The development of bottom-up and top-down interaction in the processing of goal-directed action

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PhD Psychology

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I 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 states otherwise by reference or acknowledgment, the work presented is entirely my own.

“Nothing whets the intelligence more than a passionate suspicion, nothing develops all the faculties of an immature mind more than a trail running away into the dark.” (Stefan Zweig)

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ABSTRACT

The study of action-cognition is driven by the assumption that what one can do motorically depends on what one can conceive of mentally, given a set of external opportunities (Rosenbaum, Cohen, & Jax, 2007). Therefore, a comprehensive theory of action development ought to integrate perceptual aspects of action processing with conceptual changes that give rise to increasingly abstract behaviours.

How and why children progress to higher levels of organization in the processing and coordination of purposeful behaviour is a question that has been at the core of developmental research for decades. Various competences underlying early action processing and decision-making have been identified and linked to sophisticated mental operations later in life. However, considerably less is known about the relationships between perceptual and conceptual abilities and how they interact to shape action development.

Goal-pursuit is achieved with increasing efficiency during the preschool period. In fact, by the age of first grade children show substantial abilities to regulate actions into hierarchically structured sequences of events that can be transferred across contexts (e.g., Levy, 1980; Bell & Livesey, 1985; Livesey & Morgan, 1991). The aim of this project was to investigate the perceptual and conceptual processes that drive these remarkable advances as they emerge during the preschool years. The studies in this thesis investigate top-down and bottom-up interactions in the processing of actions at various levels of abstraction. Employing a range of novel paradigms, the results of four studies highlight considerable advances in preschoolers' abilities to organise actions in terms of goal hierarchies. Findings further highlight that the ability

to extract structure at a basic level is readily achieved early in life, while higher-level action comprehension and planning abilities continue to develop throughout the childhood years.

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CHAPTER 1

The planning and coordination of goal-directed actions in early life

1.1. Introduction

It has been proposed that cognitive development ought to be understood through the functional perspective provided by "action", because all aspects of cognitive development are reflected in actions (e.g., von Hofsten, 2007; Thelen & Smith, 1994). The argument that infants' competences in goal perception and rational imitation relate to higher-level mental operations later in life is widely held, yet the developmental trajectories underlying this progression are not well understood. As such a comprehensive account of how early emerging abilities interact to shape action planning and development during pre- and primary school is clearly needed.

In cognitive science, *action planning* constitutes a generic term that refers to both: (1) the processing of any type of intentional motor behaviour, as well as (2) the planning of a specific goal-directed activity that delivers rewarding outcomes for the acting individual (e.g., Grèzes, et al. 1998; Rizzolatti, Fogassi, & Gallese, 2001). In the context of this thesis, action planning is conceptualised in the latter sense. *Action understanding,* in turn, is an internal description of an observed action that once achieved can be used to guide the organisation of future behaviour and thus provides a basis for imitative learning and more abstract forms of planning. Therefore, action comprehension plays a critical role for the planning of goal-directed behaviours and vice versa. The centrality of this influence appears especially relevant during a time in development during which most real-world action knowledge is acquired. As

Sommerville & Woodward (2005) argued: *"The ability to organize individual actions around ultimate goals is key to not only interpreting the actions of others, but also for predicting future actions based on past events, for learning from and describing novel actions to others, and for categorizing action sequences in terms of the event representations to which they belong."*. We will return to this link between planning abilities and action comprehension in the following chapters, presenting a number of studies that focused either on planning or comprehension related aspects of action processing.

Because actions can be described and understood at multiple interdependent levels, they can also be studied from multiple perspectives. Kilner (2011) proposed a categorization of actions into: (i) the kinematic level (motion trajectories), (ii) the motor level (patterns of muscle activity), (iii) the goal level (immediate purpose), and (iv) the intentional level (higher-level or overarching goals). The primary aim of this project is to provide new insights concerning the development of action cognition by investigating fundamental action-related processes at each level.

The following sections provide an overview about the perceptual and conceptual processes that have been implicated in the comprehension and execution of goal-directed behaviour. We begin this review presenting evidence about how adults and infants perceive and structure sequential behaviour in terms of action-goal hierarchies. In this context, the role of perceptual regularities in human behaviour will be discussed and integrated with developmental accounts of action perception in early life. Thereafter, we turn to the neural underpinnings of the perception and planning of goal-directed behaviour and consider the putative mechanisms that have been related to a human action network. We then review various lines of developmental research that provide cognitive accounts of the perceptual, regulatory, and higher-level processes that together shape intentional behaviour during early childhood. This chapter aims to review the wide range of evidence that is relevant to the current project, providing a background for new directions in the study of action development. Subsequent chapters will return to the concepts introduced in the following sections and discuss the theoretical accounts outlined below in relation to the specific studies in this thesis.

1.1.1. The cognitive representation of goal-directed actions

Intentional actions are guided by mental representations of goal states; i.e., anticipated action effects (e.g., Hauf & Prinz 2005; Wood & Neil, 2007). *Action planning* allows the formation of active mental representations of a target situation, and thus enhances the accessibility of goal-related cues in a particular action context (Gollwitzer, 1999).All planned behaviours and even single movements are hierarchically organised in terms of individual sub-goals and their relationships to higher-level multimodal goals (e.g., Sommerville & Woodward, 2005). In fact, the organisation of actions in terms of sub-goals (Figure 1.1.) is often so transparent that it is used in an educational context to promote learning (e.g., tasks are frequently composed of a set of sub-tasks that relate to sub-goals within the main task).

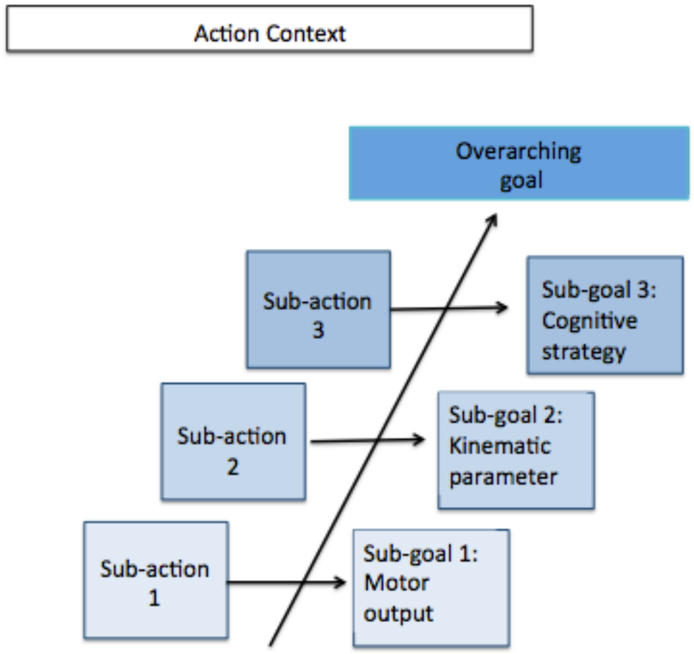

Figure 1.1. Schematic representation of goal hierarchy in intentional behaviour. In this hierarchy sub-actions at superordinate levels relate to increasingly abstract goals, spanning from the level of raw movement to specifications of the kinematic parameters involved in performing the action, to higher-level aspects of action planning (e.g., Kilner, 2011).

Identifying the links between sub-actions of a particular hierarchy across a range of contexts is critical for both the comprehension and planning of goal-directed actions. In naturalistic settings, the hierarchical structure underlying many action sequences does not need to be planned entirely *de novo* (e.g., Rosenbaum, Cohen, & Jax, 2007). Sub-goals within a sequence may well be realised with considerable autonomy (Byrne & Russon, 1998). Habits, for example, can be conceived of as mental representations of action-goal links that are triggered when action goals are activated by contextual cues. As such, habitual actions require considerably fewer planning demands than infrequently executed actions (e.g., Wood & Neil, 2007). The emergence of novel behaviours, in turn, calls for adaptations of prior plans into increasingly complex and novel sequences. In relation to cognitive development, this means that, on the one hand the ability to construct action plans improves to allow higher-level goal-pursuit, and, on the other hand, a mechanism by which learned action plans are modified must be in place to explain adaptive behaviours and learning. We return to this argument in the first empirical chapter of this thesis (Chapter 2) across two experiments that examined preschoolers' abilities to extract goal-relevant information from observed behaviour based on prior event knowledge.

Beyond identifying event structure and hierarchical relations underling goal attainment, implementing action plans requires a mechanism by which actions are evaluated and regulated in respect to outcomes. The evaluation of actions in terms of outcomes is referred to as *performance monitoring* (e.g., Botvinick et al. 2001). Figure 1.2. illustrates the relationship between performance monitoring and its central role for behavioural adaptation. Several formal theories aim to provide comprehensive accounts of the mechanisms that give rise to the regulation, coordination, and sequencing of goal-directed actions (e.g., Botvinick et al. 2001; Braver, 2012; Cooper, Ruh, & Mareschal, 2014; Norman & Shallice, 1986). Such accounts of cognitive control stress the role of a central executive or performance monitoring system that continuously updates information about the current performance against predicted outcomes. As a result, deviations from the predicted goal state can be detected and counteractive mechanisms can be generated to optimise current as well as future actions. Such an evaluative mechanism, in turn, has been argued to promote long-term learning (see Ullsperger, Danielmeier, & Jocham, 2014).

Performance monitoring is therefore a critical top-down mechanism in the transformation of observed behaviour into goal-directed actions. The next section will discuss the role of perceptual mechanisms that give rise to action comprehension in early life. We then consider how the ability to parse everyday action sequences into units develops and gradually enables young children to make sense of complex observed behaviour. We will return to the role of conflict monitoring in the following chapter.

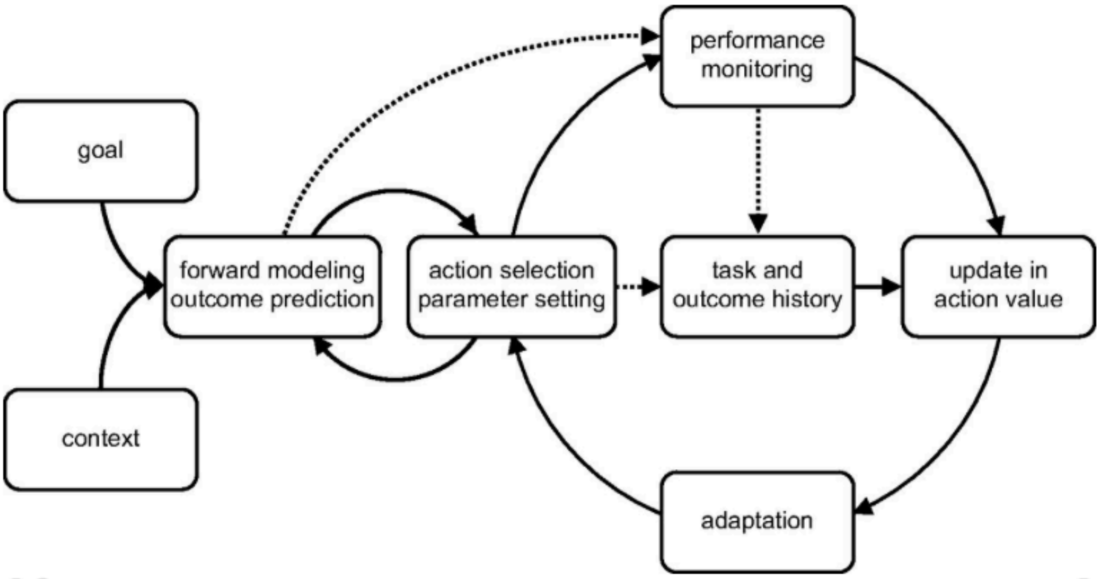

Figure 1.2. Feedback loop implicated in adaptive behaviour. To optimize outcome predictions, weighted differences between the expected and actual outcomes trigger flexible adjustments in behaviour. Performance monitoring and the evaluation of outcomes are thought to be critically mediated by cortical networks in frontal and parietal brain regions (e.g., Badre & Frank, 2012). Figure from: Ullsperger, Danielmeier, & Jocham, 2014.

1.1.2. Action perception in early development

Despite well-documented dissociations between action and perception in early life (e.g., DeLoache, Uttal, & Rosengren 2004), the existence of bidirectional links between action execution and action observation is supported by ample evidence implicating analogous cortical mechanisms (e.g., Nitshitani & Hari, 2000; Rizzolatti, Fogassi, & Gallese, 2001).

It has been argued that observed actions are consistently interpreted in terms of goals and intentions by the second year of life (e.g., Csibra, Gergely, Brockbank, Biro, & Koos, 1999; Gergely, 2001; Keen, 2011). There is much debate concerning the precise mechanisms that drive this early comprehension of movements as goal-directed. To understand the development of early action perception several outstanding questions need to be addressed. For example, what kind of information about intentionality is actually available in the surface flow of movement and which aspects can infants detect? Also, what strategies are involved in the observation of continuous action sequences and how are these skills acquired in ontogenetic development?

Interpreting actions as either goal-directed or accidental calls for a mechanism of parsing the visual input into discrete action units. Thus, the capacity to track and encode intentionality in the surface flow of action depends on a number of prior skills that allow the segmentation of continuous sequences into goal-relevant components. Research in this direction suggests that the detection of distinct actions that coincide with intentions might be achieved in various ways.

