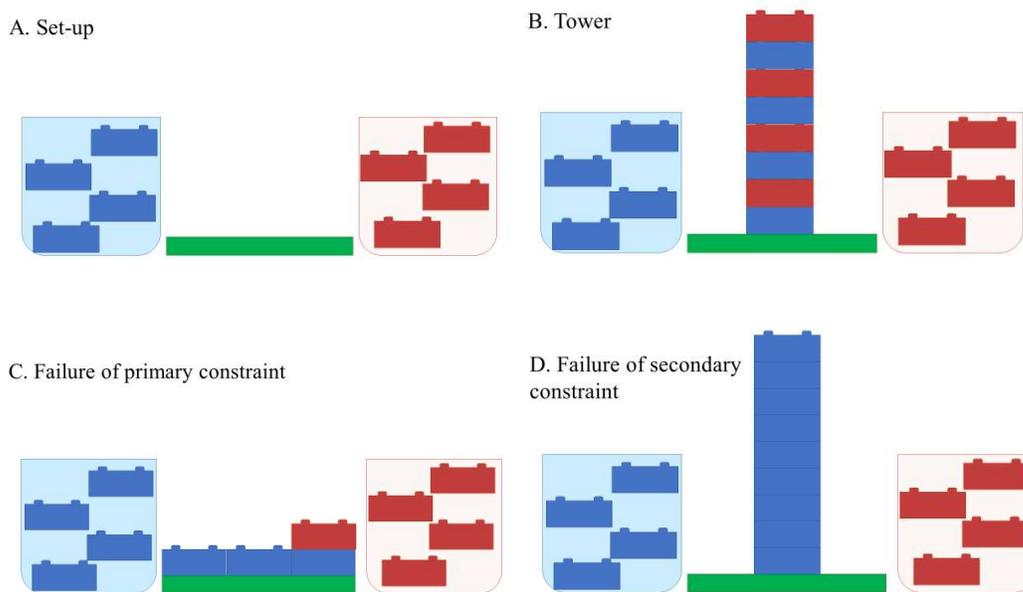


Figure 5.4. A depicts the set-up of the Tower task (Chapter 2). There was a box with blue Duplo blocks, a box with red Duplo blocks and a green baseplate in between. Children were instructed to build a tower to the height of 20 blocks while making it striped by alternating between colours (as in B). Failure to take into account the primary constraint (C) or the secondary constraint (D) are also illustrated.

Examples of failures to take into account the primary or secondary constraints are illustrated in Figure 5.4. The results of Chapter 2 showed that toddlers and preschoolers struggled to take into account the primary constraint in their action sequence planning. The most interesting finding showed that toddlers who successfully completed the primary constraint were less likely to complete the secondary constraint. In contrast, preschoolers who successfully completed the primary constraint were more likely to complete the secondary constraint.

5.3.1.1 Model specifications

In this simulation, the tower task is simplified by requiring the model to select between two colour boxes (blue/red), and three locations (left/middle/right). There are two independent sets of nodes in the cortical schema nodes, the colour nodes and the location nodes (Figure 5.5), reflecting which colour block is selected next and where this block is placed (on which location) as independent choices. The colour nodes consists of two cortical schema nodes reflecting the two block colours available: one node for blue blocks, one node for red blocks. The location nodes consist of three cortical schema nodes reflecting the possible three locations where the bocks can be placed: one node for left, one node for middle and one node for right. Once one of the colour box nodes exceeds the threshold Θ , and this colour action is selected, the location with the highest activation is then selected.

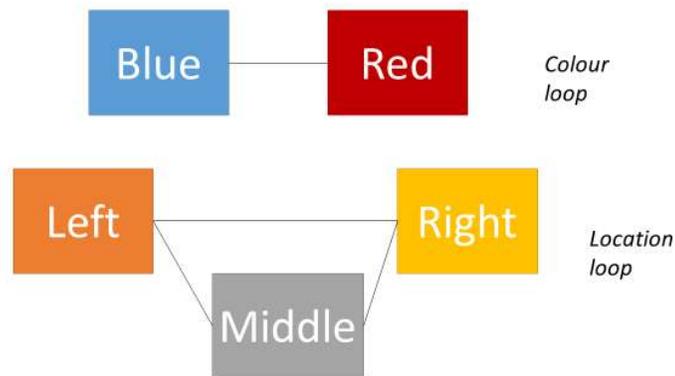


Figure 5.5. Schema nodes for the Tower task model. The schema nodes connected by the grey lines compete with each other for action selection when exceeding the threshold Θ .

This model has no extrinsic input into the PFC, only an intrinsic input from the previous box selected. The first choice whether to pick the colour blue or red, and location (left, right or middle) is dependent on random noise. The next trial begins with an increase in the intrinsic local input activation arising from the colour and location loops (Figure 5.6). The “rule” input aids the PFC towards the previously unselected colour box to ensure the alternating pattern across trials. This rule local input in the PFC is intended to reflect the remembering of the “alternating” constraint, as the PFC is involved in encoding of action rules (e.g. Wallis et al., 2001; White & Wise, 1999). The location local input fed into the GPi and PFC provides a small input to the location previously selected. This is intended to reflect remembering the constraint of “building a tower” when applied to the PFC, but also perseveration of action choice when

applied to the GPi. Indeed, action perseveration is a consequence of disease of the GPi in Parkinson's patients (e.g. Dirnberger & Jahanshahi, 2013; Lange et al., 2016).

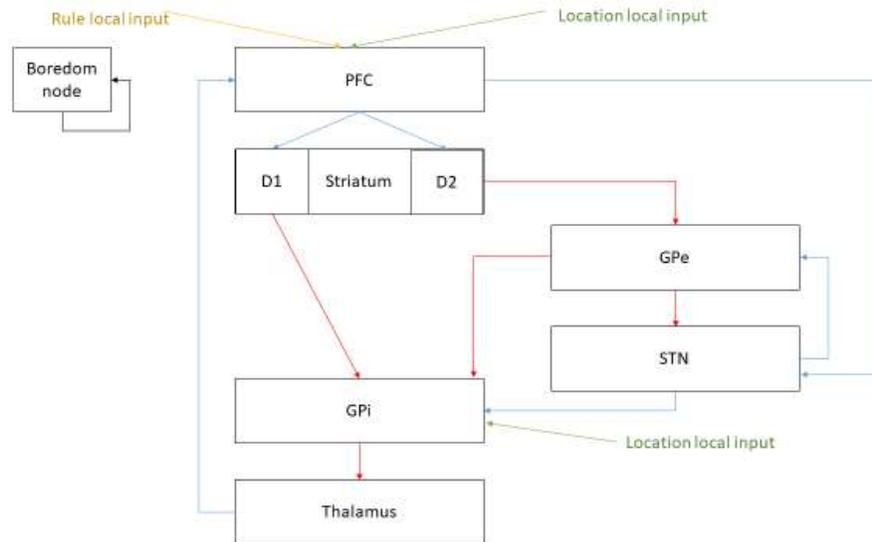


Figure 5.6. The basal ganglia nodes with intrinsic input of the Tower simulation.

As was observed in Chapter 2, many children built the tower too high (or too low) when it was clear that their tower was already as tall as it should be. To model variability in tower height, the maximum number of trials is not fixed, but instead selected in each simulation by a Gaussian normal distribution. The Gaussian normal distribution had values of μ and σ that created a histogram of the number of trials similar to children's behaviour in Chapter 2. In addition, there was a boredom node (Figure 5.6); this independent node that did not have connections other than to itself, received noise (between -0.01 and 0.01) each trial, and would cut-off the task if it reaches a threshold Θ_{box} . This activation follows a random walk; it is as likely to go up as it is to go down. This is thought to simulate boredom with the task in toddlers.

5.3.1.2 Model performance

The model captured preschoolers' behavioural performance on the Tower task. The key phenomenon captured is the reversal in age in the relationship between passing or failing the primary constraint and the secondary constraint of making a striped tower. In 2-year-olds, a negative relationship was observed, i.e., those who successfully built a tower tended to fail to make it striped, while 3-year-olds showed a positive relationship, i.e., those who successfully built a tower also succeeded in making it striped. Moreover, a reduced model (without the PFC and GPi local inputs) well captures the younger toddlers' behavioural performance (Figure

5.7). A model with only a GPi local input did not capture the negative relation between the primary and secondary constraint that was observed in 2-year-olds. Thus, both PFC and GPi local inputs are necessary to show this negative relation.

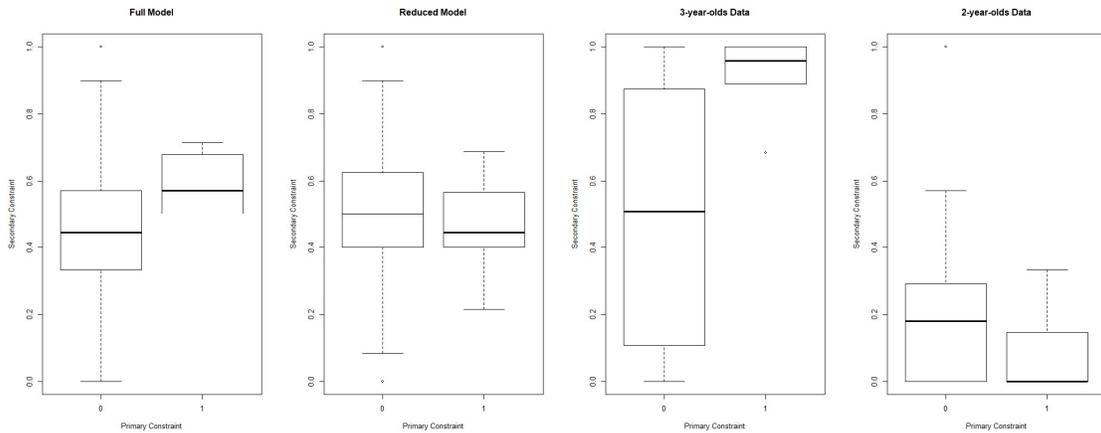


Figure 5.7. Boxplots comparing model performance of the full model and reduced model (i.e., without PFC and GPi inputs), and the behavioural data of the 3- and 2-year-olds in Chapter 2 with the score on primary constraint on x-axis (0= fail, 1=pass) and percentage striped (secondary constraint) on the y-axis. The simulation data shown is averaged over 2500 replications. In the full model and the 3-year olds' data, succeeding on the primary constraint is associated with a higher probability of succeeding on the secondary constraint. This pattern is qualitatively reversed in the reduced model and the 2-year olds' data.

In summary, children's developmental profiles observed in terms of reversal in age on the relationship between passing or failing the primary constraint and the secondary constraint on this task can be explained by increased intrinsic local inputs in the PFC and GPi appearing with increasing age.