Knowledge-driven accounts of action segmentation can only explain how existing action concepts are modified on the basis of prior event knowledge, but fail to explain how novel events are segmented at intentional boundaries. An interesting alternative explanation, that considers top-down processes in conjunction with bottom-up processes, suggests that sensory characteristics, that serve as more direct cues to detect the structure inherent in ongoing behaviour, constitute the initial basis for segmenting event sequences into distinct actions (e.g., Baldwin, Baird, Saylor & Clark, 2001, Zack, 2004). In the absence of prior event specific knowledge, action segmentation could be accomplished on the basis of movement features that correlate with the agent's intentions. It is therefore plausible that sensitivity to structure detection constitutes the critical mechanism underlying action segmentation during infancy and early childhood because these are periods during which prior event knowledge is frequently lacking (e.g., Mendoza & Baldwin, 2014).

Moreover, most everyday events contain an abundance of statistical regularities that correlates with goal-directed intentions embedded in the action stream. This may arise from predictable patterns of body motion, limb trajectory, changes in gaze direction, and timing of action sequences. Baldwin et al. (2001) propose that even infants are able to tap into such statistical patterns, in a way similar to the way they use structural information to segment continuous strings of syllables into word units (an analogy that has been frequently used, see Baldwin et al., 2001, Baird & Baldwin, 2001). Along this line of reasoning, Baldwin et al. tested 10- to 11-month-olds' responses to interruptions of goal-directed events and discovered that these infants did indeed show increased interest when the sequence was paused in the middle of an intentional action, but not when paused between boundaries of activity. The authors concluded that action sequences were parsed in terms of low-level structure detection, suggesting that infants in this study picked up on statistical regularities of predictable motion patterns and temporal dynamics. Such a mechanism of action parsing does not rely on conceptual appreciations of intentionality and causal relations.

The notion of structure detection in hierarchically organized action is, therefore, critically implicated in early action comprehension. However, structural information alone cannot explain complex causal inferences and judgments about an actor's intentions. Discerning intentions in everyday behaviour is by no means straightforward and frequently requires observers to detect coherence among discrete actions, while simultaneously disambiguating multiple goals in relation to specific contexts. Highly context dependent action knowledge is acquired with experience and is likely to interact with more general types of event processing (e.g., Baldwin, Baird, Saylor & Clark, 2001, Zack, 2004).

In summary, perceptual sensitivity to physical and temporal regularities that coincides with intentional boundaries plays a pivotal role when context-specific information and knowledge about others' motivations is not yet discernable. In this connection a constructivist account of intentional action has been put forward (Baldwin et al., 2001), suggesting that infants initially interpret goal-directed behaviour in terms of low-level structure detection, which over time facilitates a gradual development towards more fine grained and meaningful analysis of the observed behaviour. This progression is thought to ultimately result in higher-level action representations that support causal understanding as well as interpretations of intentionality. In this sense, early structure detection skills might bootstrap higher-level representations of intentional goal-directed behaviour. However, there is currently little evidence regarding the precise mechanisms that mediate the encoding and retrieval of action knowledge in young children. The neural and cognitive architecture of action representation will be discussed in the following section.

1.1.3. Action concepts and the neural substrates of action processing

Over the last couple of decades research has presented in-depth and direct descriptions of the various neural networks underling the representation of knowledge. Neuropsychological evidence has fostered the development of comprehensive theoretical accounts of the mechanisms implicated in the retrieval of conceptual knowledge for categories of entities such as people, animals and objects (e.g., Cappa, Perani, Schnur, Tettamanti & Fanzio, 1998; Damasio, Damasio, Tranel & Brandt, 1990; Gainotti & Silveri, 1996; Martin, Wiggs, Ungerleider & Haxby, 1996; Tranel, Damasio & Damasio, 1997; Humphreys & Ford, 2001). In particular, clinical findings from studies using neuroimaging, brain stimulation techniques, and neural modelling in adults now greatly shape our understanding concerning the cognitive architecture of knowledge representation (see Damasio & Damasio 1994 for a detailed discussion). Comparatively less research has explored how conceptual knowledge for action is cognitively represented and mediated by neural networks. Indeed, with the exception of neuropsychological studies investigating planning deficits in patients affected by apraxia and action disorganisation, a review of the literature reveals that there is little research on the cognitive and neural foundations subserving everyday action planning in healthy subjects (let alone developmental evidence).

A good starting point into this literature is to think about how actions are represented at a cognitive level. Action features of any particular action must be represented by cognitive codes: in other words *action concepts*. Tranel, Kemmerer, Adolphs, Damasio & Damasio (2003) propose that action concepts (or conceptual knowledge for action) constitute embodied knowledge about the movements and behaviours of both animate and inanimate entities. According to this definition, and in line with psychophysiological studies of brain activity during action and perception (e.g., Di Pellegrino, Fadiga, Fogassi, Gallese & Rizzollatti, 1992; Fadiga, Fogassi, Gallese & Rizzolatti, 2000), action concepts not only contribute to the planning of our own actions but also guide our interpretation of other's action and motor events in general.

The close link between perception and action, proposed by James (1890) and subsequently developed within ideomotor frameworks, has long been capitalised on within the experimental action research. Based on the assumption that perception and action operate on a common representational domain, the existence of a strong functional link has been described for decades (e.g., Bortoletto, Mattingley, & Cunnington, 2011; Gibson, 1966, 1979; Greenwald 1970, 1972; James, 1890; Lotze, 1952) and is now supported by neuropsychological evidence (e.g., Humphreys, Riddoch, Forti & Ackroyd, 2004). However, to date relatively little research has been initiated with the intention of investigating the internal representational structure underling this relationship.

It has been hypothesized that in order to accurately explain action planning, action concepts must have a causal, spatial, and temporal organization, as well as one dimension involving intentions and another related to body parts (see Tranel, Kemmerer, Adolphs, Damasio & Damasio, 2003). This supposition certainly resembles the early philosophical analysis of action representation by Searle (1983), who argued that the cognitive representation of action ought to be anticipatory in the sense that the effects of “own” and “other” actions need to be proactively advanced, and thus not only temporarily precede action execution but can even be completely detached in time and space (e.g., imagined actions).

In what follows, various neural systems implicated in the retrieval of action concepts will be summarised. It is important to note that this section only provides an overview of the numerous neuropsychological studies with adults, and is thus by no means exhausted.

Above all, structures associated with everyday action planning have been identified in higher-order association cortices, especially within the left premotor/prefrontal, left parietal, and left posterior middle temporal cortex (e.g., Chatterjee, 2001; Grézes & Decety, 2001; Giovannetti, Schwartz & Buxbaum 2007; Jeannerod, 1997; Schwartz, Montgomery, Buxbaum, Lee, Carew, Coslett, Ferraro, Fitzpatrick-DeSalme, Hart & Mayer, 1998; Kemmerer, Rudrauf, Manzel & Tranel, 2012). Left premotor and prefrontal cortices (Figure 1.3.), both extensively associated with cognitive control, also seem to play a fundamental role for the visuomotor processing of action. It is within the premotor region that Rizzolatti and Fadiga discovered mirror neurons in the macaque brain, now well-known for their characteristic activation during both movement production and observation of action. Moreover, canonical visuomotor neurons have been observed to fire reliably in response to the mere presentation of prehensile objects, and thus appear to play a pivotal role in the planning of actions that involve the use of tools (e.g., Bracci, Cavina-Pratesi, Ietswaart, Caramazza, & Peelen, 2012).

Processing of tool objects within this cortical region has been reported in monkeys (see Fadiga, Fogassi, Gallese & Rizzolatti, 2000) as well as humans (see Chao & Martin, 2000). Closely related to this observation is evidence from neuroimaging studies that clearly highlights the role of premotor/prefrontal cortices in executing, observing, and imagining actions involving prehensile movement (e.g., Binkofski, Buccino, Posse, Seitz, Rizzolatti & Freund, 1999; Kilner, Neal, Weiskopf, Friston & Frith, 2009). Following this lead, Johnson-Frey, Maloof, Newman-Norlund and Farrar (2003) discovered that activity within the inferior section of the prefrontal cortex is not distinctly evoked by the kinematic motion of the hands per se, but rather in response to hand-object interactions, and thus in response to the realised goal of the observed prehensile action.

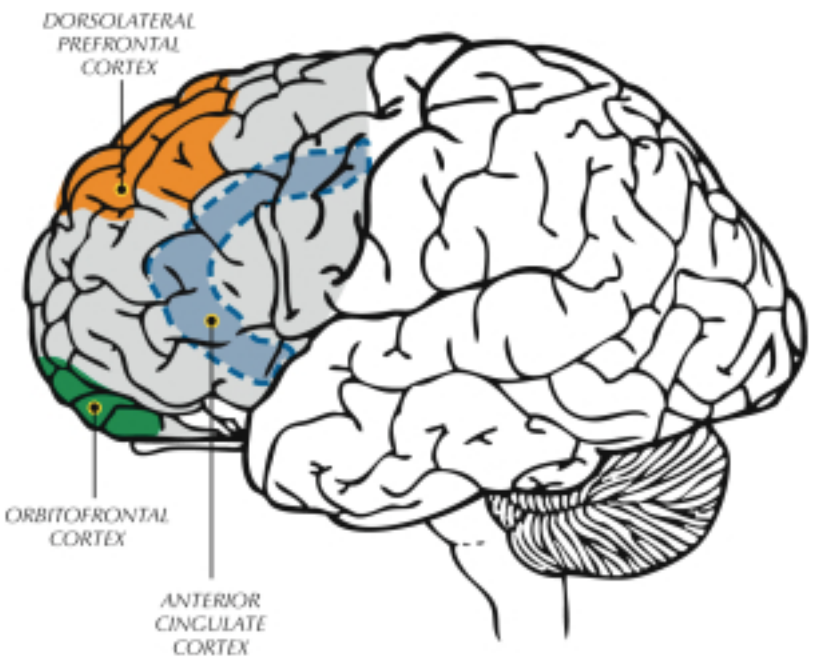

Figure 1.3. Frontal brain regions implicated in action planning and flexible adaptation of behaviour. Cognitive control in goal-directed actions is mediated by activity in frontal brain regions, such as the anterior cingulate cortex (ACC) and dorsolateral prefrontal cortex (DLPFC). Behavioural adaptations are thought to be achieved by means of reinforcement learning principles. Reinforcement learning is governed by mid-brain dopaminergic networks, which in turn interact with frontal structures (e.g., Holroyd & Coles, 2002). Figure from: www.developingchild.harvard.edu, 2011.

More posterior, somatosensory information is believed to be translated into an adequate format for action planning. Specifically the parietal cortex appears to be implicated in the production of standard hand actions such as reaching and grasping (e.g., Jeannerod, Arbib, Rizzolatti & Sakata, 1995). Moreover, networks within the parietal cortex are significantly activated during both observing purposeful hand movements (e.g., Bonda, Petrides, Ostry & Evans, 1996) and imagining hand actions (e.g., Gerardin, Sirigu, Lehéricy, Poline, Gaymard, Marsaul, Agid & Le Bihan, 2000).

Finally, the characteristic motion patterns of agents' and object's movements evoke regions within the posterior middle temporal cortex (e.g., see Dumoulin, Bittar, Kabani, Baker, Le Goualher, Pike, & Evans, 2000 for a detailed review). Several studies support the possibility that the left posterolateral temporal region, in particular, is implicated in representing more schematic aspects of actions, such as information about entities and dynamic relations between agents (e.g., Bedny, Caramazza, Grossman, Pascual-Leone & Saxe, 2008a; Grossman, Koenig, DeVita, Glosser, Alsop, Detre & Gee, 2002). Indeed, research indicates that temporal regions specifically contribute to the processing of action concepts that are organized more abstractly and in terms of conceptual properties, rather than sensory-motor experience related to visual and motion attributes (e.g., Bedny et al. 2008).

In view of the evidence reviewed, an interesting question that arises is whether the neural networks supporting action concepts overlap with those associated with the retrieval of conceptual knowledge in general. Tranel et al. (2003) turned to this question in a neuropsychological study that aimed to compare conceptual knowledge for people, tools and actions across patients with circumscribed left or right hemisphere damage. Tranel et al.'s study is particularly noteworthy here because the authors aimed to separate out action concept retrieval from lexical processing (i.e., retrieval of verb knowledge) by using pictorial stimuli. Neuropsychological profiles were related to lesion sites on a set of tasks designed to measure retrieval of action concepts and conceptual knowledge for people and tools. The results of this study were brought into connection with previous findings of impaired retrieval of conceptual knowledge for discrete entities following right hemisphere damage (anterior, inferior, temporal and occipital lesions, see Tranel, Damasio & Damasio, 1997). Intriguingly, conceptual knowledge for people and actions appeared to rely on distinct neural systems, whereas brain regions presumably involved in the retrieval of conceptual knowledge for tools showed a partial overlap with those related to action concepts. The authors argued that this finding is not entirely surprising given that knowledge about tools tends to be defined by characteristic motion patterns (e.g., a hammer hammers, a screwdriver screws, etc.). Additional support for a distributed left lateralised network implicated in action planning comes from functional neuroimaging studies with healthy subjects (e.g., Bracci, Cavina-Pratesi, Ietswaart, Caramazza & Peelen, 2012; Johnson-Frey, Newman-Norlund & Grafton, 2005).

Finally, it is noteworthy that there are a number of methodological impediments to this line of research. For instance, investigating habitual and everyday action planning in the laboratory environment poses considerable challenges. Many of the mistakes and action slips that can potentially inform us about everyday action planning require a high level of resemblance to real-world conditions for them to occur (see Schwartz 2007 for a similar point).