5.3.2 Simulation 2: The House Building Task

In Chapter 3, preschoolers' hierarchical action sequences were investigated. Three-, 4- and 5-year-olds were asked to build a Duplo house following an action sequence with a goal hierarchy while ignoring distractors (Figure 5.8). The results revealed an improvement in age in the ability to plan and execute these action sequences.

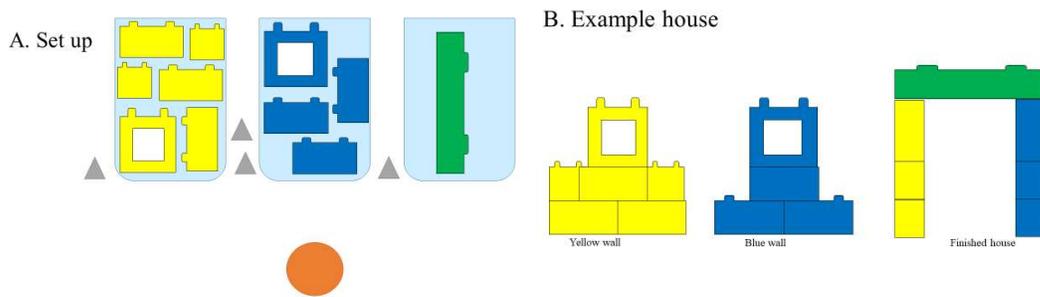


Figure 5.8. The set-up of the house task (A). There was a box with blue Duplo blocks, a box with yellow Duplo blocks, and a box with a green roof. Grey triangles reflect distractor object placed between the boxes. Children pressed the orange button to open the boxes and grasp a block. Children were instructed to build a house following an action sequence with a goal hierarchy (B).

5.3.2.1 Model specifications

The cortical schemas consists of one set of schema nodes, each representing a different block colour-location pairing (Figure 5.9). These schemas correspond to the three potential locations of the boxes with the blocks needed for the action sequence (blue blocks, yellow blocks and green blocks) and one for the location of distractors. As described above, each schema node is connected to a separate parallel basal ganglia loop. An action node is selected when its activation level exceeds the threshold Θ .

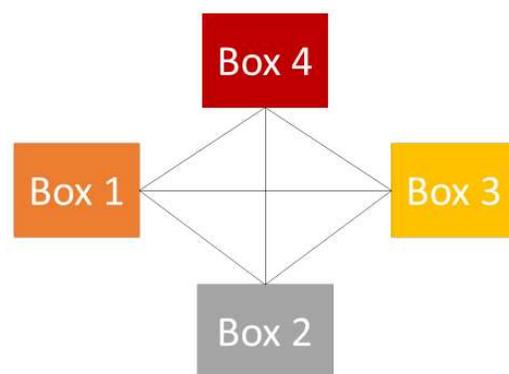


Figure 5.9. Schematic nodes within the House task model. The schema nodes connected by the grey lines compete with each other for action selection when exceeding the threshold Θ .

The model has as extrinsic input a sequence consisting of 8 planned actions, corresponding to the maximum number of block selections trials. The extrinsic input is thought to come from a higher-level system representing the action steps based on the instruction video. An example of a planned action sequence might be [1 1 1 2 2 3 3] with location 4 as distractor box location. This extrinsic input sequence feeds the relevant PFC nodes throughout a block; so on each trial there is an extrinsic input (0.20) to the corresponding schema node. There is also a small intrinsic perseveration local input of the previous box location applied to the GPi generating perseverative behaviour (Figure 5.10).

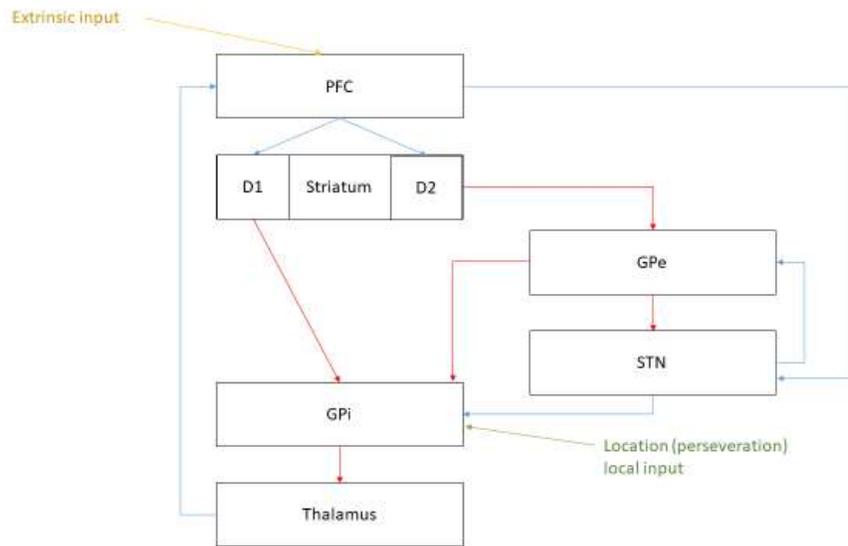


Figure 5.10. The basal ganglia nodes with extrinsic input and intrinsic local input of the House simulation.

5.3.2.2 Model performance

If action selection time is assumed to be modelled by the number of cycles taken by the model to reach selection threshold on each trial, then the model was able to capture adult-level behaviour showing increased action selection time at branch points compared to non-branch points (Figure 5.11; Arnold et al., 2017; Ruh et al., 2010).

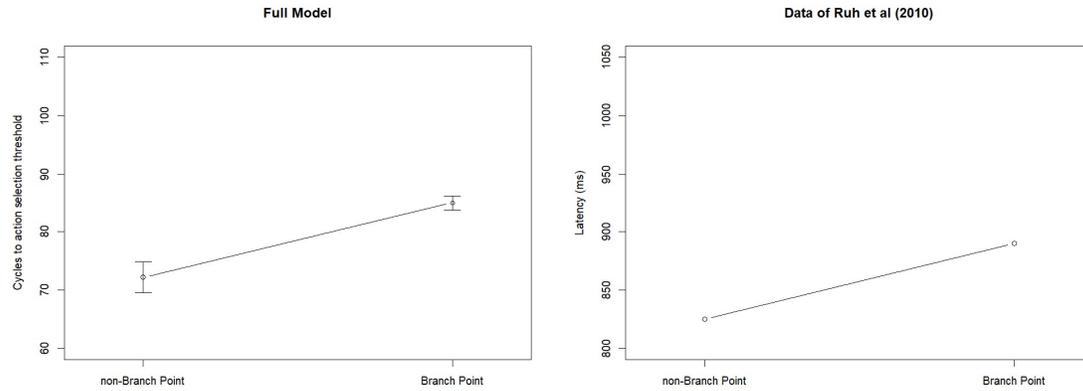


Figure 5.11. Model performance on branch points vs. non-branch point trials compared to the data of Ruh and colleagues (2010). The simulation data shown is averaged over 2500 replications. Error bars reflect standard deviation. The data on the right side is taken from *Action selection in complex routinized sequential behaviors* (page 960) by N. Ruh, R.P. Cooper & D. Mareschal, 2010, *Journal of Experimental Psychology: Human Perception and Performance*, 36(4), 955-975.

The number of colour switches made in the action sequences was recorded (as in Chapter 3) to assess the model’s performance against children’s performance. In so doing, it is important to note here is that the model could continue to pick the same box location for the whole duration of the study because the boxes would not empty as they would in the real-life task. Consequently, the model can show more extreme perseverative behaviours than children in real-life.

The full model captures the 5-year-olds’ colour switching behaviour best, whereas the younger children’s performance is well explained by a model without an extrinsic rule input on the PFC, but including an intrinsic location local input on the GPi (Figure 5.12).

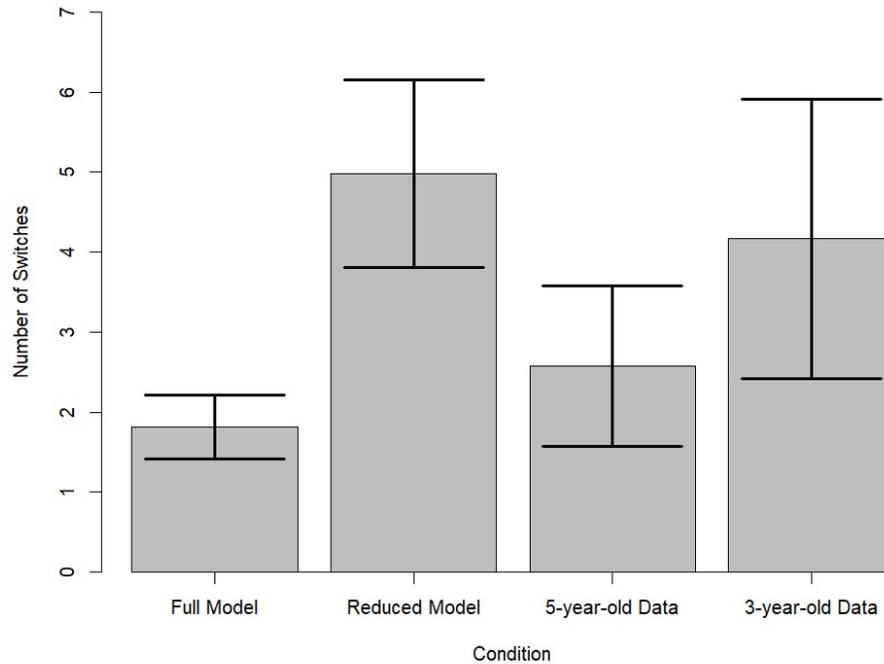


Figure 5.12. Bar plot showing number of colour switches made by the full model and the reduced model (without the PFC input), compared to the children’s data of Chapter 3. The simulation data shown is averaged over 2500 replications. The error bars reflect standard deviations.

5.3.3 Simulation 3: The Colouring Task

Freier and colleagues (2017) investigated preschoolers’ ability to follow goal constraints in their action sequences. Three- and 5-year-olds were instructed to complete a task which involved colouring in all farm animals following the arrow and using each of the three colours equally often (Figure 5.13). They found that 5-year-olds were able to complete the task successfully, whereas 3-year-olds were only able to follow the lowest goal constraint (i.e. colour the animals following the arrow).

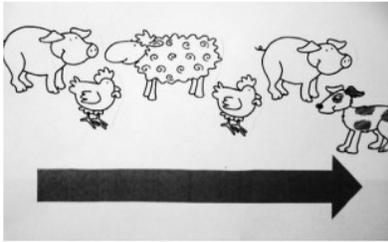


Figure 5.13. The experimental set-up of the Colouring task. Figure adapted from *Preschool children’s control of action outcomes* (page 3) by L. Freier, R.P. Cooper & D. Mareschal, 2017, *Developmental Science*, 20, e12354.

5.3.3.1 Model specifications

This simulation does not address the first level of goal constraint (i.e. colour the animals following the arrows) because both age groups showed ceiling level performance with regards to this constraint. Thus, the task is represented by one set of cortical schema nodes with three cortical nodes reflecting each of the colours the child can pick (Figure 5.14). As before, each schema node is linked to a separate parallel basal ganglia loop. Each simulation consists of 6 action trials, one for each of the 6 farm animals in the task. A colour is selected if the corresponding schema activation exceeds the threshold Θ .

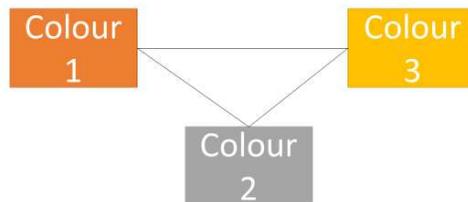


Figure 5.14. Schema nodes within the Colouring task model. The schema nodes connected by the grey lines compete with each other for action selection when exceeding the threshold Θ .

Children could use a “grouped” or a “cycled” strategy to implement the secondary goal in this task. The simulation captures both of these strategies using different local inputs. An intrinsic rule local input is applied to the PFC, based on the strategic approach the model adopts, reflecting the memory of the rule and the strategy chosen to follow the rule. Furthermore, there is an intrinsic perseveration local input applied to the GPi (Figure 5.15). The grouped approach follows a pattern like: 1 1 2 2 3 3. To capture this strategy, on the second trial, the model first

has a positive intrinsic local input on the PFC on the same colour as previously selected, followed by a negative local input on that colour after the next trial. The cycling approach follows an alternating pattern like: 1 2 3 1 2 3. Here, the model has an intrinsic negative local input on the same colour after each trial. An intrinsic negative local input of half this value was applied to that colour in the PFC two trials back.

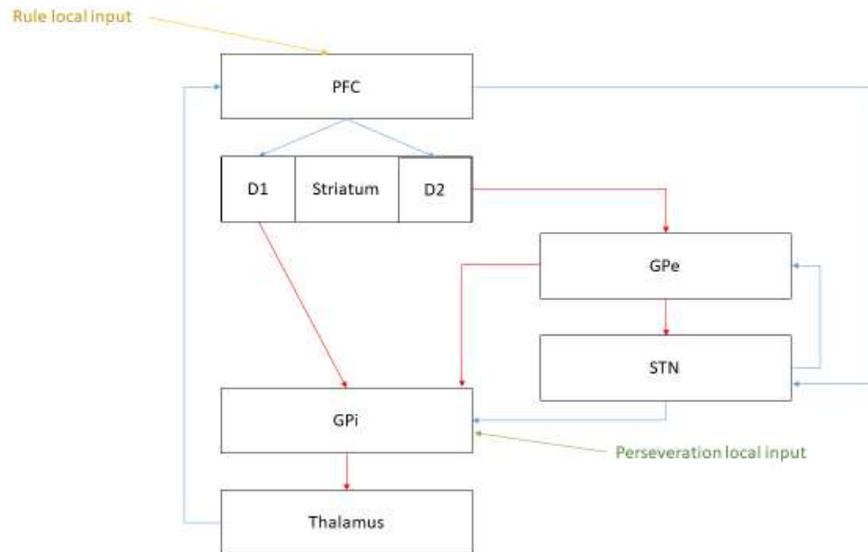
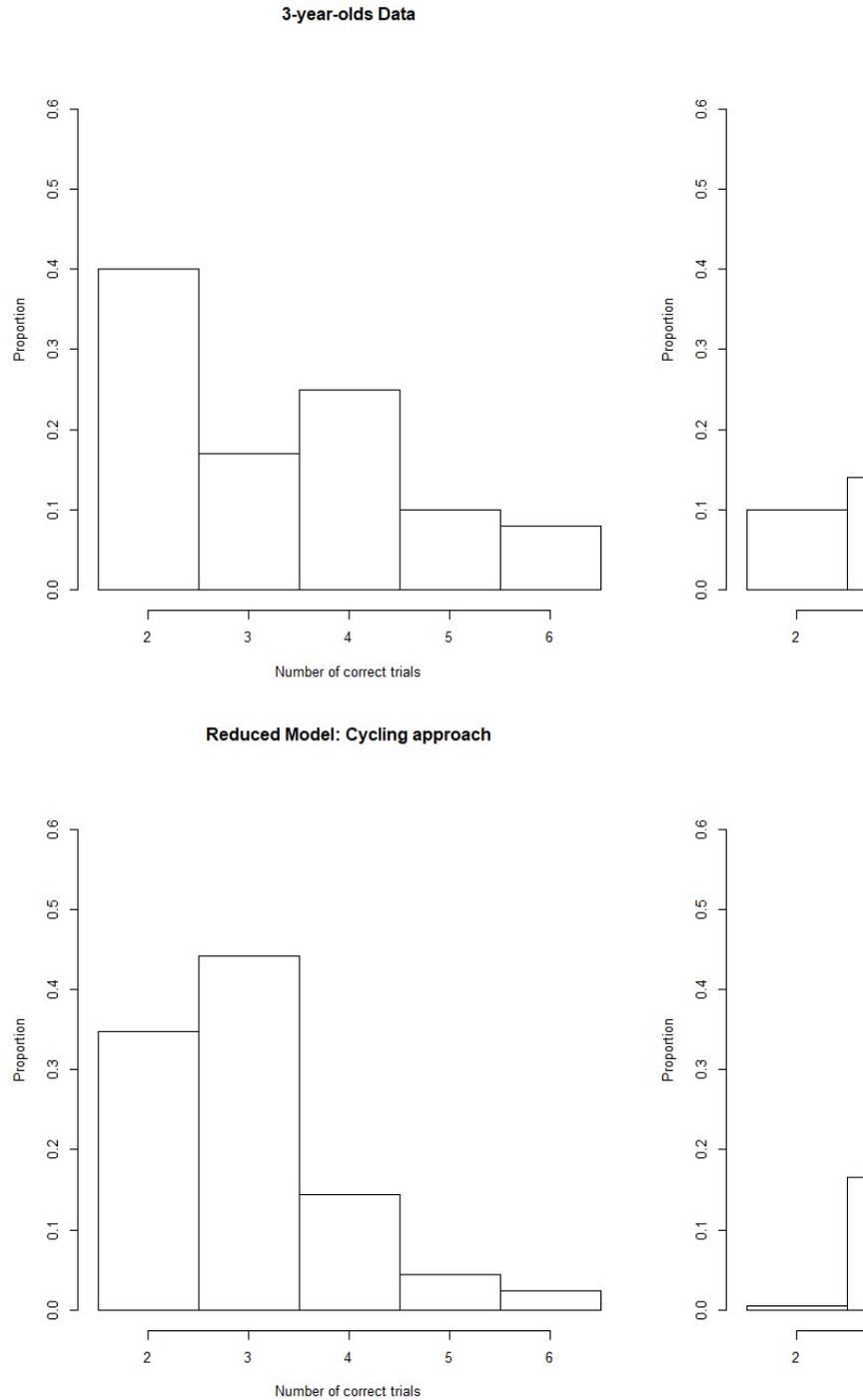


Figure 5.15. The basal ganglia nodes with intrinsic local input of the Colouring model.

5.3.3.2 Model performance

The full model captured 5-year-olds' behaviour in the task. Here again, removing the PFC local input (that reflected memory of the rule) and the GPi local input (preservation of behaviour) fits the 3-year-olds' behaviour well (Figure 5.16). Thus, as in previous tasks, children's developmental profiles from 3 to 5 years of age can be explained by increased intrinsic local input in the PFC and GPi with increasing age.



*Figure 5.16. Model performance compared to colouring data in Freier et al. (2017). The y-axis reflected the proportion of children/simulations that had that number of correct trials. The simulation data shown is averaged over 2500 replications. The child data is adapted from Figure 3 from *Preschool children's control of action outcomes* (page 5) by L. Freier, R.P. Cooper & D. Mareschal, 2017, *Developmental Science*, 20(2), 1-13.*

5.3.4 Simulation 4: The Dimensional Change Card Sorting

Goal neglect in the dimensional change card sorting task (DCCS) in preschool years is a widely documented phenomena (e.g. Marcovitch et al., 2007, 2010; Zelazo et al., 1996). The task involves a pre-switching phase in which cards have to be sorted according to either one dimension (colour or shape), while in the post-switching phase the cards have to be sorted according to the other dimension (Figure 5.17). Experimental data shows that 4-year-olds were most often correct in switching to sort the card according to a new rule, while 3-year-olds struggled to switch (Zelazo et al., 1996).

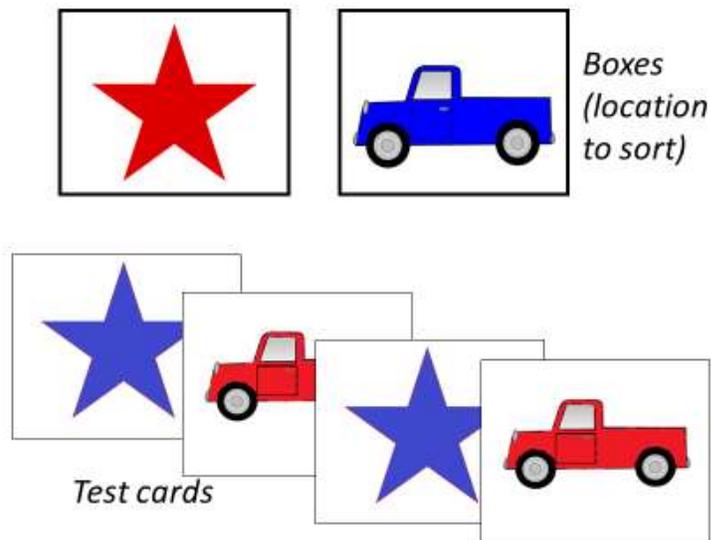


Figure 5.17. The set-up of the dimensional change card sorting task (DCCS).

5.3.3.1 Model specifications

In this simulation, the task was modelled as two higher-level cortical schemas representing the rules (sort by colour vs. sort by shape) and two lower-level cortical schemas representing the two sort locations (Figure 5.18). The box schemas reflects the outcome box with two nodes; one with red stars on left, and one with blue trucks on right. The rule schemas influences the box schemas. As above, each schema node is connected to a separate parallel basal ganglia loop. In the pre-switch phase (5 trials), the model is instructed to sort the cards according to shape. The post-switching phase (12 trials) requires the model to sort the cards according to colour. A card is sorted if the activation level of one of the outcome boxes (cortical schema nodes of outcome) reaches or exceeds the threshold Θ .