In summary, significant progress has been made in relating planning impairments to lesions in specific areas of the brain. However, clinical samples tend to be diverse and the relation between brain damage and behavioural impairments is by no means straightforward. Nonetheless, neuropsychological efforts continue to provide insight into the neural underpinnings of action planning by incorporating multiple formal measures of concept retrieval, lesion-deficit statistical mapping, and power analysis of lesion overlap. Indeed, careful considerations of findings from lesion studies (e.g., Norman & Shallice, 1986), together with computational accounts (e.g., Cooper &

Shallice, 2000), indicate that typical planning deficits demonstrated by patients could well be understood as an exaggeration of typical planning errors that occur under reduced cognitive resources due to fatigue, distraction, and divided attention (e.g., Gold & Park, 2009; Giovannetti, Schwartz & Buxbaum 2007; Schwartz, 2007; Schwartz, Montgomery, Buxbaum, Lee, Carew, Coslett, Ferraro, Fitzpatrick-DeSalme, Hart & Mayer, 1998).

From a developmental perspective, mechanistic accounts of action processing are first and foremost grounded in behavioural evidence. However, the maturation of action related brain networks has been addressed in several longitudinal studies. For instance, using mechanical tensor maps in 3- to 15-year-olds, Thompson et al. (2000) identified several waves of peak growths affecting most noticeably the corpus callosum in a rostral-causal direction. Repeated scanning of children from the age of 3 to 6 years revealed that the fastest growth rates during the preschool period occurred in frontal callosal networks that regulate the planning and organization of new actions. The finding of rapid structural changes in this area is in line with PET studies reporting considerable increases in glucose metabolism in the frontal cortex from 2 to 4 years of age (e.g., Chungani, Phelps, & Mazziotta, 1987). Relatedly, Gogtay et al. (2004) used MRI scanning techniques to visualize the development of grey matter density across the cortex. The results of this study suggest that lower-order somatosensory and visual cortices mature prior to higher-order associative cortices. Consecutive scanning between the ages of 4 – 21 years indicated that maturational changes in frontal lobes begin in the primary motor cortex and progress anteriorly over superior and inferior frontal areas, as well as laterally over parietal regions. As such, regions associated with motor and sensory basic functions are first to develop, while brain regions that are linked to executive functions, attention, and motor coordination undergo a protracted development until adolescence. Interestingly the development of left hemisphere regions (prefrontal and inferior parietal areas) was observed to mature earlier than equivalent right hemisphere cortices, presumably reflecting the fact that most children in Gogtay et al.'s study were right-handed. The authors of this study proposed that the cellular substrates for these cortical changes originate from a combination of dendritic pruning, myelination, as well as substantial changes in the packing density in different cortical regions.

In the next section we turn to several lines of developmental research that have provided in-depth descriptions of early action planning and associated regulatory abilities. Specifically, evidence of young infants' perception of goal-directed behaviour will be related to higher-level inferences about complex action-outcome relationships. In addition, it will be argued that findings within the problem-solving research relate to young children's abilities and limitations in action planning. Finally, this chapter concludes with some considerations on the preschool period as a time in development during which critical executive skills undergo substantial advances.

1.1.4. Action planning and the regulation of sequential behaviour

Action and decision making research in human adults has demonstrated that action planning occurs under strict capacity limitations and thus fully rational planning, in terms of exact estimations of action outcomes, is highly infeasible (see Botvinick & Toussaint, 2012). Nonetheless, simple strategies are acquired to achieve reliable action planning in most everyday activities. Perhaps the most significant advances in the ability to plan, monitor, and correct actions can be observed in young children's behaviour.

The current consensus among developmental researchers is that at the age of two years, toddlers' self-generated actions are goal-driven and that the perceived actions of others are interpreted in terms of goals. Consequently, toddlers are to some extent able to match a representation of a goal with an outcome. Nevertheless, relatively little is known about action planning after this point in ontogenetic development. In other words, once an action can be planned with respect to a goal what are the developmental changes that drive young children's increasing ability to organize their actions in ever more complex, hierarchically-organised, action sequences? This gap in the literature is somewhat surprising given that children demonstrate remarkable improvements and flexibility in their goal-directed behaviours during the preschool years.

A main line of research investigating how perception, motor skills and cognition come together in intentional behaviour during childhood revolves around the development of problem solving abilities. As mentioned above, by the second year of life action planning is clearly evident in toddlers' intentional actions, as demonstrated in a variety of problem-solving tasks (see among others Chen & Siegler, 2000; Chen et al. 2010; Claxton, et al. 2009; Karmiloff-Smith & Inhelder, 1978; Keen, 2011, Koslowski & Bruner, 1972; Manoel & Moreira, 2005; McCarty, Clifton & Collard, 1999, 2001). However, although toddlers might have all the relevant cognitive components to solve a problem, they might fail to organize them into a successful action sequence (e.g., Koslowski & Bruner, 1972; Bates, 1980).

In a typical problem-solving task, children plan sequential actions and anticipate action effects, while at the same time working to maintain a clear goal structure in mind. The development of these abilities is clearly interdependent. For example, Chen et al. (2010) tested 18- to 21-month-olds on their ability to build a wooden block tower, and found that when he retested the same children at the age of 3 years, children who tackled this task better at a younger age now showed significantly greater skills in their fine motor control. Although, in this particular study, the main focus was kinematic precision and movement timing, building a block tower does require children to engage in action planning that involves an organization of various consecutive steps. In addition, all children in this study mastered the task and were able to complete relatively high towers, indicating that the children monitored the effectiveness of their actions and made appropriate corrections when necessary. However, developmental evidence suggests that before three to four years of age, toddlers' action correcting strategies are rather limited (e.g., Jones, Rothbart & Posner, 2003; Zelazo & Müller, 2002).

Further evidence relevant to problem-solving, comes from studies investigating young children's abilities to plan ahead in search of an optimal solution. Kaller et al. (2008) tested 4- and 5-years-olds in a classic 'Tower of London' task and discovered that although all children were able to generate correct action plans internally, only 5-years-olds demonstrated optimal anticipatory planning abilities. A classic 'Tower of London' task arguably measures higher-level problem solving abilities. However, solutions may well be discovered by means of a step-by-step forward processing approach, rather than on the basis of anticipatory sub-goal planning. The results of this study, therefore, point towards age-related effects in terms of search depths for the most appropriate solution, as well as backward validation of performed sub-actions within a sequence. Backward validation is a concept that is closely related to performance monitoring. In the context of sequential actions, backward validation allows the detection of errors and thus adaptations (and indeed re-planning) of action even before outcomes occur.

In close analogy to the problem-solving literature are works investigating the development of self-regulatory behaviours in preschool children (e.g., Carlson & Moses, 2001; Jones, Rothbart & Posner, 2003; Luria, 1973). The central role of executive functions for the planning, regulation, and control of action sequences, has been established in numerous studies with neuropsychological patients and typically developing children (e.g., Bush, Luu & Posener, 2000; Casey, Trainor, Giedd, Vauss, Vaituzis, Hamburger, Kozuch & Rapoport, 1997; MacDonald, Cohen, Strenger & Carter, 2000). Specifically, it is possible that executive functions are strongly involved in maintaining mentally specified goals during the execution of action plans, while inhibiting goal-unrelated actions that might be triggered by contextual features. This argument is supported by behavioural studies focusing on inhibition of inferring response tendencies in young children (see among others Carlson & Moses, 2001; Diamond & Taylor, 1996; Luria, 1959; Posner & Lang, 1999; Simpson & Riggs, 2007).

During the preschool period, the ability to inhibit prepotent actions and engage action-related executive control undergoes dramatic developmental changes (Figure 1.4.). For instance, in a cross-sectional study by Jones et al. (2003), 3- and 4- years-old preschoolers were asked to follow the instructions given by one toy animal (typically self-directed actions such as touching their noses), while ignoring the commands of another. Results show a remarkable increase from 22% ability to inhibit incorrect responses in the 3-year-olds to 90% in the 4-years-olds. In addition, 4- but not 3-years-olds in this study demonstrated increased awareness of performance errors, as indicated by a reliable slowing in reaction times following incorrect actions. The authors interpret this finding as strong evidence for a change in the ability to respond to conflicting information, and put forward the idea that both the ability to make use of inhibitory control and executive attention in action ought to expand greatly during preschool years[1]. However, similar studies measuring children's abilities to carry out actions under conflicting conditions report on going development that reaches at least into the seventh year of life (e.g., Rueda, Fan, McCandliss, Halparin, Gruber & Posner, 2004). Davidson et al. (2006) compared 4- to 13-years-olds' performance in an executive control subtask (within a battery of higher-level tasks) that was in many ways analogous to the task employed by Jones et al. (2003). What Davidson and colleagues found was that inhibitory control of responses was exercised at a significantly greater cost for 4-year-olds than 6-years-olds.

Together these results indicate that self-regulatory processes, involved in the ability to maintain, modify, and delay distal goals undergo important changes during the fourth year of life and most likely are subject to a long developmental progression that continues well into late childhood.

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[1] It should be noted that there is an ongoing debate about whether error detection in this context develops prior to inhibitory control (as suggested by Posner & Rothbart 1998), or if in fact the ability to detect action errors depends on similar mechanisms as inhibitory control of action, which thus far has not been explicitly investigated.

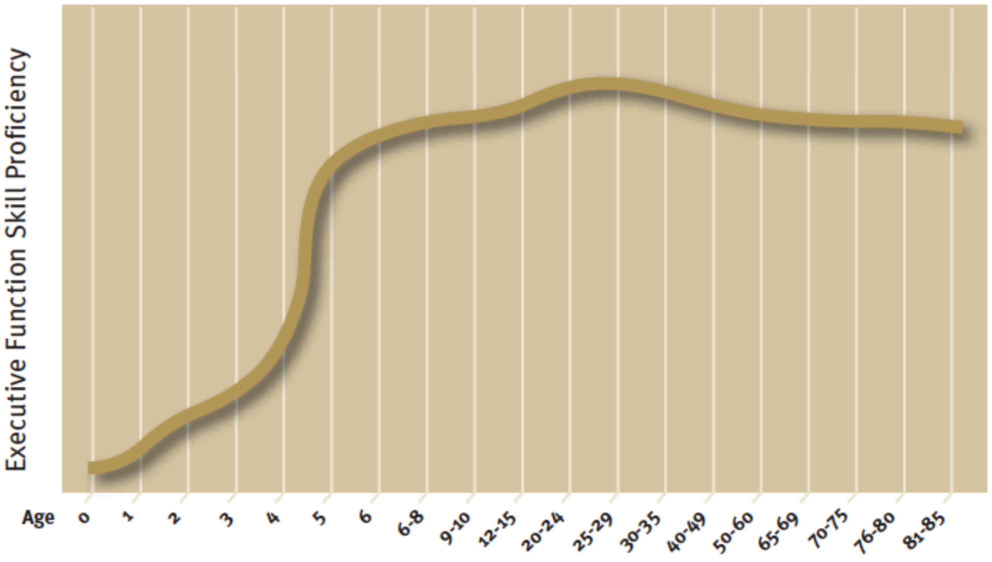

Figure 1.4. The development of executive functions. Data from 476 participants ranging in age from 3 to 85 years on the NIH Toolbox for the Assessment of Neurological and Behavioural Function (NIH-TB). Results suggest rapid development of executive function skills between the ages of 3 and 5 years. Figure from: Weintraub et al. (2013).

Finally, it has been suggested that advances in executive functions go hand in hand with developing an understanding of mental states, and that this would hold true for one's own thoughts and beliefs as well as for those of others. Similar to previously outlined findings from executive control studies, the developmental link between self-regulatory behaviour and theory-of-mind has been observed to become especially evident around the fourth year of life, when children perform correctly on tasks that require them to exert a considerable amount of self-control (e.g., day and night Stroop task, Gerstadt, Hong, & Diamond, 1994; Window tasks, Russell, Mauthner, Sharpe, & Tidswell, 1991; DCCS card sorting test, Zelazo, 2006). It is generally agreed that around the same time in development children master most variations of 'false-belief' tasks (e.g., other's false beliefs, memory of own false belief, second-order false belief; for a review see Montgomery & Koeltzow, 2010). The argument that self-processes and a theory-of-mind understanding develop in tight connection seems sensible given that children before the fourth year of life have a good understanding of how people will act in terms of goals, but fail to understand that sometimes people have wrong beliefs about how to act or might carry out unsuccessful actions in pursuit of goals. Conceivably, on going experience in a wide range of action contexts and an improved understanding of self-processes involved in goal-directed behaviour might ultimately facilitate the transfer of knowledge from one situation to another.

1.2. Methods to study early planning and regulation of goal-directed behaviour

The cognitive abilities and mechanisms underlying the perception and execution of higher-level actions have been studied in many productive ways. Over the last decades various research methods have been combined to provide explanations of the transactional processes underlying goal-directed behaviour.

Attempts to relate findings across cognitive domains have produced convergent evidence using multiple methodologies such as behavioural assessments, eye-tracking, motion capturing, TMS, heart-rate monitoring, and functional imaging techniques. When studying young children and infant development, fundamental methodological and ethical issues cannot be overlooked. For instance, because MRI-based neural imaging methods are typically not feasible for use with very young children, research exploring the neurocognitive profile of preschool children in relation to action planning is almost completely lacking. Moreover, studying action development the preschoolers is especially problematic because action-related processes are greatly affected by striking inter-individual variability and reduced within-individual reliability (e.g., Kushnerenko, Ceponiene, Balan, Fellman, & Naatanen, 2002; Morr, Shafer, Kreuzer, & Kurtzberg, 2002; Thierry, 2005). Nevertheless, some methods have been adapted to the study of child development reasonably well and provide valid means with which to investigate the dynamic internal processes that underlie goal-directed behaviour.

In the chapters that follow, we discuss different methods specifically chosen for their suitability for answering the questions we are interested in. The next section will discuss the pros and cons of behavioural methods, EEG, and motion-capture techniques with respect to the study of goal-directed behaviour in preschoolers. More in-depth descriptions of these methods and their application for the purpose of this project can be found in the specific method sections of each study.

1.2.1. Behavioural studies

Behavioural paradigms provide an important methodology to study action development. Some of the earliest systematic descriptions of young children's behavioural performance on problem-solving tasks continue to shape current accounts of action development (e.g., Inhelder, Sinclair, & Bovet, 1974; Piaget 1926; Stern, 1926).

Despite the long tradition of using behavioural tasks in developmental psychology, comparing performance across studies with even subtle methodological differences is never straightforward. As discussed in the previous sections, the use of standardised tests and well-controlled laboratory-based experiments has contributed fundamentally to what we now know about action perception and problem solving during the preschool period. However, there appears to be an increasing awareness within the action research community that the field needs to move towards more ecologically valid tasks that can provide insights into how young children plan and control actions in everyday environments. While there is no one way of measuring the relationship between performance on any task and everyday ability, there is a strong argument for including both higher and lower demand variables to investigate cognitive processes that are engaged in realistic environments (e.g., Chaytor, Schmitter-Edgecombe, & Burr, 2006). In Study 1 (Chapter 2) we ask how planning interacts with external opportunities during the execution of a realistic action sequence. Study 2 (Chapter 3) presents evidence from an ecologically valid behavioural task in which the completion of a set of subordinate rules results in goal attainment at higher levels.

As mentioned above, behavioural experiments provide a fitting methodology to investigate action cognition in the context of the current project and in the study of action development overall. Not withstanding a trend in cognitive science towards multi-method approaches, behavioural measures continue to enrich studies that primarily employ other methods such as EEG and motion capturing. For example, in Study 4 (Chapter 5) behavioural data complements EEG data to answer the question of whether preschoolers' explicit judgement of action-goal relationships relates to mid-latency electrophysiological activity. Given that identical behaviour can result from different mechanisms, behavioural measures alone struggle to provide direct evidence for hypothesised mechanisms underling behavioural performance. Arguably, there are no theoretical reasons to limit detailed investigations of action cognition to a single research method. However, combining methods is not without its challenges and may even have considerable pitfalls, such as involving researchers from diverse scientific backgrounds that may differ greatly in their experimental approach (see Yoshikawa, Kalil, Weisner, & Way, 2008 for a discussion of this).

While behavioural methods generally inform us about overt performances (e.g., performance accuracy), numerous behavioural tasks also provide suitable indirect measures that tap the underlying cognitive processes (e.g., in terms of reaction times, or types of errors). Behavioural measures can be adapted to provide engaging and child-friendly tasks, which in turn allows researchers to run substantially more and longer test trials than possible with most other methods. However, there are also a number of pitfalls associated with the use of behavioural methods with preschoolers.

Testing preschool children can be challenging for many reasons. First of all, the degree to which behavioural responses can be obtained critically depends on children’s abilities to comprehend and retain verbal task instructions. As mentioned above, during the preschool period, children demonstrate large inter-individual differences in terms of virtually all cognitive abilities. Therefore, tasks need to be appropriate for a wide range of language, working memory, attention, and motoric capacities. Task instructions should be easily comprehensible, while the tasks themselves need to strike a balance between being engaging and quantifiable. Secondly, preschoolers’ difficulties to regulate emotional responses constitutes one of the main reasons for high dropout rates in this age group. Therefore, preschoolers' temperament, motivation, and willingness to comply behaviourally, need to be taken into account, especially when testing without the presence of caregivers.

1.2.2. Electrophysiological measures (EEG/ ERP)

Electroencephalography (EEG) and more specifically event-related potentials (ERPs) provide a safe and suitable measure of stimulus-related brain activity in adults and young children (Figure 1.6.). ERPs are averaged variations in scalp potentials (i.e., summed voltage generated by groups of transitorily polarized neurons) that are time-locked to the onset of distinct external stimuli or behavioural responses.

ERP methods provide a powerful measure of electrophysiological patterns of brain activity with a millisecond temporal resolution. Because the voltage of cells other than those aligned at a 90 degree angle to the cortex is mostly cancelled out, what EEG methods pick up is for the most part activity that originates from large groups of co-linear pyramidal cells that fire in synchrony (see Lucks, 2005). The electrical activity within a given region of the brain gives rise to positive and negative waveforms of distinct ERP components. Distinct ERP components are interpreted as reflecting the neural processes generated by the underling brain regions[2]. The distinct

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[2] ERP components at every electrode site reflect a mixed signal of both the electrical activity of scalp regions underling recording sites as well as activity propagated from other regions of the brain. Conceptually, components are considered as neural signals that originate from specific neuroanatomical modules and that is functionally related to certain conditions or operations. Some components, such as the N400, in fact consist of multicomponent conglomerations and further advances in source localizations techniques are needed in order to isolate individual sub-components that give rise to the N400 (see Lucks 2005).

topographical distributions of two ERP components is therefore taken as evidence that distinct neural processes are implicated, while differences in voltage amplitude and time-course are frequently considered as modulated by the same underlying neural source (see Lucks 2014 for a comprehensive discussion of ERP methods). For instance, in Study 4 (Chapter 5) we discuss distinct mid-latency ERP components that have been implicated in the processing of dynamic human actions.

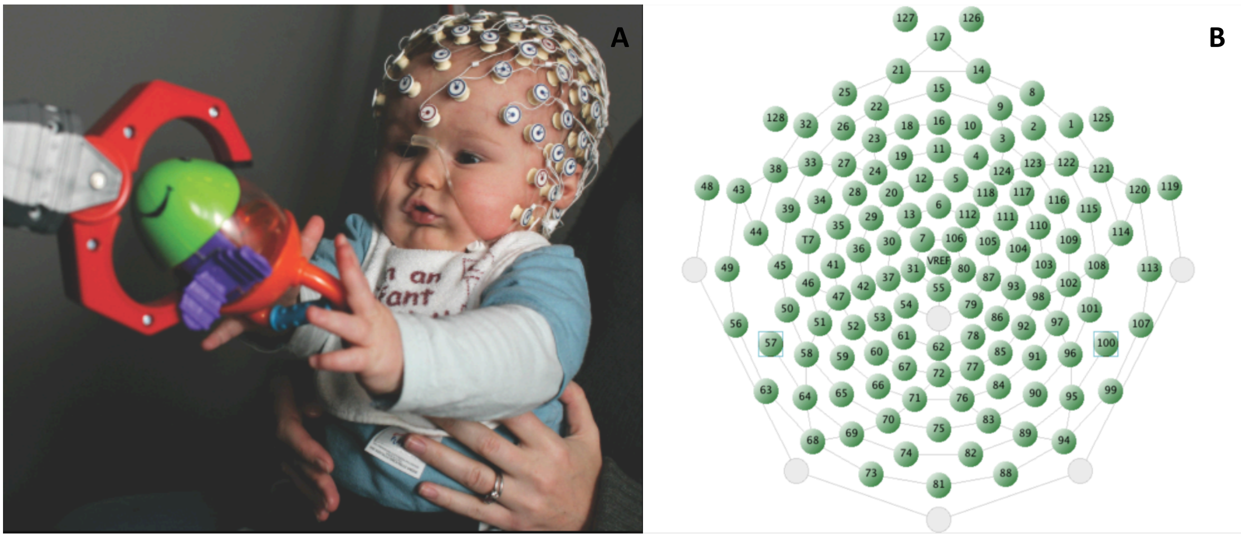

Figure 1.6. Geodesic Sensornets (EGI Inc., Eugene, Oregon). EEG data acquisition during a reaching task (A). Typical layout of a high-density sensor array comprised of 128 recording channels (B). Source: http://www.cbcd.bbk.ac.uk/babylab.

EEG/ERP techniques make it possible to measure real-time brain activity, thus providing an excellent method for studying the time-course of action processing with a millisecond temporal resolution. Another major advantage for the study of child cognition is the fact that ERPs offer insights into the "hidden" brain responses that underlie complex cognitive processes without the need for overt manifestations of behaviour. ERPs essentially reflect brain activity generated when specific mental operations are performed, and thus provide a non-invasive measure with which to investigate the mechanisms involved in both perceptual and conceptual aspects of action processing.

While generally delayed in infants, the overall time-course of ERP components appears to be otherwise comparable in infants and adults. In fact, several studies have evaluated the extent to which infant and adult ERPs reflect equivalent components (e.g., de Haan, Pascalis, & Johnson, 2002; Pascalis, de Haan, & Nelson, 2002). Therefore, EEG/ERP methods can critically inform us about the development of neural activity underlying action perception and planning abilities. However, interpreting brain activity across development and in relation to behavioural findings is by no means straightforward. In addition, there are a number of challenges involved in recording ERPs during the preschool period (see below). As a results evidence relating 3- and 5-year-olds ERPs to infant and adult data is almost completely lacking.

As others have pointed out (e.g., Thierry, 2005) electrophysiological measures of child cognition are noisy and technically difficult to obtain. This appears to be especially the case during the preschool period. In fact, for ERP paradigms the preschool years are the kind of in-between period that makes data acquisition notoriously problematic. A typical developing preschooler's motor behaviour is not constrained by the physical limitations that positively impact on the ERP signal-to-noise ratio during infancy, while the abilities to inhibit prepotent responses and regulate emotions are yet to develop.

The vast majority of developmental ERP evidence concerns perceptual processing and automatic attentional responses, probably because these are the type of operations that are expected from very young children. Moreover, difficulties in capturing children's visual attention over the minimum number of trials required for ERP analyses have led to a preference for auditory stimuli over the use of visual stimulation. In fact, auditory stimuli may even be presented during sleep, which dramatically reduces motor artefacts.

It should also be noted that time-locking of ERPs to the onset of visual events works generally best when stimuli are static and appear suddenly. In realistic behaviour, however, goals neither appear nor disappear suddenly, nor are actions static in nature. Clearly, in order to inform us about natural sequential behaviour, ERP methods need to be adapted to allow the presentation of dynamic events. Chapter 5 will return to this point in the context of a study in which we used video material of naturalistic actions to investigate preschoolers' perception of higher-level goals.

Finally, probably the most infamous shortcoming of EEG methods is the *inverse problem* [3] and the current lack of widely accepted techniques to reliably localise the source of neural generators. The generators of ERP components are not directly measurable and the number of likely dipoles that give rise to individual components can only be approximated using constraining techniques.

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[3] The *inverse problem* refers to the circumstance that electricity does not travel in a straight line and ERPs generated in any part of the brain can be detected at very distant sites (depending on how many cells are activated, the distribution of neural tissues, the cortical structure, etc.). Moreover, when electrical currents hit the skull, ERPs are smeared laterally. Thus, any one distribution of voltage measured at the scalp could be generated by an infinite number of dipoles (see Lucks, 2005).

1.2.3. Motion capture

Motion capture is the process of sampling and recording a live motion sequences with the aim of translating it into motion data that allows for a 3D reconstruction of the performance. In other words, transforming a live performance into a digital version of the action. Figure 1.5. shows a typical setup for indoor motion capture.

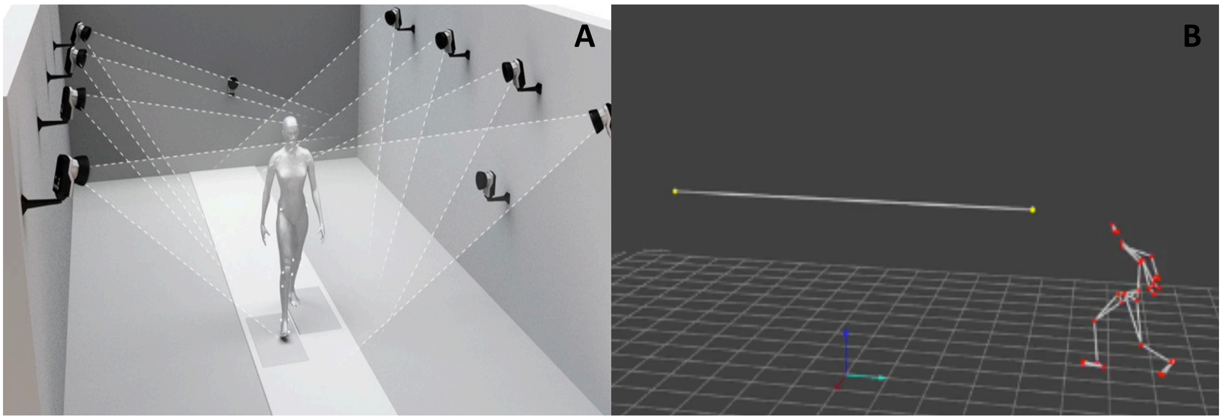

Figure 1.5. Example of optical system setup and data reconstruction. Optical marker-based motion capture systems use spherical passive retro-reflective markers (approximately 4 mm diameter), which are then traced by multiple cameras at about 100Hz sampling rate. A marker can be placed anywhere on the participant's body (A). Marker positions are reconstructed three-dimensionally and kinematic information is extracted for motion analyses (B). Source: http://www.qualisys.com.