Here, in contrast to the Tower task, the colour and location schemas are dependent. This is because in the DCCS task, the rule has an influence on the choice of where you must sort which card, while in the Tower task, the location you put the block and which block you select are hypothesised to be independent action selection processes.

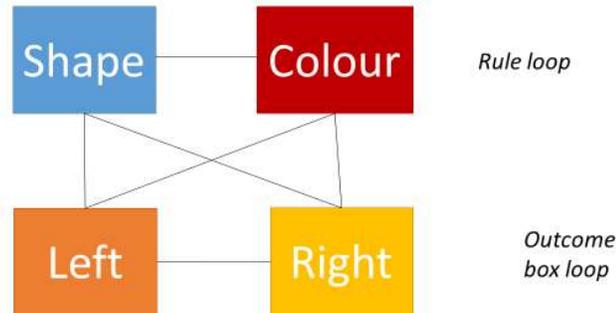


Figure 5.18. Schema nodes within the DCCS task model. The schema nodes connected by the grey lines compete with each other for action selection when exceeding the threshold Θ .

The model has an extrinsic rule input into the PFC rule schema which comes from the goal-node, reflecting ongoing memory of the task goal. The goal-node in the PFC remembers the instruction throughout the task. In addition, the rule cortical schema node influences the outcome box cortical schema node in the PFC. There is a perseveration (location) local input in the outcome box cortical schema node in the GPi reflecting perseveration of behaviour (Figure 5.19).

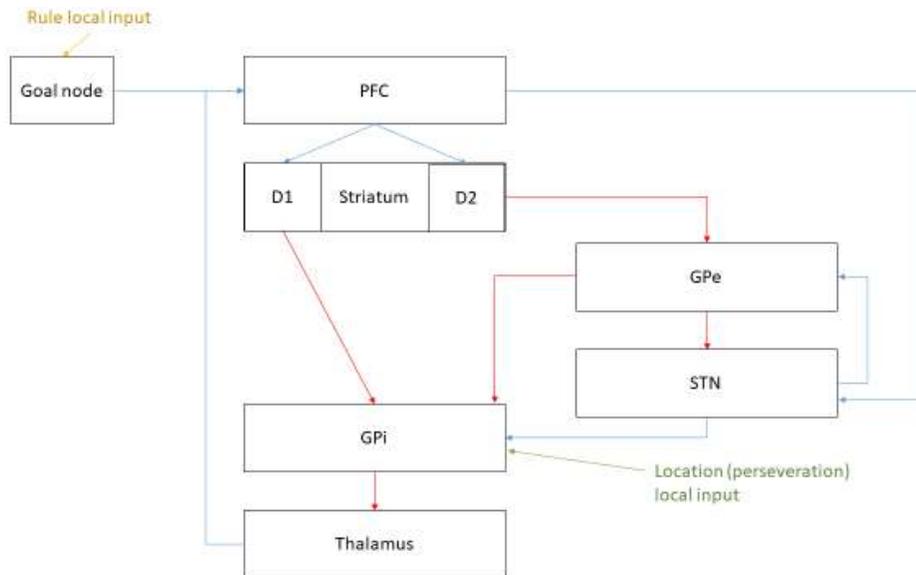


Figure 5.19. The basal ganglia nodes with local input in the DCCS model.

5.3.3.2 Model performance

The original paper (Zelazo et al., 1996) assessed performance on a binary scale; children who were correct on 10 or more of the 12 test (or post-switch) trials were classified as passing, while children who were correct on fewer were classified as failing.

The full model captured the 4-year-olds' data the best, while a reduced model without the PFC input in the rule cortical schema nodes (reflecting memory of the goal), but including the perseveration local input on the GPi captured the 3-year-olds' behaviour by showing perseveration in their card sorting (Figure 5.20).

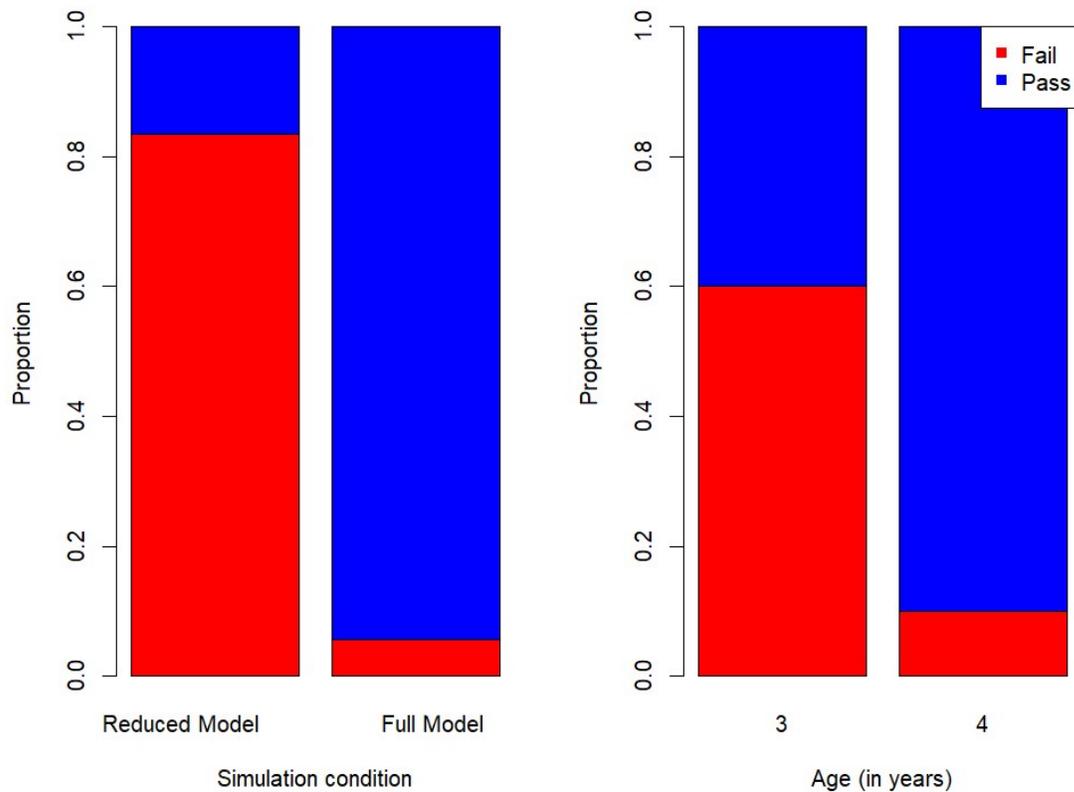


Figure 5.20. Proportion bar plots comparing model performance (left) to child data (right). The simulation data shown is averaged over 2500 replications. The data on the right hand side is adapted from *An age-related dissociation between knowing rules and using them* (page 43) by P. Zelazo, D. Frye, and T. Rapus, 1996, *Cognitive Development*, 11(1), 37-63.

Furthermore, the model showed a decrease in the number of correct sorted cards when there was a GPi local input but no PFC input in the rule cortical schema nodes (reflecting the goal) (Figure 5.21). Thus the rule input in the PFC seems to be essential in the development in performance on the DCCS task.

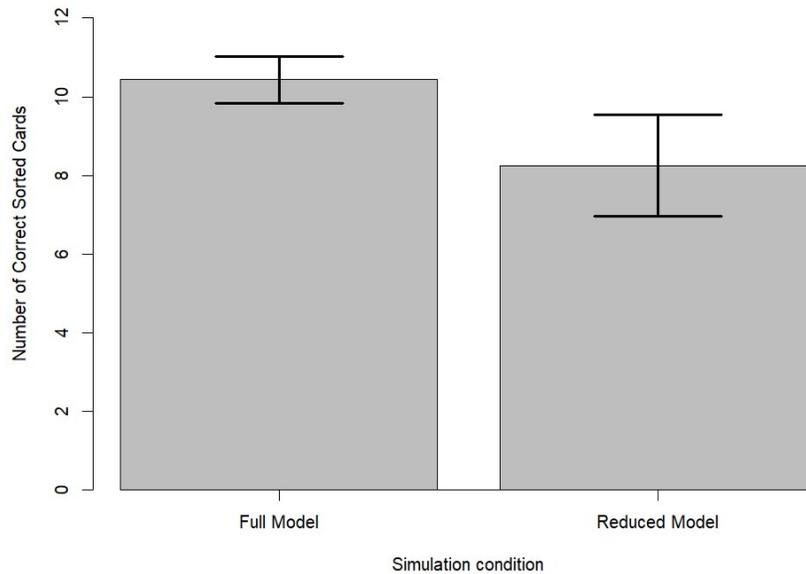


Figure 5.21. Card sorting accuracy of the full model and the reduced model without the PFC local input (but with the GPi local input). Error bars reflect standard deviation. The simulation data shown is averaged over 2500 replications.

5.4 Discussion

This chapter has investigated the novel hypothesis that action selection problems could underlie problems with goal-directed action sequencing observed in the preschool period. Four tasks were modelled; the Tower task of Chapter 2, the House task of Chapter 3 and 4, the Colouring task (Freier et al., 2017) and the DCCS (Zelazo et al., 1996). In all of these tasks, children demonstrated an improvement in the ability to align actions or action sequences according to task goals over toddlerhood and the preschool period. A computational model based on the neural architecture of the basal ganglia (Caso & Cooper, 2020) was used and adapted to simulate performance on each of these tasks.

The simulations suggest that action *selection* and action *planning* interact in development. However, these simulations clearly demonstrated that the development of the *goal representation* in the PFC is the most important factor for explaining improvements in goal-directed action sequences in this period within this theoretical framework. This is consistent with the *graded goal representation* account, which proposes that goal representation become

gradually stronger over development, and that this underlies improvements in goal-directed action performance (e.g., Munakata, 2001).

For the DCCS task simulation, it was demonstrated that adding an extrinsic PFC input reflecting the goal (i.e. breaking the link between the goal and the cortical schema node) could explain the development observed over the preschool years. A reduced model without this input made more mistakes in sorting the cards in the post-switching phase and demonstrated clear perseveration behaviours, similar to those observed in 3-year-olds. When the extrinsic PFC input reflecting the rule was added to the model, it captured 4-year-olds' performance, showing an ability to adapt flexibly to changes in the sorting rule.

In the House task (Chapter 3) simulation, the addition of an extrinsic PFC input improved the model's behaviour; an improvement that is also observed in children over the preschool period. The full model showed a similar level of colour switches as did 5-year-olds, while the reduced model without this input showed more colour switches and action step mix-ups as observed in 3-year-olds.

While these results suggest that the PFC goal representation is the primary factor driving development, the first set of simulations suggests that development in the subcortical basal ganglia loops related to action selection might also play some role. This could indicate that subcortical action selection circuits are not fully matured in the early preschool/toddlerhood period, and might therefore have an influence on observed improvement in action sequencing across this age.

For example, in the Tower task (Chapter 2) simulation, it was found that the addition of both an intrinsic PFC local input (reflecting goal memory) and an intrinsic GPi local input (perseveration of behaviour) could explain the development from a 2-year-old's level of performance to a 3-year-old's level of performance. The full model showed a positive relation between the primary and secondary goal constraints, as observed in 3-year-olds. In contrast, the reduced model (without both forms of intrinsic local input) showed a negative association between the primary and secondary goal constraint, as observed in 2-year-olds. Here, removing only the intrinsic PFC local input was not sufficient to produce the negative association observed in 2-year-olds. Thus, changes in both subcortical basal ganglia action selection circuits and PFC goal representation circuits contribute to changes in performance between 2- and 3-years of age.

Similarly, with respect to performance on the Freier et al. (2017) colouring task, behavioural development could be explained by an interaction between intrinsic PFC local input (reflecting the goal) and intrinsic GPi local input (reflecting perseveration behaviour). The full model showed a performance distribution with most simulations finishing 6 correct actions, similar to the 5-year-olds' behaviour. In contrast, the reduced model without these local inputs showed that most simulations only successfully completed 2 or 3 actions, similar to 3-year-olds' behaviour.

In summary, the main conclusion from this modelling is that the goal representation or the use of goal representation in action planning is indeed the main factor driving improvement in action selection and action sequencing following task goals over the preschool years. This is in line with the proposals such as that goal representation gradually become stronger over development (Munakata, 2001) or that issues in cognitive control underlie action problems in childhood (Freier et al., 2017). Immature basal ganglia action selection can still contribute to development, especially earlier in development; however, the current modelling work suggested that is not the main driver of development during the preschool years.

But what does it mean that the performance of younger children can best be explained by a model with reduction or absence of local inputs at key subcortical structures and prefrontal cortex, i.e. what does the changes in the local input in the model respond to? It was hypothesised that these changes reflect that younger children are less sensitive to input, requiring more of an extrinsic or intrinsic push to fire (i.e. select that action). This is supported by the claim that younger children have a greater contribution of neural noise relative to signal leading to more time needed to process the information in that signal because of lower signal-to-noise ratios and larger behavioural and neural variability (Deutsch & Newell, 2005; Dinstein et al., 2015).

A limitation of the current work is that the models described in this chapter did not model how the prefrontal cortex *creates* action plans to achieve these task goals. The model focussed on action *selection* from among several existing action options, but did not provide an account of action planning or action execution *per se*. Future research can extend this model by taking into account goal selection and action planning to achieve these goals. A full model including action planning and execution would provide a more comprehensive understanding of the development of actions and how these different aspects interact.

A more minor limitation of the current modelling work is the lack of the mixed strategy and random strategy in the Colouring task. Most 3-year-olds demonstrated a random strategy, and children with a random strategy were also less likely to achieve the goal. In contrast, most of the older children demonstrated a cycling strategy (not a grouped strategy); the cycling strategy was associated with better chances of completing the goal (Freier et al., 2017). Furthermore, some children demonstrated a mixed strategy which blended the cycling and grouped strategies. Future models should take into account the different strategies and how this relates to achieving the outcome.

Future modelling work should also investigate whether the model is also able to explain different forms of the DCCS tasks such as those described by Marcovitch and colleagues (2007, 2010). Here, they demonstrated that children performed better on the test cards if more redundant cards (identical cards to targets) were in the test-set than conflict cards (test cards) (Marcovitch et al., 2007, 2010). Lastly, future modelling work can extend the current model of the basal ganglia frontal cortex loop to other tasks assessing action sequences development in early childhood, such as the dressing a doll in a school uniform task (Yanaoka & Saito, 2017) and the baking a toast for cat or mouse task with distractions to assess routine action sequences (Yanaoka & Saito, 2019, 2020).

5.4.1 Conclusion

In summary, this chapter investigated whether immature action selection in the basal ganglia contributes to the development of achieving a task goal in tasks involving action sequencing. It modelled the operation of basal ganglia - frontal cortex loops on four tasks in which empirical evidence of development in actions and action sequencing is observed over the preschool period. The modelling results suggest that while action selection and action planning might interact in development, action planning and/or goal representation is the main driver of development during the preschool years.

The next chapter will reflect on the different chapters and how these relate to each other and the wider literature. Furthermore, some general limitations will be discussed, and some future perspectives will be suggested.

CHAPTER 6

General discussion

Goal-directed action sequences are crucial in our everyday acting. This thesis aimed to investigate the development of planning and execution of goal-directed action sequences in toddlerhood and the preschool period in naturalistic settings. Furthermore, it investigated how the development of goal-directed action sequences relates to the development of the core components of executive functions (i.e. working memory, inhibition and set shifting), and motor competence. Moreover, dynamic processes in planning were studied using optical motion capture to explore what dynamic markers can reveal to us about the development of hierarchical action sequence planning. Lastly, this thesis aimed to investigate the involvement of brain areas in the development of action sequences using fNIRS and computational modelling.

This chapter starts with a discussion of the main findings of the previous chapters and the implications of the research that was presented in this thesis. Furthermore, limitations and future directions will also be discussed.

6.1 General overview of the thesis

Previous literature has demonstrated that adults are proficient at planning and executing action sequences with only occasional lapses. Recent evidence has shown that the planning and control of these action sequences develops substantially over the preschool years and might be related to the development of executive functions. The foregoing chapters discussed the empirical evidence regarding toddlers' and preschoolers' action sequence planning, its relationship to executive functions, and potential brain mechanisms underlying the planning, selection and control of action sequences.

The most common type of action sequence described in literature is an action sequence with a hierarchical goal structure (Cooper et al., 2014; Cooper & Shallice, 2000, 2006; Jeannerod, 1997; Lashley, 1951; Miller et al., 1960; Rosenbaum et al., 2007). For example, making a cup of coffee consists of the main goal of making a cup of coffee with several subgoals such as adding milk, and each of the subgoals in turn consists of several action steps. However, not all action sequences consist of a hierarchical goal structure, but instead some action sequences are simpler; they might have goal constraints, or just might follow a strategy to achieve its goal.

For example, dividing several marbles between you and your friend is an action sequence with only one goal with an alternating strategy, distributing the marbles in equal parts between you and your friend.

Chapter 2 began by investigating two forms of simple action sequences in toddlers: planning and execution of (i) simple alternating actions, and (ii) action sequences with multiple goal constraints. Toddlers between 24 and 36 months of age were instructed to sort coins in an alternating pattern between two boxes, dividing the coins equally. The ability to plan simple alternating actions following a pattern improved over toddlerhood, and was related to improvements in working memory capacity and motor competence.

Furthermore, the same toddlers were tasked to build a tower using two goal constraints: (i) build the tower to the correct height, and (ii) build a striped tower by alternating between two colours. Toddlers struggled to keep track of both goal constraints in their action sequences, and toddlers who were successful at the first goal constraint were less likely to be successful with the second goal constraint. Three-year-olds improved and were more likely to be successful with both goal constraints in their action sequences. Furthermore, this ability was related to improvements in working memory capacity. In contrast to the alternating coin task, motor competence did not appear to influence performance on this task, perhaps because building a tower with big Duplo blocks required less fine precision in terms of motor skills than grasping and sorting small coins.

In short, these results suggested that some simple forms of action sequence planning and execution develop in toddlerhood, and that action sequences were related to improvements in executive functions, especially working memory. This study was the first to investigate the development of planning alternating actions in toddlers, and it showed evidence of the ability to plan actions with a repeating pattern earlier in development than demonstrated in the previous colouring task (Freier et al., 2017). In Freier and colleagues (2017), 5-year-olds were able to cycle between three colours pencils in their colouring action sequences, while in Chapter 2 young preschoolers showed an ability to plan and execute action sequences according to simple alternating pattern. Alternating might be a precursor of cycling actions abilities. Other studies have also demonstrated that understanding, recognising and planning alternating patterns was an important skill that continues to develop and improved understanding of mathematic in preschoolers (Papic, 2007; Papic et al., 2011; Papic & Mulligan, 2007).

The tower building task demonstrated that some 3-year-olds were able to follow two goal constraints in their action sequence planning. This was in contrast with Freier and colleagues (2017) who reported that 3-year-olds were unable to follow the second goal constraint of cycling between three colours in colouring farm animals. Contrasting results such as these emphasises the importance of considering the task context in which actions are planned. For example, building alternating patterns with big Duplo blocks in Chapter 2 might be an easier or more familiar task than cycling between three coloured pencils while colouring (Freier et al., 2017). Thus, difficulties in action sequence planning observed in toddlers or preschoolers may not necessarily point out a general impairment in the ability to plan action sequences, but might better reflect difficulties with the specific task restrictions.

Both types of action sequence planning abilities were related to executive functions, especially working memory updating. Working memory updating was related to the performance of simple alternating actions and action sequences with multiple goal constraints, whereas inhibition was related to the ability to stop acting once the goal was achieved. Previous literature has already demonstrated a link between executive functions and action sequence representation in preschoolers (Yanaoka & Saito, 2019). Executive function development has also been linked to motor behaviour (Livesey et al., 2006) and motor planning in infancy and childhood (Gottwald et al., 2016; Pennequin et al., 2010).

As many action sequences in daily life have a hierarchical goal structure, the two subsequent chapters focused on action sequences with a goal hierarchy investigating more in depth. Chapter 3 assessed preschoolers' ability to plan and execute actions with a hierarchical goal structure. Preschoolers were instructed to build a Duplo house following a given goal hierarchy. The main outcome measures were whether children were able to keep track of the main goal, followed the subgoal structure and avoided distractor objects.

The results demonstrated that maintaining the key goal of the goal hierarchy improved with age over this period. In addition, specific executive function components were related to different aspects of action sequence planning: inhibition was related to avoiding distractor objects, whereas updating was related to executing actions following the subgoal structure.

This confirmed previous findings suggesting that the planning and control of hierarchical action sequences developed over the preschool period (Yanaoka & Saito, 2017; 2019; 2020). As in Chapter 2, improvements in executive functions were related to improvements in the performance of action sequences. Of particular interest is that in Chapter 2, inhibition was

related to halting actions when the goal was achieved, and in Chapter 3, inhibition was related to avoiding actions irrelevant to the goal hierarchy. Therefore, it seems that inhibition skills are essential in avoiding actions that do not achieve the goal. Updating (of working memory) also seemed to be important in all action sequences tasks in Chapter 2 and Chapter 3.