Investigating kinematic parameters such as motion trajectories, acceleration, and deceleration is one step forward in answering the question of why movement has the form it does. Clearly, the discrete motion segments of complex actions are not solely shaped by the passive dynamics of our bodies. Especially in the execution of sequential activities, individual segments are joined and connected in a way that reflects considerable planning and control. From an embodied cognition perspective, motion kinematics are not completely specified *a priori,* but rather emerge in real time from interactions between the properties of the body with internal control structures and the environment (e.g., Wilson & Golonka, 2013). Capturing motion therefore provides an indirect measure of interacting resources distributed across the brain and body as motion unfolds in specific contexts.

In relation to goal-directed behaviour, several studies have used motion capture techniques to examine the spatiotemporal representation of reaching actions in adults (e.g., Tipper, Howard, & Houghton, 1998; Tipper, Howard, & Jackson, 1997). While participants have little or no awareness of motion patterns involved in common actions (e.g., reach-to-grasp actions), they nevertheless show systematic differences in the kinematic parameters of object manipulation as a function of object category and position (e.g., Jervis, Bennett, Thomas, Lim, & Castiello, 1999). Therefore, an important advantage of this method is that it captures planning related processes that implicitly impact on the kinematic output and even anticipated movements.

Various motion capture technologies (e.g., optical, mechanical, and magnetic systems) are suitable for investigating the physical interactions that take place during goal-directed actions. Optical systems have the important advantage that sensors can be arranged flexibly. In contrast to mechanical systems, optical motion capture requires minimal marker configuration on the body, leaving joints unconstrained, and thus the flow of motion unimpeded. This makes optical systems highly suitable for the study of natural goal-directed actions in children. The sensors used in optical systems are virtually unbreakable and, overall, well-tolerated by children and even infants. Moreover, optical systems allow the capture of large-scale movements in open environments with an overall high sampling rate.

However, some of the drawbacks of optical motion capture systems are that they are limited to positional data (angles need to be calculated) and occlusion of sensors causes marker identification issues during post-processing.

In Study 5 (Chapter 6), we present an experiment in which we employed optical motion-capture techniques to explorer how the processing of perpetual and conceptual features affects real-time kinematic motor output in adults and across childhood (6 - 12-year-olds).

1.3. Objectives

To summarise the forgoing sections, this project used a range of novel behavioural tasks, ERP methods, and motion capture techniques to investigate how preschoolers perceive goal-directed events and use this knowledge in their own execution of hierarchically structured sequential behaviour. Combining these methods allowed us to investigate the developmental trajectories of action-related processes at different levels of abstraction, ranging from the level of raw movement, to cognitive processes, as well as the neural mechanisms involved. As we shall see in the following chapters, the preschool period constitutes a time in development during which planning and control abilities undergo important advances with respect to goal pursuit. Specifically, the project aimed to:

1) Investigate the impact of action perception on 3- and 5-year-olds' planning of a familiar action sequence.

2) Evaluate preschoolers' strategic action planning in an ecologically valid task.

3) Contrast the degree to which 3- and 5-year-olds endogenously detect the need to adjust top-down control in the face of conflicting information.

4) Identify the neural mechanisms that are functionally implicated in the semantic analyses of higher-level goals across preschoolers and adults.

5) Assess how covert cognitive processes influence the kinematic parameters of adults' and children's reach-to-grasp actions.

The individual studies in this project address a wide range of action related processes, spanning from the perception and comprehension of other people's actions to the ability to plan and and organise one's own behaviour. However, from the evidence reviewed above it should be clear that action comprehension and production are fundamentally linked. As we shall see in the next chapter, observing other people engage in a sequential event critically influences preschoolers' subsequent execution of the sequence. As argued above, the overall lack of developmental evidence concerning action cognition during the preschool period stands in sharp contrast to the remarkable improvements that preschoolers reflect in carrying out complex goal-directed behaviours. The current project set out to identify the critical mechanisms and processes that drive action development during this crucial time in development. To this end, most of the studies described in the next chapters focus on preschoolers three to five years of age. Some studies, however, sought to situate preschoolers' performances and electrophysiological profiles in respect to children near the end of the childhood years and adults. All findings are discussed in relation to action representation at specific levels of abstraction, ranging from the perception of complex goal hierarchies to the planning of a reach-to-grasp action. Together, the next five chapters provide novel and wide ranging insight that advances the field of action cognition in understanding the developmental trajectories implicated in hierarchical event processing. Before moving on to a detailed description of the individual studies, the next section will briefly outline the methods used in this project.

CHAPTER 2

The Planning and Execution of Natural Sequential Actions in the Preschool Years[4]

2.1. Introduction

Preschool children's abilities to learn from observation has been the focus of considerable theoretical and empirical work. A wealth of developmental research suggests that young children reliably over-imitate modelled actions. Across two experiments, we asked whether a single misleading demonstration significantly impacts preschoolers' planning and execution of a familiar event sequence. In Experiment 1, we found that despite sufficient task knowledge, 3- and 5-year-olds readily incorporated irrelevant modelled actions into their own performances. In Experiment 2, we found that when the underlying event structure was spatially cued, over-imitation was no longer apparent in preschoolers' re-enactment of the sequence. These findings serve as evidence for a tight coupling between perceptual and conceptual processing systems in early action planning. Taken together, findings from both experiments suggest that over-imitation behaviour in these tasks results from a failure to evaluate the observed links between procedural components of the sequence in respect to the overarching goal of the task. These results further contrast with the existing developmental literature by suggesting that, in the context of familiar actions,

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[4] Freier, Cooper, & Mareschal, (2015). The planning and execution of natural sequential actions in the preschool years. *Cognition, 144,* 58-66.

over-imitation significantly decreases during the preschool period. Findings are discussed in the context of preschoolers' abilities to plan and execute sequential actions.

2.1.1. Goal-directed sequential actions

Natural actions tend to unfold over extended periods of time in hierarchically structured sequences. Within this hierarchy, higher-level goals are represented at the top level and are composed of more basic goals, which in turn are organised into sub-goals at the next level, descending in this manner to the lowest level (e.g., Barker & Wright, 1954; Grafton & de Hamilton, 2007; Lashley, 1951). Successful action planning involves at least some knowledge about how the intended outcomes can be achieved. Thus structuring hierarchical events into discrete goal-directed units plays a fundamental role in determining which components that make up an action sequence are necessary in order to accomplish our goals, and which action features should be left unspecified, thus making fast adaptation to contextual variations possible (e.g., sub-movements of a given action that determine the manner with which the action is carried out). As mentioned in Chapter 1, formal theories in psychology have argued that goal / sub-goal hierarchies are central to both parsing observed sequences and planning ones own wilful behaviours (see among others Cooper, & Shallice, 2006; Lashley, 1951; Norman, & Shallice, 1986; Rosenbaum, Cohen, & Jax, 2007; Zacks & Swallow, 2007; Zacks & Tversky, 2001). In the same vein, several lines of research have argued that imitation of goal-directed actions is fundamentally mediated by hierarchically structured event representations (e.g., Bekkering, Wohlschläger, & Gattis, 2000; Byrne & Russon, 1998). However, little is known about how representational hierarchies are acquired in a way that assures consistent goal attainment while at the same time allowing enormous flexibility in the organisation of sequential actions.

Furthermore, natural everyday actions tend to be embedded into a continuous flow of dynamic goal-directed behaviour. Pauses marking the boundaries of distinct actions are rare (see Asch, 1952; Baldwin, Baird, Saylor, & Clark 2001; Heider, 1958; Newtson & Engquist, 1976). At the same time, natural actions are frequently disrupted mid-sequence by unpredicted events or actions that relate to outcomes other than the primary goal. This discontinuity poses a particular challenge for the parsing of sequences composed of sub-actions with varying degrees of familiarity. In order to learn from the observation of a natural behaviour, actions relevant to specific goals must first be discovered within the stream of motion that makes up the event. Equally, goal-irrelevant elements embedded within an observed action sequence need to be identified as such and later disregarded when re-enacting the sequence.

Despite the remarkable abilities that even toddlers demonstrate in parsing complex sequential actions of others (e.g., Baldwin, et al. 2001), relatively little is known about the development of action processing during the toddler and preschool years. This gap in the literature is surprising given that this is when children become particularly adept at taking observed behaviour into account in order to achieve internally and externally specified goals.

Within the social domain, a wealth of evidence has spoken to the importance of imitative behaviour as a driving force for the acquisition of cultural knowledge and early appreciations of other’s intentions (see Over & Carpenter, 2012, for a recent review). For instance, 3-year-olds reliably imitate the complex structure underlying novel multistep event sequences, indicating a good ability to parse dynamic behaviour systematically and to relate it to goals (e.g., Whiten, Flynn, Brown & Lee, 2006). Indeed, preschool children appear to reproduce even complex events so consistently that they may include irrelevant elements of the observed behaviour. This sort of indiscriminate imitation, also referred to as over-imitation (Lyons, Young, & Keil, 2007) or over-copying (Whiten, Horner, & Marshall-Pescini, 2005), has been considered a kind of default mechanism by which children learn to perform new actions through observation (Whiten et al. 2005). This line of thinking is further supported by findings from social learning studies in 3- to 5-year-olds (see Horner & Whiten, 2005; McGuigan, Whiten, Flynn, & Horner, 2007), indicating that preschool children copy a model’s actions although some elements of the sequence are clearly irrelevant in order to reach the outcome. Lyons et al. (2007) further demonstrated that a strong tendency to over-imitate modelled actions persists even when preschoolers are specifically asked to perform only the necessary steps of the action sequence and leave “silly extra things” out. The authors suggest that given that causal factors are not always transparent in human actions, blanket copying of behaviour enables children to assimilate new skills even when the underlying causal relations are poorly understood. Indeed, there are good reasons why children should exhibit susceptibility to over-imitation, as copying may facilitate the complex skill acquisition and only occasionally lead to inappropriate actions, which in turn will be corrected later in development (Whiten, McGuigan, Marshall-Pescini, & Hopper, 2009).

Findings demonstrating young children’s tendency to overly copy actions they observe are particularly striking when considered in the light of studies claiming relatively sophisticated “rational imitation” in preverbal infants as young as 12-months (Zmyj, Daum, & Aschersleben, 2009; Schwier, van Maanen, Carpenter, & Tomasello, 2006), and 14-months of age (Gergely, Bekkering, & Kiraly, 2002). Similarly, infants appear to re-enact actions constrained by enabling relations more systematically than when links between actions are arbitrary (e.g., Bauer & Fivush, 1992; Brugger, Lariviere, Mumme, & Bushnell, 2007). It thus appears that a tendency to over-imitate observed behaviour emerges later in ontogenetic development.

Imitation of causally irrelevant actions has been observed to increase from the age of three to five years (McGuigan et al., 2007) and arguably becomes even more reliable with increasing age (e.g., Marsh, Ropar, & Hamilton, 2014; McGuigan, Makinson & Whiten, 2011; McGuigan, et al., 2012). There are various explanations as to why the degree of over-imitative behaviour ought to increase with ongoing development (e.g., Horner & Whiten, 2005; Kenward, 2012; Kenward, Karlsson & Persson, 2011; Lyons, Damrosch, Lin, Macris & Keil, 2011; McGuigan, Gladstone & Cook, 2012). These resemble one another only in the deep divide that they draw between cognitive and social factors.

To avoid confounds with prior event knowledge, over-imitation in adults and children has been explored using novel and relatively abstract tasks. However, as discussed above, in real life settings observers tend to have some prior knowledge regarding the task at hand or may even entertain expectations about events given the context in which they are carried out. As others have noted, when an action sequence is not well understood most sub-actions preceding the outcome are likely to be encoded as causally significant at any point in development (Kenward, et al. 2011; see also Williamson & Markman, 2006). Moreover, there is currently no evidence suggesting that either social mechanism or causal reasoning singlehandedly accounts for over-imitation behaviour in young children and adults. While recently more comprehensive perspectives have been put forth (e.g., Marsh, Ropar, & Hamilton, 2014; Over & Carpenter, 2012), an integrative account of over-imitation incorporating contributions from social factors, causal reasoning, and prior knowledge to higher-level event processing is clearly missing.

The primary aim of our first study was to examine over-imitation in the context of a familiar target sequence involving the manipulation of a set of well-known objects. To this end children viewed a pre-recorded video demonstrating a woman preparing a sandwich (the overarching goal) among various goal-irrelevant distractor actions. Thereafter, children were prompted to complete the task themselves. Prior evidence suggests that toddlers are somewhat reluctant to reorganise familiar sequences that are newly modelled in relation to the temporal order in which they are presented (e.g., Bauer & Thal, 1990; O'Connell & Gerard, 1985). It thus appears rather unlikely that when re-enacting a relatively familiar event sequence preschoolers would give up already established representations and exhibit blanket copying of a misleading demonstration. Alternatively, one might expect to observe a trade-off between the preschoolers' reluctance to override existing event knowledge and the tendency to over-imitate modelled actions.

In view of the developmental research discussed above, we predicted that 3- and 5-year-olds would weight the misleading demonstration differently. More specifically, we expected that younger children would struggle to identify irrelevant sub-actions as such and may further show overall greater susceptibility to perceptual influences of the action context (e.g., the array of objects per se). In turn, older children were expected to structure the observed event in terms of specific procedural components and their relative outcomes, and thus disregard irrelevant actions that did not fit the sequential hierarchy.