In Chapter 2, the *spinning pots* task was used to assess working memory (updating), while in Chapter 3, the *backward digit span* task was used. Although labelled differently in this thesis, both assess a similar common aspect of executive functions; namely, *working memory updating*. This means that both evaluated the ability to hold information in mind as well as updating and manipulating this information (Garon et al., 2008). However, the working memory score (percentage correct irrespective of order) in Chapter 3 only assessed the ability to hold information in mind; this was not found to be related to action sequence abilities. These results further demonstrated that investigating how the core components of executive functions relate to *specific* segments of action sequence behaviour is beneficial for understanding the development of the performance of action sequences, as updating and inhibition were related to specific components of action sequence planning. Previously, studies have only linked executive functions to performance on action sequence tasks in general (Yanaoka & Saito, 2017, 2019, 2020).

Unlike Chapter 2, motor competence was not related to planning scores or the motion capture measures recorded. However, in Chapter 2, motor competence was also not related to action sequencing with Duplo blocks. It was therefore assumed that by 2 years of age, children had adequate motor competence to control their action sequences using Duplo blocks. However, the motor competence required for more precise actions such as sorting small coins might still be developing over toddlerhood. Previous studies have shown that fine motor skills still continue to develop over toddlerhood (Berk, 2017; Boyd & Bee, 2013; Colson & Dworkin, 1997).

In Chapter 3, optical motion capture was used to reveal the dynamic mechanisms of hierarchical action sequence planning. Motion capture techniques provide a window on the developing mind. Motion capture can be used to reveal temporal progressions of decisions and actions (Freeman et al., 2011; Song & Nakayama, 2009). Previously, motion capture has been used to investigate the development of online decision making processes of inhibition and set shifting tasks (Erb et al., 2017; 2018), but these results demonstrate that the method can be

extended to investigate the development of other cognitive processes such as action sequence planning.

It was shown in Chapter 3 that good planners freeze their non-reaching hand during the execution of a subgoal, while relaxing their hand at branch points when planning the next subgoal. This effect was argued to reflect increased task focus on executing the current subgoal. Similarly, freezing behaviour in their postural sway has been observed in children when they executed a more difficult task of counting backwards compared to the easier task of reading simple sentences out loud (Blanchard et al., 2005). The suggestion from this work was that ‘freezing motor degrees of freedom’ helps cognitive focus on the more difficult task.

Chapter 4 replicated and extended the findings in Chapter 3. Preschoolers were once more instructed to build a Duplo house with a hierarchical goal structure. Once again, it was shown that the ability to plan action sequences improved over preschool years. Again, inhibition was related to avoiding actions irrelevant to the goal hierarchy. Furthermore, children who followed the goal hierarchy showed more freezing of their non-reaching hand when executing a subgoal.

The behavioural results of Chapter 3 were mostly replicated in Chapter 4. Children improved over age in planning and executing their action sequences according to the key goal and inhibition was the strongest predictor of the ability to avoid distractors. Combining these results with the results of Chapter 2, in which inhibition was found to relate to the ability to end the action sequence when the goal was achieved, shows that inhibition is an essential skill necessary to avoid executing actions that are not compatible with the task goal.

In contrast to the findings reported in Chapter 3, there was no evidence that updating abilities were related to executing actions according to the subgoal structure in Chapter 4. However, in Chapter 2, updating abilities were found to be related to effective performance of action sequences in toddlers. Thus, it is possible that there was not enough power in the study reported in Chapter 4 to confirm this relatively weak effect. Future research should investigate this further.

The motion capture results of Chapter 3 were also replicated in Chapter 4. Good planners showed freezing of their non-reaching when they executed actions within a subgoal. This effect was especially evident when trials where the child pressed the button with both hands were excluded. Interestingly, some participants in Chapter 4 used the strategy of pressing the buttons with both hands, something that was not observed in Chapter 3. It might be that the way the set-up of the boxes (5 instead of 3) was wired resulted in more force needed to press the button

in order for the boxes to open, and this might have resulted in children using both of their hands to create more force.

While in Chapter 3 individual difference in inhibition were related to this freezing of the non-reaching hand as assessed in the motion capture, in Chapter 4 individual differences in working memory updating were found to be associated with this freezing. Thus, while it is clear that executive functions are related to cognitive focus while executing the current subgoal, it remains unclear what the exact relationship is between executive functions and action sequencing, specifically which component or components are the most important to freezing in goal-directed action sequencing.

In addition, in Chapter 4, fNIRS was used to investigate changes in brain activation patterns during action sequence planning. Despite, the small sample size with valid data, the results suggested that the dorsolateral prefrontal cortex was involved in planning action sequences. The dorsolateral prefrontal cortex was more active in 5-year-olds at branch points (i.e. decrease in deoxygenated haemoglobin), when a switch from one subgoal to another is required, than during actions completed within a subgoal. This effect was absent in 3-year-olds, who struggled to plan and execute action sequences with a hierarchical goal structure. Moreover, there was some evidence that the right homolog to Broca's area might be involved. Broca's area, historically considered only important in speech production (e.g. Lazar & Mohr, 2011), has also been suggested to be involved with its right homolog in hierarchical actions in adults (Koechlin & Jubault, 2006; Wakita, 2014).

Previous studies have also found that the dorsolateral prefrontal cortex is involved in action sequence planning (Kaller et al., 2011; Tanji et al., 2010). The neural activity in this area reflected forthcoming movements in multistep actions in monkeys (Mushiake et al., 2006). In addition, the dorsolateral prefrontal cortex was the only area that was only activated during planning of actions, but not during the execution phase in adults (Glover et al., 2012; Johnson-Frey et al., 2005). Lastly, patients with lesions in the dorsolateral prefrontal cortex were reported to show planning impairments (Burgess et al., 2000). This all suggests that the dorsolateral prefrontal cortex is an important area involved in action sequence planning. It is therefore reassuring to find developmental changes in activation of the dorsal lateral prefrontal cortex from 3 to 5 years of age.

However, the dorsolateral prefrontal cortex is not the only area that is involved in the development of planning, selection and execution of action sequences. The basal ganglia are

heavily involved in action selection and so their maturation may also play a role in the development of action sequence. In Chapter 5, computational modelling was used to investigate whether immaturities in the *basal ganglia – frontal cortex* loops could explain or partially explain action and action sequence development observed over the preschool period. Four tasks with empirical evidence of development in actions and action sequences were modelled using a model based on the neural architecture of the basal ganglia (Caso & Cooper, 2020). For both the DCCS task and the House task (Chapter 3), performance was best modelled by adding an extrinsic PFC input to the basal-ganglia prefrontal cortex loop, suggesting that prefrontal cortex development is the primary factor for driving action sequence development in these task. However, in the Tower task (Chapter 2) and the Colouring task (Freier et al., 2017), development could best be modelled by adding intrinsic PFC and GPi input, providing some evidence that, for these tasks, both changes in action selection and action planning might interact during development. However, overall, goal representations and/or action planning in the prefrontal cortex was found to be the main driver of the development of actions and action sequence performance during preschool years.

Finally, as mentioned in the Chapter 1, actions are embedded within the context that they are planned and executed in. The studies in this thesis aimed to use a more naturalistic environment than static lab tasks to reveal the richness of everyday action opportunities and competence. Duplo blocks can be used to construct complex structures by bringing them together, but just as easily these structures can be broken down or the blocks can be combined into new structures. The current studies demonstrated how a naturalistic task can be used to investigate the development of cognitive functioning in 2- to 5-year-olds. Moreover, wireless and wearable methods such as optical motion capture and fNIRS can be used to investigate these cognitive functions at different levels. In short, the studies in this thesis revealed that the combination of a naturalistic study setting and wireless equipment is particularly suitable to investigate the development of children’s cognitive functioning.

6.2 Limitations and lessons learnt

There are a number of limitations that need to be considered in respect to these results. A number of factors that might influence or relate to action sequences performance have not been investigated. For example, the results might have been affected by extraneous factors such as preschool attendance, parental education, home situations and their socio-economic background. These variables have been demonstrated to influence early cognitive development

in past studies (e.g. Bietenbeck et al., 2019; Bradley et al., 1989; Burger, 2010; dos Santos et al., 2008; Jacobsen et al., 2017; Roberts et al., 1999; Seidler & Ritchie, 2018). None of the studies reported in this thesis controlled for these potential factors.

Children's *motivation* to achieve the task goal was also not considered in the results. Motivation is a key part of planning. Planned actions will not be executed if there is no motivation to achieve the action's goal (Friedman et al., 1987). In the current studies, participants were asked to plan and execute a construction (such a house or a tower) using Duplo blocks. It is true that most toddlers and preschoolers were motivated to play with Duplo, with only 3 participants out of the 170 over all studies in this thesis having to be excluded because they did not interact with the Duplo blocks. This is a low drop-out rate for developmental studies. However, it should be mentioned that while participants were engaged and happy to play with Duplo blocks, this did not necessary make them motivated to complete the task according to the instructions. Indeed, while toddlers can act in a goal-directed manner, they are also easily distracted (Bullock & Lütkenhaus, 1988) and might have preferred to build something else. Future research should include a verbal check to ensure that the child is aware of what they built, and exclude children who admitted to building something different while knowing the goal of the task (if they provide evidence that they were not motivated to achieve the task goal). For example, a child might repeat that Fluffy wanted to build a tower, but instead admit that they had built a speedboat in full knowledge of what Fluffy wanted them to do.

Creativity might also have played a role in children's success or failure at building a tower or a house. For example, more creative children might have had different ideas of what to do with the building blocks instead of following the task instructions, resulting in more apparent failures, despite potentially being able to plan and execute goal-directed action sequences. As children get older, they were demonstrated to more creative (Urban, 1991). A creativity task such as the Just Suppose task where children have to generate ideas (Massonnié et al., 2019) could be used to investigate this effect on planning behaviour. However, it has also been found that the ability to follow instructions improved with age (Vlietstra, 1982). Together with the observed improvement in following the task goal with age found in these studies, this suggest that creativity might only have played a small or non-existing role in the results.

Another key limitation of these studies is that the verbal check for memory of task goal may not have been sufficiently sensitive to ensure that the child remembered the goal of the task when unable to execute the action sequences appropriately. In Chapter 2, toddlers and

preschoolers were asked, after completing the planning task, ‘do you remember what Fluffy wanted you to do?’ However, almost none of the participants gave a direct answer to this question. Verbal abilities in toddlers are limited (Colson & Dworkin, 1997). Most toddlers confirmed non-verbally by nodding that they believed their tower was identical to the one on the picture on the wall; however, it remains an open question whether they actually remembered the goal, and believed to have built the tower, or whether they just provided a social response of nodding.

In Chapters 3 and 4, the child was questioned about the main goal and subgoals after viewing the instruction movie when they said they were ready to build. If the child indicated that they were unsure or made a mistake, the different subgoals were discussed anew with the child. At the end of the task, when the child indicated that they were finished, it was checked what the child had built and whether it was similar to the instruction movie. Again, some shy preschoolers never verbally responded to the question of what they had built, with most children simply nodding that their construction was similar to the instruction movie. A potential solution to this problem would be to create a forced choice recall situation where they have to point to a picture of the correct goal, with other equally fun and interesting options available. For example, in the house task, the child might have to choose between a picture of the correct house, a picture of a speedboat with coloured blocks and a picture of a complex castle.

Chapter 2 and Chapter 3 demonstrated that finding a suitable set-shifting task for toddlerhood and the preschool period to assess this component of executive functioning is difficult. For example, in Chapter 2, the Trucks task, previously used in Hughes and Ensor (2005; 2006), showed no improvement over age, suggesting that the task was insensitive to improvements in set shifting that are associated with age. Similarly, in Chapter 3, the adapted shifting task was also found to be insensitive to age. This suggests that shifting might not have emerged as a dissociable core components of executive functions in toddlers and preschoolers (Hendry et al., 2016; van der Ven et al., 2013). However, in Chapter 4, the Land/Food game (Carteron et al., in preparation) was found to be an appropriate task to assess set shifting in this age range in terms of showing individual variability in scores that correlated with age across this age range.

Similarly, in Chapter 2, the inhibition task showed a ceiling effect in 2- and 3-year-olds’ performance, despite having being previously used in a similar age group (Friedman et al., 1987). Thus, this task might not be the most sensitive to measure individual differences in

inhibition in toddlerhood. Instead perhaps the Shape Stroop or Baby Stroop tasks (Garon et al., 2008) would have been more suitable to detect individual differences in inhibition in toddlerhood. The go/no-go inhibition task used in Chapter 3 and Chapter 4 was a better measure of individual differences in inhibition in preschool period.

These studies provided evidence for an association between executive functions and action sequence planning. However, it remains unclear whether executive functions underlie planning in daily life or whether planning improvements in daily life underlie executive functions development. The traditional view in the literature is that these core components of executive functions improve, and this benefits more complex processes such as planning (i.e. complex forms develop from simpler forms; Diamond et al., 2013; Garon et al., 2008; McCormack & Atance, 2011). However, it has also been suggested that executive functions emerge from the ability to plan and control motor actions (Gottwald et al., 2016) or that children's improved performance on daily life task demands results in specific skill improvement in the service of goals that can be measured by improvement in executive function components (Doebel, 2020).

Although this thesis does not provide direct evidence about developmental antecedents or causes of action planning improvements in toddlerhood and preschool period, we can speculate about the causes. As discussed in the introduction, causal reasoning might play a role in infancy; i.e. one has to understand what our action can cause to happen in the world (Frye et al., 1996) in order to plan a sequence of linked actions constructed to achieve a specific goal. Furthermore, motor competence and executive functions might also influence action planning development; however, whether these underlie action planning or action planning underlies these functioning remains unclear. Although not satisfactory, the truth is most likely an interaction between all of these factors. Lastly, an important factor underlying action planning might be scaffolding experience that parents give their children (Rogoff, 1991). For example, there might be a gradual increase in the complexity of action sequences parents ask their children to plan, starting with helping their child to stir the spoon, while later letting them plan and act themselves. Future research could investigate how parent scaffold their children's action sequences throughout toddlerhood and childhood.

Testing toddlers and children is challenging because they are often unwilling to continue with a boring task. More naturalistic situations with fun toys like Duplo blocks in which the child is free to move around improved task compliance. However, this brings a new set of challenges, especially with regards to neuroimaging. For example, methods such as

electroencephalography are extremely sensitive to movement artefacts. However, fNIRS is relatively resilient to motion artefacts (Lloyd-Fox et al., 2010; Mehnert et al., 2013; Moriguchi & Hiraki, 2013; Pinti et al., 2020), making it suitable for use in young children. However, even fNIRS is not completely resistant towards motion artefacts.

In Chapter 4, wearable fNIRS was used to investigate brain activation in prefrontal cortex during action sequence planning. The channel exclusion percentages in the planning task (when the child was free to move around) ranged from 39% to 96% ($M = 71\%$, $SD = 19\%$) in 5-year-olds and 50% to 93% ($M = 72\%$, $SD = 12\%$) in 3-year-olds. The exclusion percentages were only a bit better in 5-year-olds in the inhibition task ($M = 57\%$, $SD = 22\%$, $range = 24\%$ to 98%), but not for the 3-year-olds ($M = 72\%$, $SD = 21\%$, $range = 28\%$ to 93%).

There are two important conclusions can be drawn from this. First, for 3-year-olds, the 54cm cap that was used in the study might have been too loose. This would have resulted in the optodes not making good contact with the skull. This could have resulted in many noisy channels. Therefore, it would be better in these two age groups (3- and 5-year-olds) to use different cap sizes (for example 52 and 54 cm circumference respectively) to ensure the best fit and placement.

Secondly, in 5-year-olds, there was a difference in the exclusion rates for fNIRS channels between the more freely moving planning task and the more rigid sitting still inhibition task. This suggests that even despite the fact that fNIRS is relatively resilient to motion artefacts, more movement in the task does result in more noisy channels. However, in this instance, motion artefact correction techniques could provide an opportunity to improve the data quality. Indeed, poor data quality resulting from movement artefacts is a well-known challenge in adult studies using naturalistic settings and tasks with unrestrained movement. One possible corrective would be the use of an orientation sensor that can assess acceleration in 3D space in combination with gyroscope orientation in 3D space on the fNIRS cap (also named inertial measuring unit; de Almeida Ivo et al., 2021), which can be later used to model the artefacts associated with these movements in a GLM-based analysis.

It is important that this inertial measuring sensor is located on the cap to ensure it captures the movement of the child. However, the weight of the sensor and the lack of space on the child-sized cap made it impossible to use this method in the current study. Future studies might focus the array of optodes around only the area of interest, freeing up space and weight for a potential inertial sensor. For example, in Chapter 4, our main region of interest was the dorsolateral

prefrontal cortex, but the cap also covered the primary motor cortex and the premotor cortex. With regard to the specific research question and hypothesis, these channels were redundant, and could be removed allowing one to use an inertial measuring sensor to improve data quality.

In short, fNIRS in freely moving preschoolers in naturalistic tasks can be used to investigate the development of brain activation patterns. However, a tight fitting cap of the right size and potentially an inertial measuring unit could be used in the future to improve the fNIRS data quality.

As already shortly mentioned in Chapter 3, the motion capture gloves could have influenced participants' movements. It is likely that these effects were small or absent, because the gloves were fine-fitted and there were different sizes ensuring a good fit. Furthermore, the gloves were more likely to impact the grasp, and not the reaching movement which was investigated in Chapter 3 and 4. However, children might still have shown different movement kinematics than they would have without wearing these gloves.

This is a problem that is present at almost all studies; participants might act differently in front of a camera, or be influenced by the strange things we make them wear (i.e. motion capture gloves, fNIRS cap) and might therefore behave differently than in normal everyday life. There is probably no perfect solution to this problem, but it is important to make participants as comfortable as possible and create settings that remind them of their everyday life as much as possible thereby maximising naturalistic behaviours in experimental settings. A good example is the “Preschool room” environment in the ToddlerLab used in Chapter 4 where wireless techniques can be used to investigate behaviour in a setting that looks like a colourful preschool room with small tables and chairs, and toys.

As shown in these studies, action occurs within a context, and cannot be understood without considering the context. For example, in Chapter 2, the ability to plan simple alternating sequences and the ability to plan action sequences with multiple goal constraints showed different developmental trajectories in toddlers, but this might be related to the different motor demands of the tasks (i.e. constructing with big Duplo blocks vs. sorting small coins). Thus, actions should be considered within the context and situation they occur, once again making it important to use more naturalistic settings and tasks if we wish to understand action selection in the real-world.

The instruction videos used in Chapter 3 and 4 were not necessarily a perfect illustration of task instructions in free real-life actions. However, this was used with the aim to provide some

guidance on the action sequence that the child was to execute. Furthermore, everything that resembled a house was scored as ‘keep track of the main goal’, even if it was not identical to the video. For example, in Chapter 3, everything with a roof and at least two walls was scored as a house and taken to show that the participant successfully followed the main goal in their action sequences.

Lastly, the COVID-19 pandemic impacted the studies reported in the thesis in several ways. A part of the sample in Chapter 2 and the full sample in Chapter 4 was tested with increased distance between the experimenter and the participant, and all adults wearing face covering. Although this thesis does not study social behaviour, the fact that the experimenter was wearing a face mask could have influenced the results. For example, it might be more difficult to understand the task instructions for the participants. Given the similarity in results between Chapter 3 and 4, it is unlikely that this made a significant impact. Furthermore, the pandemic resulted in a smaller sample size ($n = 31$) than intended in Chapter 4, because testing in person was restricted and delayed. This resulted in low number of participants with valid data in some analyses, for example the prefrontal activation analysis in the planning task. Future research should confirm these finding in a larger sample size.

6.3 Where to next?

Taken together, these studies go some way to providing a better understanding of action sequencing development in more naturalistic environments. The simplest form of action sequences developed over toddlerhood; toddlers improved their ability to plan simple alternating action sequences as well as action sequences with two goal constraints between 2 and 3 years of age. Action sequence planning with a hierarchical goal structure developed over the preschool period. Both in toddlerhood and the preschool period, improved performance on action sequences could be related to improvements in executive functions.

Studying action sequences in more depth during the preschool ages, using motion capture methods, revealed a surprising freezing behaviour in good planners when executing a subgoal in their action sequences. Furthermore, neural mechanisms of action planning and selection were investigated using fNIRS in one study and computational modelling in a second study. While some action selection factors in the basal ganglia may also be at play, the development of goal representations in the prefrontal cortex, and especially the dorsolateral prefrontal cortex, was argued to be the primary motor for the development of goal-directed action sequence planning.

But of course, the preschool period is not *just* a critical period for the development of complex planning behaviour. It is also an important time for the development of *social* and *collaborative* behaviour that lays the foundation for social life through the rest of life (Halle & Darling-Churchill, 2016). Real-world action planning often occurs in the company of others, and these joint actions are integral to human social interaction and communication (Brownell, 2011). Furthermore, interactions with other people in the world fine-tune our action planning (Roepstorff & Frith, 2004). Our prefrontal cortex can be seen as the top of our motor cortex; planning its actions that the motor cortex executes. In turn, these social actions with parents or peers might provide top-down guidance for fine-tuning our action planning system. Furthermore, parents might scaffold their children's action planning (Berk & Winsler, 1995).