To preview our findings, we observed that in the absence of a misleading demonstration both 3-and 5-year-olds demonstrated comparable competencies to carry out the familiar target sequence. When, however, children viewed a misleading demonstration prior to task performance clear patterns of over-imitation behaviour emerged in both age groups. Moreover, we found that the tendency to re-enact irrelevant actions decreased during the preschool period. We argue that the ability to assess sequential actions in terms of goal hierarchies is a demanding task even when goal-related elements are well understood.

2.2. Experiment 1

We presented 3- and 5-year-olds with either a misleading demonstration of the target action (a woman preparing a sandwich) or an unrelated event (a woman wrapping a gift). Experiment 1 thus involved four groups of participants in a 2x2 multifactorial design. Prior investigation confirmed that preschool children are frequently exposed to meal preparing activities, while having negligible experience in carrying out these actions themselves. The extent of children's experience with the target action was further assessed using a questionnaire that parents completed during the test session.

The study was approved by the institutional ethics committee and conducted according to the principles of the Declaration of Helsinki.

2.2.1. Methods

Participants

Preschool children's performances were investigated across two age groups: 3 (range = 36-47 months; *M* = 40.4 months; *SD* = 2.9 months) and 5 years (range = 60-70 months; *M* = 64.7 months; *SD* = 2.8 months). All conditions included 15 children (total N = 60; female = 34). Parental consent was obtained for each participant. Parents also completed a questionnaire assessing the level of direct experience children had in performing the target sequence, as well as the degree to which the event did indeed constitute a familiar sequence for the child. All children included in the final sample had observed the target action numerous times within an everyday context and were also familiar with watching video material. None of the children included in this study had ever independently performed the entire sandwich making sequence.

Procedure

All children participating in this study were tested individually within local preschools, and all testing was video recorded for later analysis. Within each age group children were randomly assigned to either: (1) a *misleading demonstration condition* (a woman preparing a sandwich), or (2) an *unrelated demonstration condition* (a woman wrapping a gift). The aim of the later was to assess 3- and 5-year-olds' abilities to perform the target action based on prior experience alone. This control condition was included to provide an estimate of children's baseline knowledge in this task. Moreover, this condition served to assess whether 3-and 5-year-olds' performances reflected similar levels of object exploration and whether children showed preferences for certain objects.

Children in each condition watched a pre-recorded action sequence (either sandwich preparation or gift wrapping), which showed a continuous stream of everyday behaviour and included a total of 13 objects. At the beginning of each clip, the female demonstrator looks at the camera and then goes on to perform 13 discrete sub-action (6 goal-directed sub-actions and 7 distractor sub-actions). In order to minimize ostensive influences on the children's subsequent action, she does not direct her gaze into the camera during this time. All individual sub-actions are summarised in Table 2.1. Goal-directed and irrelevant actions occur interleaved and without breaks between individual elements of the sequence. Figure 2.1. shows the stimulus setup for the misleading demonstration condition.

Every participant watched a single demonstration followed by one test phase. Without further instructions, the experimenter asked each child to view either the misleading or unrelated pre-recorded event (approximately 2 minutes in duration). During this time the experimenter stepped back and monitored that all children viewed the entire demonstration. Thereafter, children were guided to a child-sized table, where they encountered all objects displayed in the misleading demonstration. Children were prompted to perform the task with a picture illustrating a generic jam sandwich and the instruction "Can you make me a jam sandwich, while I speak to your mum/dad?”[5]. The experimenter and the caretaker withdrew and directed their attention away from the child towards the parent questionnaires. Caretakers were instructed not to look at their children or comment on their performance until the children had verbally indicated that the final goal of the task had been reached.

Figure 2.1. Spatial distribution of goal-relevant (3) and distractor objects (10) in the pre-recorded action sequence. The demonstration involved 13 discrete actions in a continuous sequence. Relevant (6) and irrelevant elements (7) of the sequence were presented interleaved. In the test phase of Experiment 1, all children encountered the objects displayed as shown in the misleading demonstration.

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[5] Over-imitation paradigms frequently highlight that demonstrated actions should be precisely copied, by either ostensively signalling or directly instructing children to imitate (e.g., “Watch what I do and do it just like I did”, “Watch what happens because I’m going to let you have a go in a minute.”). In our task we aimed to keep instructions neutral in an attempt to avoid biasing towards over-imitation behaviour.

Table 2.1. Discrete Sub-actions in the Experimental Condition

	Goal-Relevant Actions	Goal-Irrelevant Actions
1.		Taking a bag of sugar out of a transparent glass jar.
2.		Taking the lid off a large red jar and filling it with the sugar (1.).
3.	Taking two slices of bread out of their packaging.	
4.	Placing the bead slices (3.) next to each other on the workspace.	
5.		Taking a small mixing bowl.
6.	Opening a jar of jam.	
7.		Scooping the jam (6.) into the mixing bowl (5.) and stirring it.
8.	Selecting a knife from a set of tools.	
9.		Taking a second bag of sugar and pouring its content into the red jar (2.).
10.	Spreading jam (6.) onto the bread (3.).	
11.		Putting the lid on the red jar (2.) and shaking it.
12.	Combing the two pieces of bread (4.).	
13.		Peeling a banana and placing it on the workspace next to the sandwich.

Scoring

Several measures were developed to assess preschoolers' abilities to plan and execute the familiar target sequence, as well as to quantify the degree of over-imitation evoked in this task. All recorded test sessions were transcribed and coded by two independent coders in terms of intrusion of irrelevant actions, sequencing errors, number of objects manipulated, and total time acted. These measures were defined as follows:

Intrusion scores: All actions carried out on objects classified as "distractor objects" were either irrelevant or superfluous to attaining the overarching goal and were thus considered intrusions of distractor actions. This measure was operationalised by dividing the time acting on distractor objects by the total performance time (from making contact with the first object to affirming that the goal had been reached). Intrusion scores therefore provide an index of the proportion of over-imitation behaviour in relation to the overall performance. Similar proportion scores have been used in previous studies to tap over-imitation behaviour (e.g., "irrelevant imitation score", McGuigan et al. 2007; McGuigan & Whiten, 2009).

Error rates: An error classification was derived from previous research on sequential behaviour in healthy participants (Ruh, Cooper & Mareschal, 2010) and from research with neuropsychological populations (Schwartz et al., 1998). Any behaviour that fell under the following categories contributed to one error score: sequencing errors; i.e. omissions and anticipations of sub-actions, perseveration; i.e. repetition of successfully implemented sub-action or failure to terminate actions, and object substitutions; e.g. using a screwdriver to spread jam instead of a knife.

Number of objects manipulated: The three objects needed to accomplish the task were coded as relevant objects. All other objects that children overtly manipulated were coded as distractor objects. This measure thus correlates with intrusion scores. However, while intrusion scores give an estimate of the proportion of time spent occupied with distractor objects, the number of objects that had been manipulated during that time provides additional information regarding the number and range of distractor actions that children produced.

Total time: Performance times were measured from the first object manipulation to indicating that the goal had been reached. Therefore, this measure provides valuable information regarding discrepancies between action planning and execution. For instance, it might be expected that 5-year-olds generally act faster in this task because they do not exhibit difficulties manipulating objects that require fine motor dexterity (such as a knife). If, in fact, differences in overall performance time are due to differences in the skilled manipulation of goal-relevant objects, it should be expected that 3- and 5- year-olds differ only in terms of the total time needed but not on the number of objects used to accomplish the goal.

In addition to these primary measures several behaviours were coded but excluded from more detailed analyses due to their rare or unsystematic occurrence. For instance, mid-sequence pausing, picking up of objects without performing any identifiable action, and correcting actions were all coded but their low frequencies (< 1%) did not permit further analyses.

2.2.2. Results

Preliminary testing indicated no violations of multivariate assumptions. Initial analyses revealed no significant main effects or interactions of gender or direct experience with the task as indicated by parents in the questionnaires. Interrater reliability analysis indicated substantial consistency among coders (Cohen's kappa = 0.76). Performance differences across conditions (misleading demonstration / control) and age groups (3 years / 5 years), in terms of the combined performance measures (Intrusion scores / Error rates / Relevant objects manipulated / Irrelevant objects manipulated / Total time), were analysed using a between-groups multivariate ANOVA. In order to investigate the relation of Age group and Condition with each dependent measure separately, the original alpha level was adjusted to .01.

Table 2.2 summarises all means and standard deviations. Initial multivariate analyses, revealed statistically significant differences between 3- and 5-year-olds on the combined dependent variable F(5, 52) = 6.14, p < .001; η_p^2= .37, as well as a significant multivariate main effect for Condition F(5,52) = 13.4, p < .001; η_p^2 = .56. In addition, we found a significant interaction between Condition and Age group F(5,52) = 4.75, p = .001; η_p^2 = .31. Univariate analysis indicated that the interaction between Age group and Condition was highly significant in terms of Intrusion scores F(1,56) = 18.6, p < .001; η_p^2 = .25, such that, in contrast to 5-year-olds, 3-year-olds were on average over three times more prone to perform distractor actions after having observed the target sequence including distractor actions (*M* = 46%, *SD* = 24% vs. *M* = 14%, *SD* = 16%), but were in fact consistently less engaged in distractions in the control condition than were 5-year-olds (*M* = 1%, *SD* = 3% vs. *M* = 4%, *SD* = 11%).

Figure 2.2. illustrates scores for each age group and condition. Further significant interaction effects of Age and Condition were observed in relation to the Total performance time F(1,56) = 8.02, p = .006; η_p^2 = .13 and Distractor objects manipulated F(1,56) = 15.6, p < .001; η_p^2 = .22, indicating that 5-year-olds acted generally faster than 3-year-olds, but this difference was far more pronounced in the misleading demonstration condition (*M* = 4.36 min., *SD* = 2.12 min. vs. *M* = 9.36 min., *SD* = 4.60 min.) than in the control condition (*M* = 2.60 min., *SD* = 1.31 min. vs. *M* = 3.34 min., *SD* = 2.25 min.). Similarly, approximately equal numbers of distractor objects were manipulated by 3- and 5-year-olds in the control condition (*M* = 0.5, *SD* = 1.9 vs. *M* = 0.3, *SD* = 0.5) but not in the misleading demonstration condition, with 5-year-olds manipulating fewer objects than 3-year-olds (*M* = 1.9, *SD* = 2.0 vs. *M* = 5.1, *SD* = 1.9).

These results suggest that although Age group as a factor explains 37% of the observed variance, Condition appears to be the more influential factor on the combined performance measure. Indeed, considering the effect of Condition for all dependent variables separately, univariate tests showed substantial main effects for Intrusion scores F(1,56) = 45.4, p < .001; η_p^2 = .45, total time F(1,56) = 26.7, p <.001; η_p^2 = .32, and number of Distractor objects manipulated F(1,56) = 66.5, p < .001; η_p^2 = .54. No significant main effects or interactions were found for Error rates or Number of relevant objects manipulated.

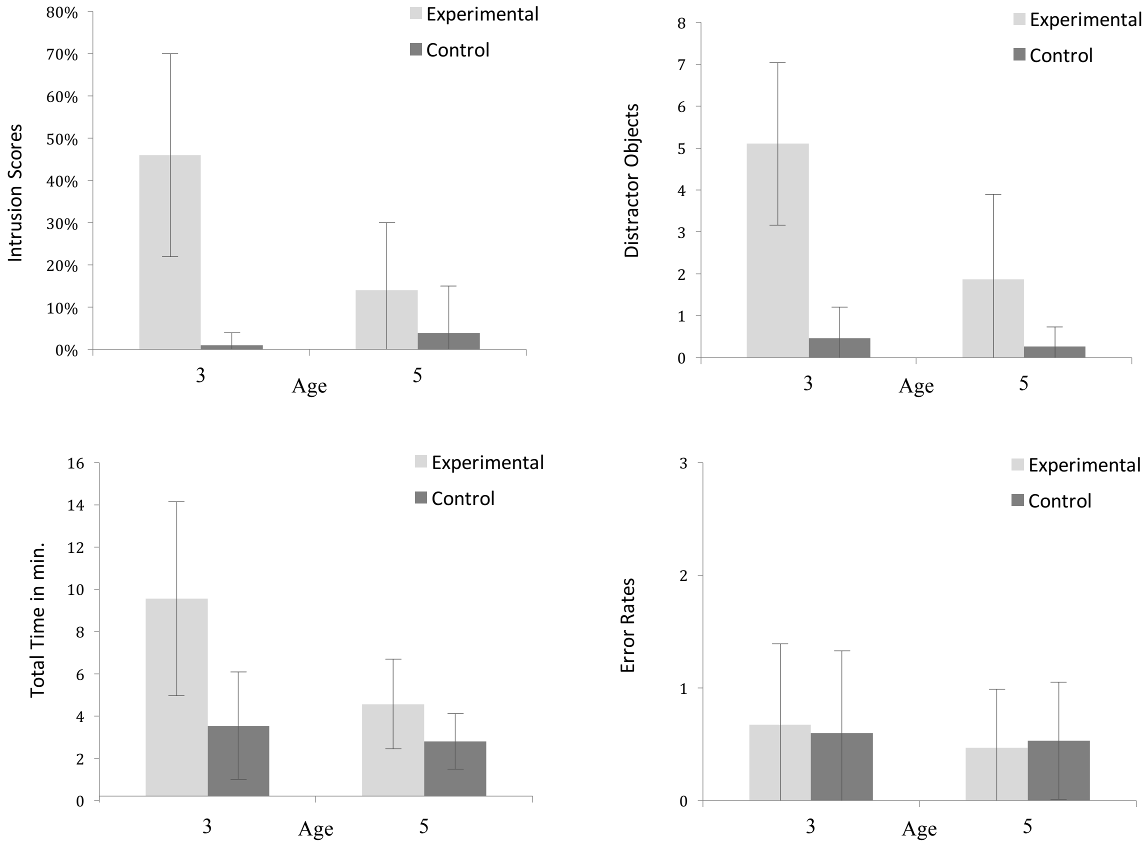

Figure 2.2. Means of intrusion scores, number of distractor objects manipulated, total time, and error rates, plotted by age group and condition.

Table 2.2. Descriptive Statistics 1

	Condition	Age	Mean	SD	N
Error Rates	experimental	3	.67	.72	15
		5	.47	.52	15
	control	3	.60	.73	15
		5	.53	.52	15
Intrusion Scores	experimental	3	.46	.24	15
		5	.14	.16	15
	control	3	.01	.03	15
		5	.04	.11	15
Time Total in minutes	experimental	3	9.36	4.59	15
		5	4.36	2.12	15
	control	3	3.34	2.55	15
		5	2.60	1.31	15
Number of relevant objects manipulated	experimental	3	2.80	.41	15
		5	3.00	.01	15
	control	3	2.88	.35	15
		5	2.90	.26	15
Number of distractor objects manipulated	experimental	3	5.07	1.94	15
		5	1.87	2.03	15
	control	3	.47	.74	15
		5	.27	.46	15

SD = standard deviation; N = number of participants. Error Rates = total number of errors. Intrusion scores = time acting on distractor objects divided by total acting time.

2.2.3. Discussion

Real-life sequential actions are frequently interrupted by actions other than those directly relevant to achieving one particular outcome. The ability to parse dynamic events into goal-relevant and irrelevant components plays a pivotal role in learning from observation. In Experiment 1, we asked whether preschoolers' planning and execution of a familiar event sequence was significantly influenced by prior viewing of a misleading demonstration.

Overall, results in Experiment 1 indicate that 3- and 5-year-olds demonstrated similar competencies to perform the target sequence based on prior event knowledge alone. Moreover, results suggest that preschoolers in both age groups did not demonstrate a general preference to manipulate objects in any particular order (e.g., the first three objects within the line-up). Our control data confirms that both age groups were well able to identify actions that were linked to the overarching goal of the task in a meaningful way, and were further able to relate sub-actions in terms of their hierarchical organisation. However, in contrast to 5-year-olds, 3-year-olds' re-enactment of the target action was significantly more influenced by a single misleading demonstration. A strong tendency to incorporate irrelevant actions was apparent in terms of all outcome measures. After having viewed a misleading demonstration 3-year-olds overall required not only more time, but also used ten times as many distractor objects to accomplish the target sequence. In fact, 3-year-olds closely matched their performance to the observed demonstration in the sense that after watching the misleading demonstration half of their actions were irrelevant to producing the overarching goal. Their actions instead bore a strong resemblance to the demonstrated sequence, in which the time dedicated to relevant and irrelevant elements was effectively the same. The event knowledge of 5-year-olds appeared to be more consolidated, facilitating re-enactment of action outcomes rather than producing the exact manner with which a particular goal had been achieved.

The tendency to copy irrelevant aspects of a demonstrated sequence is well established in the developmental literature and should increase during the preschool years (e.g., McGuigan et al. 2007; McGuigan & Whiten, 2009; Yu & Kushnir, 2014). There are various reasons why we observed the reverse pattern in the context of a familiar event. Studies investigating over-imitation typically instruct children to retrieve objects from novel opaque or transparent boxes. On these tasks the precise movements of the retrieval action provide a measure for over-imitation (e.g., pressing a button, pulling a lever). As Kenward and colleagues have argued (Kenward, et al. 2011), for action performance to truly qualify as overly imitative children must be able to tell apart necessary from unnecessary actions and yet choose to perform them as a result of having seen a demonstration including both. Our control condition clearly demonstrates that preschoolers in both age groups had sufficient prior knowledge to plan and execute the target action as such, yet children in the experimental condition (and more so the younger children) opted to perform irrelevant actions as a result of a single demonstration.

Secondly, over-imitation has been explored in paradigms in which misleading demonstrations were presented over multiple successive trials (e.g., Horner & Whiten, 2005; McGuigan, et al. 2007; Kenward, et al. 2011; although see also Lyons et al. 2011; Lyons, et al. 2007; Yu & Kushnir, 2014). The repeated presentation of irrelevant actions at a fixed time-point within an overall poorly understood sequence should be expected to increase the likelihood that these actions will indeed be encoded as necessary components of the event hierarchy. In natural events, goal-related elements tend to be relatively stable whereas random elements usually vary. It is well known that even infants track statistical regularities in observed events when learning about action-effect contingencies and causal relations (e.g., Kirkham, Slemmer, & Johnson, 2002; Sobel & Kirkham, 2006; 2007). Arguably, when a misleading action sequence is ostentatiously demonstrated over multiple trials, then even adults may search for explanations as to why irrelevant elements should be incorporated. Importantly, such alternative explanations may not relate to the primary goal of the event in any obvious way. Meyer and Baldwin (2011) showed that when adults segment on going behaviour into sub-actions, they seem to rely on frequency information with which motion elements co-occur rather than predictive information relating the various sub-actions. One interpretation put forth by Baldwin and colleagues (2001) is that the sub-actions used in their task were not tied together by overarching goals. Thus, co-occurrence frequencies may have gained relevance because participants were unable to generate predictions about the event. These findings again highlight the importance of anchoring perceptual information to goals.

Thus, a tentative hypothesis for the developmental pattern observed in the current study is that younger preschoolers struggle to relate consecutive sub-actions to concrete outcomes within the goal hierarchy. It should be noted that according to this view, over-imitation behaviour in our task results from a failure to break down the observed event sequence in a meaningful way rather than as a consequence of inferred causality or a desire to socially comply. This suggests that cuing lower-level goals may considerably improve performance in this task. A wealth of research has spoken to the interplay between action and perception in lower- and higher-level action processing in both infants (e.g., Daum, Vuori, Prinz, Aschersleben, 2009; Thelen & Smith; 1994) and adults (e.g., Haazebroek, Van Dantzig, Hommel, 2013). One way to investigate this hypothesis further is to examine whether children would benefit from external cues that facilitate the detection of temporal links between procedural subcomponents of the event. In Experiment 2, we address this issue by arranging the array of objects spatially in line with the serial order of the task.

2.3. Experiment 2

The aim of Experiment 2 was to establish whether preschoolers' re-enactment of a misleading demonstration is, at least in part, controlled by external perceptual cues. More precisely, we examined whether cueing the underlying event structure would allow even the youngest children in this study to privilege goal-directedness over over-imitation. To this end, we aligned the array of objects spatially according to the temporal structure of the action sequence. As mentioned at the outset, in everyday action contexts of varied complexity, preschool children are likely to consider multiple sources of information to organize events, depending on the strength of their prior knowledge, and the availability of social as well as contextual signals. Indeed, one would expect perceptual cues to gain relevance in the absence of more consolidated event knowledge. As children increasingly rely on top-down knowledge to organize the problem space in familiar actions, the presence or absence of such perceptual cues should cease to impact on performance. Consequently, we anticipated that 3-year-olds in particular would benefit from external cues in this task.

2.3.1. Methods

Participants

As in Experiment 1, we recruited a sample of 30 3-year-olds (range = 36 – 45 months; *M* = 40.5 months; *SD* = 2.64 months, female = 18) and 30 5-year-olds (range = 60-70 months; *M* = 64.4 months; *SD* = 3.04 months, female = 15). All children were randomly assigned to experimental and control conditions (15 children per group; N = 60). Parental consent was collected for all participants in this study. To be included in the final sample children had to meet the same criteria as for Experiment 1. The study received approval from the institutional ethics committee and was conducted according to the principles of the Declaration of Helsinki.

Procedure

The methods, scoring, and analysis procedures were adopted from Experiment 1 with the following exception: all objects displayed in the performance phase were spatially positioned in a serial left-to-right order and thus according to successive sub-actions of the sequence. Distractor objects were lined up after the last relevant object. The order of distractor objects was the same as in Experiment 1.

2.3.2. Results

Preliminary analyses revealed no significant effects or interactions of gender and task experience on any dependent measures. Interrater reliability among coders was high (Cohen's kappa = 0.89). First we analysed performance differences across conditions (misleading demonstration / control) and age groups (3 years / 5 years) in terms of our combined performance measure (intrusion scores / sequencing errors / number of objects manipulated / total acting time). The original alpha level was adjusted to .01 for all following analyses of individual measures.

Table 3 summarises all means and standard deviations. A between-groups multivariate ANOVA revealed that the interaction between Age and Condition was not significant. Nor was the main effect of Condition. However, the main effect of Age group was marginally significant F(4,53) = 2.5, p = .05; η_p^2 = .16. Follow-up univariate analyses of variance suggest that this effect was mainly driven by Total time of performance F(1,56) = 8.5, p = .005; η_p^2 = .13. On average 3-year-olds required about 1.3 minutes longer to perform the target actions than 5-year-olds (*M* = 4.09 min., *SD* = 1.78 min. vs. *M* = 2.82 min., *SD* = 1.66 min.). Although performance in both age groups was generally fast, this time difference corresponds to an increase of 56% in the 3-year-olds compared to 5-year-olds in the misleading demonstration condition alone (*M* = 4.65 min., *SD* = 1.59 vs. 2.99 min., *SD* = 2.10 min.). No other factors reached significance. In terms of Condition, 3- and 5-year-olds manipulated a comparable number of distractor objects across the misleading demonstration (*M* = 1.3, *SD* = 1.7 vs. *M* = 0.53, *SD* = 0.74) and control groups (*M* = 1.0, *SD* = 1.3 vs. *M* = 0.73, *SD* = 1.4).

Comparing across Experiments

In order to directly compare results from our two experiments, we ran an additional set of analyses including Experiment as a factor. Multivariate analyses of variance confirmed highly significant interaction effects between Experiment and Condition F(5,108) = 13.77, p < .001; η_p^2 = .39 as well as Experiment and Age Group F(5,108) =

4.91, $p < .001$; $\eta_p^2 = .19$. Furthermore, we observed an Experiment x Condition x Age Group interaction $F(5,108) = 6.53$, $p < .001$; $\eta_p^2 = .23$. Follow-up univariate tests, using the Bonferroni adjusted alpha level of .01, revealed that Relevant objects $F(1,112) = 10.0$, $p = .002$; $\eta_p^2 = .08$, Distractor objects $F(1,112) = 15.6$, $p < .001$; $\eta_p^2 = .12$, Total time $F(1,112) = 7.67$, $p = .007$; $\eta_p^2 = .06$, and Intrusion scores $F(1,112) = 18.6$, $p < .001$; $\eta_p^2 = .14$ all reached significance. In fact, Errors was the only factor for which the three-way interaction did not reach significance.

In addition we found a main effect for Experiment $F(5,108) = 223.73$, $p < .001$; $\eta_p^2 = .91$ indicating that children in Experiment 2 performed significantly better compared to children in Experiment 1 in terms of Intrusion scores $F(1,112) = 64.92$, $p < .001$; $\eta_p^2 = .37$, Total time $F(1,112) = 164.41$, $p < .001$; $\eta_p^2 = .59$, Relevant objects $F(1,112) = 270.4$, $p < .001$; $\eta_p^2 = .71$, and Distractor objects $F(1,112) = 32.5$, $p < .001$; $\eta_p^2 = .22$ (see Table 2 and 3 for means and standard deviations).

Table 2.3. Descriptive Statistics 2

	Condition	Age	Mean	SD	N
Error Rates	experimental	3	.27	.46	15
		5	.47	.52	15
	control	3	.40	.73	15
		5	.33	.49	15
Intrusion Scores	experimental	3	.14	.17	15
		5	.02	.04	15
	control	3	.12	.17	15
		5	.08	.17	15
Time Total	experimental	3	4.65	1.58	15
		5	2.99	2.10	15
	control	3	3.52	1.82	15
		5	2.60	1.09	15
Number of relevant objects manipulated	experimental	3	3.00	.00	15
		5	3.00	.00	15
	control	3	3.00	.00	15
		5	3.00	.00	15
Number of distractor objects manipulated	experimental	3	1.33	1.72	15
		5	.53	.74	15
	control	3	1.00	1.03	15
		5	.73	1.43	15

SD = standard deviation; N = number of participants. Error Rates = total number of errors. Intrusion scores = time acted on distractor objects divided by total acting time.

2.3.3. Discussion

The ability to organise event representations and infer how procedural components connect within sequential actions undergoes considerable development during toddlerhood that lasts well into the preschool years (e.g., Fivush & Mandler, 1985; Koslowski & Bruner, 1972). In Experiment 2, we investigated whether preschool children would overcome over-imitation behaviour in a sequential task as a result of increased external event structure. To this end, we re-arranged our object display from Experiment 1 in line with procedural components of the event hierarchy. Bottom-up processing was expected to aid the discovery of temporal relations among consecutive actions within the sequence.