Collaborative planning does not only involve planning your own actions but also requires you to adjust your behaviour to the other's actions (Meyer et al., 2010; Paulus, 2016). There is some evidence that the preschool period is an important period for the development of collaborative planning behaviour (Gauvian & Rogoff, 1989; Warnicken et al., 2014). Future research should therefore focus on collaborative planning in naturalistic situations to investigate how parents scaffold their children's ability to plan a joint action sequences. Here, motion capture techniques can be used to reveal kinematic patterns associated with collaborative planning and fNIRS can be used to investigate synchronization in brain patterns between collaborative partners.

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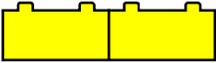
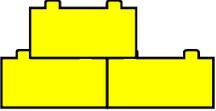
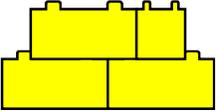
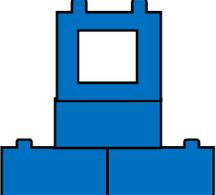
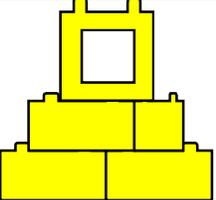
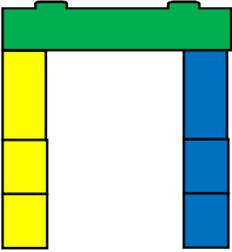
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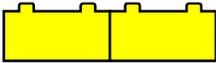
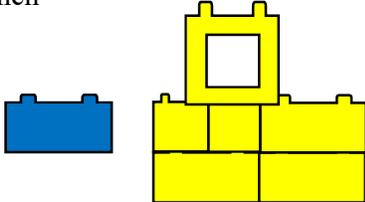
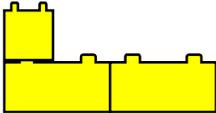
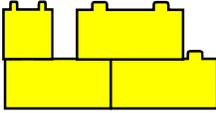
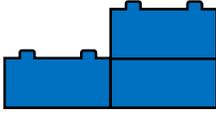
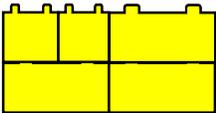
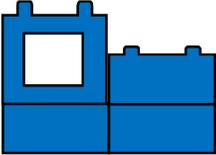
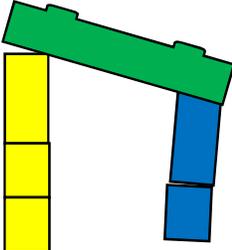
APPENDIX

Examples of trajectories and corresponding houses in Chapter 3.

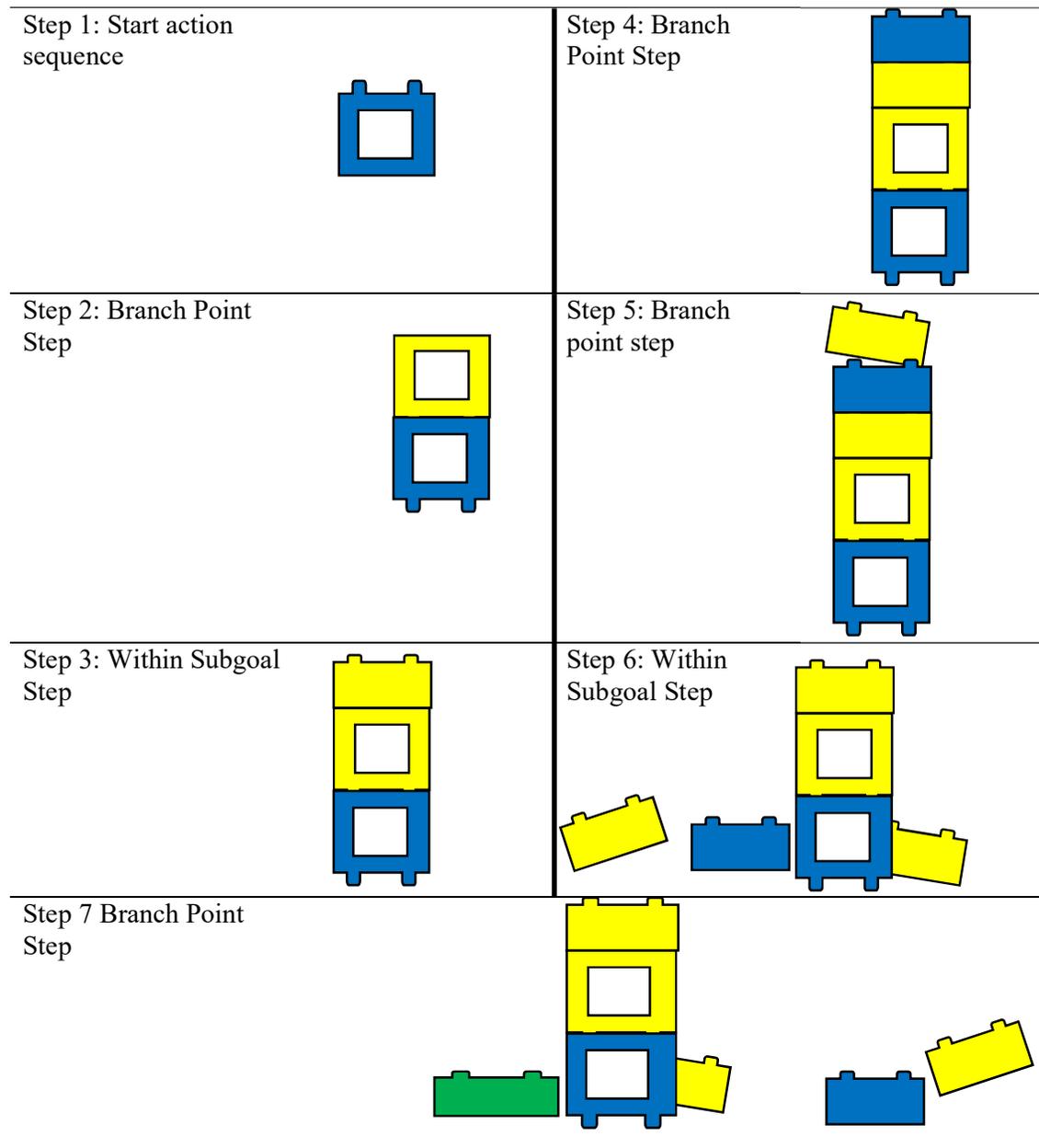
Example 1; age: 64 months; main goal score: 1; subgoal score: 1; distractor score: 0

<p>Step 1: Start action sequence</p> <div style="text-align: center; margin-top: 20px;">  </div>	<p>Step 6: Branch Point Step</p> <div style="text-align: center; margin-top: 20px;">  </div>
<p>Step 2: Within Subgoal Step</p> <div style="text-align: center; margin-top: 20px;">  </div>	<p>Step 7: Within Subgoal Step</p> <div style="text-align: center; margin-top: 20px;">  </div>
<p>Step 3: Within Subgoal Step</p> <div style="text-align: center; margin-top: 20px;">  </div>	<p>Step 8: Within Subgoal Step</p> <div style="text-align: center; margin-top: 20px;">  </div>
<p>Step 4: Within Subgoal Step</p> <div style="text-align: center; margin-top: 20px;">  </div>	<p>Step 9: Within Subgoal Step</p> <div style="text-align: center; margin-top: 20px;">  </div>
<p>Step 5: Within Subgoal Step</p> <div style="text-align: center; margin-top: 20px;">  </div>	<p>Step 10: Branch Point Step <i>(side-view)</i></p> <div style="text-align: center; margin-top: 20px;">  </div>

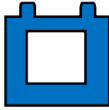
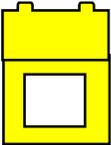
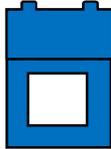
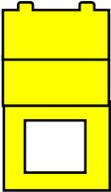
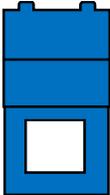
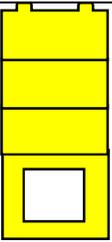
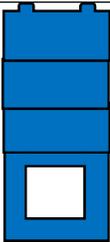
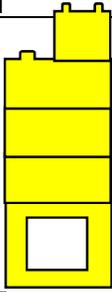
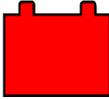
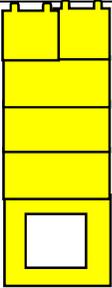
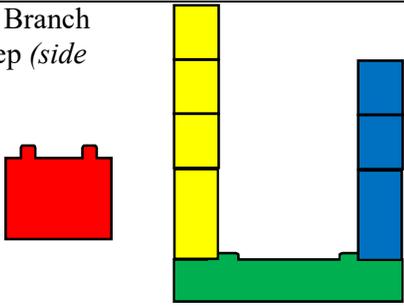
Example 2; age: 53 months; main goal score: 1; subgoal score: 0; distractor score: 0

<p>Step 1: Start action sequence</p> 	<p>Step 6: Branch Point Step</p> 
<p>Step 2: Within Subgoal Step</p> 	<p>Step 7: Branch Point Step</p> 
<p>Step 3: Within Subgoal Step</p> 	<p>Step 8: Within Subgoal Step</p> 
<p>Step 4: Within Subgoal Step</p> 	<p>Step 9: Within Subgoal Step</p> 
<p>Step 5: Within Subgoal Step</p> 	<p>Step 10: Within Subgoal Step</p> 
<p>Step 11: Branch Point Step (<i>side view</i>)</p> 	

Example 3; age: 40 months; main goal score: 0; subgoal score: 0; distractor score: 0



Example 4; age: 41 months; main goal score: 0; subgoal score: 0; distractor score: 1

<p>Step 1: Start action sequence</p> 	<p>Step 7: Branch Point Step</p> 
<p>Step 2: Within Subgoal Step</p> 	<p>Step 8: Within Subgoal Step</p> 
<p>Step 3: Within Subgoal Step</p> 	<p>Step 9: Within Subgoal Step</p> 
<p>Step 4: Within Subgoal Step</p> 	<p>Step 10: Within Subgoal Step</p> 
<p>Step 5: Within Subgoal Step</p> 	<p>Step 11: Distractor</p> 
<p>Step 6: Within Subgoal Step</p> 	<p>Step 12: Branch Point Step (<i>side view</i>)</p> 

Example 5; age: 53 months; main goal score: 1; subgoal score: 1; distractor score: 0