Findings in Experiment 2 are in good agreement with the pattern of results observed in our initial experiment (Figure 2.3). Both 3- and 5-year-olds were able to plan and perform the familiar multistep target sequence. Results further show that, when objects were spatially aligned in accordance with the serial order of the event, children no longer demonstrated over-imitation on any of our behavioural measures. Figure 3 illustrates the general pattern of results across both age groups in the example of intrusion scores. More precisely, a 32% decrease of over-imitation behaviour was observed in 3-year-olds when directly compared to Experiment 1, mirroring the result previously observed for 5-year-olds. Although there was certainly less scope for improvement for 5-year-olds in this task, their performance between Experiment 1 and 2 also improved with a decline in intrusion scores of 12%, leaving 5-year-olds' performance in the misleading demonstration condition indistinguishable from age-matched control children on all measures. Moreover, the results from this experiment clearly diverge from the pattern observed in our initial experiment in which Condition was the principal factor of the observed differences. In fact, developmental differences in terms of performance time, in the absence of any other age-dependent effects, are almost certainly attributable to 5-year-olds' greater dexterity.

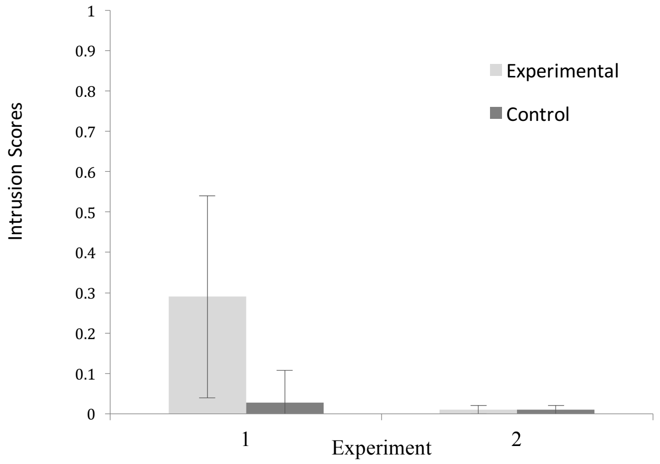

Figure 2.3. Intrusion scores collapsed across age groups plotted by Condition in Experiment 1 and 2.

2.4. General Discussion

Engaging in purposeful behaviour requires attention to those aspects of the environment that are appropriate for our intentions and disregard for others which may cause interference. Much of the knowledge needed to carry out novel actions is acquired by observing others. From a developmental perspective, an intriguing question is how young children reliably learn from observation despite the many opportunities and demands coming form naturalistic surroundings.

The ability to match the representation of a goal with an outcome has long been thought of as a departure point for more sophisticated analysis of intentional human behaviour. Indeed, preschool children appear to quickly learn from demonstrations and show increasing flexibility when integrating newly acquired knowledge with existing event representations. Considerable research has spoken to how toddlers and even infants develop an understanding of observed actions by establishing simple explanatory relations between various elements: the action, the goal state, and the constraints of the physical reality (e.g., Csibra, Bíró, Koos, & Gergely, 2003; Csibra, Gergely, Bíró, Koos, & Brockbank, 1999; Gergely, Nádasdy, Csibra, & Bíró, 1995; Csibra & Gergely, 2009). This is all the more impressive given that goal-directedness in action is highly context dependent (e.g., Gergely & Csibra, 2003).

In natural everyday settings preschool children entertain expectations about many of the events unfolding before them. When performing an action for the first time, prior event knowledge interacts with more immediate influences of the specific action context. In this study, we presented 3- and 5-year-olds with a familiar event sequence that was composed of both actions that could be linked to specific goals and actions that did not appear to serve the overarching goal of the sequence in an interpretable way.

The psychological mechanisms underlying the tendency to overly copy observed actions are not well understood. There has been much speculation in recent years as to why children and adults sometimes re-enact even overtly irrelevant actions while other times imitate selectively. One major line of thinking relates to the idea that children are inclined to copy all observed actions in a social context, regardless of their causal relevance, because they either naturally believe (Csibra & Gergely, 2009; 2011), or are somehow led to believe by the experimenter (Lyons, et al. 2011), that ostentatiously demonstrated actions ought to be performed. According to this reasoning, the degree of over-imitation is expected to become more pronounced with increasing age. Once children engage in pedagogical settings, their wish to produce modelled outcomes is likely to increase along with the desire to comply socially.

An alternative hypothesis postulates that the over-copying of observed actions aids the achievement of goals when the underlying causal relations are not well understood (e.g., Horner & Whiten, 2005; Kenward, et al. 2011; Whiten, Horner, & Marshall-Pescini, 2005; Whiten, et al. 2009). The idea that children assume that even irrelevant demonstrated actions must serve an unknown purpose seems especially feasible in situations where tasks are novel. However, this hypothesis may also be extended to explain why children over-imitate in more familiar contexts. Thus, regardless of whether the children in our task considered sub-actions as causally linked to the overarching goal, it is certainly possible that they perceived the distractor actions as serving a hidden purpose linked to ancillary goals.

Our results strongly suggest that, despite the high familiarity with the target action, preschool children's planning was perceptually informed by both a prior demonstration and the presence of external cues in this task. In particular young children's re-enactment reflected a high susceptibility to over-imitation behaviour as a result of a single misleading demonstration. Importantly age effects associated with strong over-imitation tendencies disappeared when procedural components of the sequence were spatially cued. Given that such cues were sufficient to eradicate performance differences between conditions, social accounts of over-imitation cannot provide a comprehensive explanation for the observed pattern of results in this particular task. However, we do not take this to mean that children *never* over-imitate in order to socially conform or that their re-enactment of modelled actions is not also influenced by the demonstrator-child interaction. In the current study we were cautious to avoid social signals that are well-known to impact on over-imitation behaviour in children (e.g., eye contact, real-life demonstrations, peer interactions, social valances, group membership; see Zmyj & Seehagen, 2013, for a recent review of studies using real-life and televised demonstrations performed by adults and peers). Moreover, various characteristics of agents (e.g., adult vs. peer model, in-group over out-group model) have been observed to influence imitative behaviour based on factors such as the perceived reliability of the demonstrator and group membership (e.g., Buttelmann, Zmyj, Daum, & Carpenter, 2013; McGuigan, et al., 2011; Wood, Kendal, & Flynn, 2012; Zmyj, Aschersleben, Prinz, & Daum, 2012). For this reason, the same adult model demonstrated all event sequences in this study. In spite of this, we observed a great deal of over-imitation behaviour. Over-imitation in our task decreased when action planning was externally supported, suggesting that the ability to organise observed actions in terms of hierarchically nested sub-actions critically influenced preschoolers' tendency to faithfully copy modelled actions. Our findings, therefore, raise the distinct possibility that over-imitation of fairly familiar events may result from a failure to organise the entirety of observed behaviours in a meaningful way rather than an active attempt to mimic observed actions as faithfully as possible.

With respect to the observed developmental effects, one could argue that action planning of a familiar event ought to improve between the ages of three and five as older children have more experience with our target sequence. Conceivably, ongoing experience in a wide range of action contexts and improved self-regulation during the first five years of life could ultimately facilitate the transfer of knowledge from one situation to another. In addition, the ability to maintain and modify a relative distal goal, shifting attention from one sub-task to another, and inhibit prepotent actions, is expected to undergo profound changes during the fourth year of life (e.g., Kaller, Rahm, Speer, Mader & Unterrainer, 2008, for a similar point). However, this argument cannot readily explain the developmental trend in our study, as both 3- and 5-year-olds were well able to structure their own actions according to task demands in the absence of a misleading demonstration, as well as when serial step-by-step planning was facilitated spatially. This observation is in line with the notion of graded goal representations supporting mechanisms of cognitive control in young children (Munakata. O'Reilly, & Morton, 2007; Munakata & Yerys, 2001). According to this view goal-directed events are represented with varying strengths over the course of development. While strong event representations are required to endogenously generated cognitive control to guide information processing, weaker representations may still produce accurate outcomes if exogenously cued (e.g., Munakata & Yerys, 2001; Towse, Lewis, & Knowles, 2007). Results from the current study endorse this view and further suggest that more consolidated event representations of 5-year-olds may have reinforced the detection of conflict between irrelevant actions and the overarching goal of the observed sequence. In fact, the ability to monitor cognitive control to support sequential actions has been found to improve between three and five years of age (Freier, Cooper, & Mareschal, in press).

In the current study, only half of the demonstrated sub-actions could be linked to the overarching goal in a meaningful way. In the absence of any knowledge of how to link observed actions to specific outcomes and the overarching goal, one could still generate two ecologically valid predictions: (1) that actions are generally goal-directed, and (2) that sub-actions that follow each other tend to form part of the same goal-directed sequence. Our results therefore favour the interpretation that young preschoolers struggled to organize relevant and irrelevant sub-actions in relation to the overarching goal of the event, and thus ascribed hidden purposes to irrelevant distractor actions. Our findings further suggest that spatial features of the event context significantly influence how young children perceive and construct complex sequential actions. The present study thus adds to existing work by suggesting that over-imitation behaviour in a familiar sequential task is significantly modulated by the ability to represent observed actions in terms of underlying goal hierarchies. Advances in young children's organisation of complex hierarchical actions is ultimately reflected in their ability to incorporate observed actions flexibly into their own behaviours and to generalise action-outcome relations to novel events.

We now turn to the question whether preschoolers' planning abilities are influenced by inferences about the causal structure of the event. To tackle this question we presented children with a novel sequential task, in which causal links between event and outcome guided potential interventions.

CHAPTER 3

Preschool Children's Control of Action Outcomes[6]

3.1. Introduction

Naturalistic goal-directed behaviours require the engagement and maintenance of appropriate levels of cognitive control over relatively extended intervals of time. In two experiments, we examined preschool children's abilities to maintain top-down control throughout the course of a sequential task. Both 3- and 5-year-olds demonstrated good abilities to access goals at the lowest level of the representational hierarchy. However, only 5-year-olds consistently aligned their response choices with goals at superordinate levels. These findings suggest that the ability to maintain top-down control and adjust behavioural responses according to goals at multiple levels of abstraction undergoes a marked improvement throughout the preschool period. Results are discussed in relation to current accounts of cognitive control and the monitoring of conflict in sequential action.

3.1.1. Cognitive control

A clear transition from being primarily activity oriented to increasing action control and attention to task requirements can be observed during the toddler period and early

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[6] Freier, Cooper, & Mareschal, (2015). Preschool children's control of action outcomes. *Developmental Science.*

childhood (Bullock & Lütkenhaus, 1988). Some of the fundamental prerequisites for representing action goals are laid out during first year of life (e.g., Sommerville & Woodward, 2005). For instance, it has been observed that 6-9 month-old infants are able to perceive simple actions as directed towards goals (e.g., Woodward, 1998, 2003). Similarly, 12-month-old infants appear to reflect some degree of flexibility in their interpretation of actions as goal directed or not depending on the causal context of the event (e.g., Gergely et al. 1995). Along with this emerging goal-directedness there appears to be an increase in the extent to which toddlers monitor the effectiveness of their actions and learn how to coordinate multiple means-ends relations (e.g., Brownell, 1988; DeLoache, Sugarman, & Brown, 1985; Jennings, 2004). During the preschool years, advanced attentional control in rule-guided behaviour aids the accomplishment of ever more spatially and temporarily distal goals. There is substantial evidence suggesting that increased engagement of executive sub-functions in goal-directed behaviour is strongly predicted by age (Anderson, & Reidy, 2012; Espy, Kaufmann, McDiarmid, & Glisky, 1999; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003). In particular, before the age of 3 to 4 years, children's executive control and action-correcting strategies appear to be limited (e.g., Jones, Rothbart, & Posner, 2003; Zelazo & Müller, 2002). This is a time of increasing abilities to endogenously generate cognitive control in pursuit of higher-level goals.

The degree to which cognitive control is recruited varies considerably depending on the task, in part because complex action sequences are composed of hierarchically nested sub-actions. For instance, everyday actions that involve the realisation of numerous goals, at multiple levels of abstraction, are likely to demand higher levels of cognitive control than sequences of a simpler goal structure (e.g., Amso, Haas, McShane, & Badre, 2014). Similarly, relatively unpractised actions may increase the demand for top-down control relative to well-known routines in which goal relevant knowledge may be accessed fairly automatically (e.g., Cooper, Ruh & Mareschal, 2014; Cooper & Shallice, 2006; Wood & Neal, 2007). However, relatively little is known about how goal hierarchies are managed during the preschool years.

The introduction chapter outlined several theoretical models that provide frameworks for how cognitive control may reduce the occurrence of conflict in tasks that require the parallel processing of competing inputs (e.g., Botvinick et al. 2001; Cooper & Shallice, 2000; Desimone & Duncan, 1995; Miller & Cohen, 2001; Norman & Shallice, 1986; Schneider & Detweiler, 1987). In these models control is implemented by biasing information processing towards the overarching goal of a particular task, thus resulting in a reduction of conflict during task performance.

Current mechanistic explanations of cognitive control propose that specific brain regions within the prefrontal cortex (PFC) support the strategic retrieval of knowledge representations from working memory (e.g., Badre, 2008; Chatham & Badre, 2013; Badre & Wagner, 2007; Miller & Cohen, 2001; Koechlin & Summerfield, 2007). Wide-ranging neuropsychological research suggests that frontal circuits supporting cognitive flexibility, planning, and the organisation of goal-directed behaviour undergo profound changes during the preschool years, and continue to develop into early adulthood (e.g., Anderson, 1998; Brydges, Reid, Fox, & Anderson, 2012; Diamond 2002; Giedd & Rapoport 2010; Levin et al. 1991; Luria, 1973; Posner & Rothbart, 1998; Yakovlev & Lecours, 1967; Welsh, Pennington, & Groisser, 1991).

In adults, a wealth of neuroimaging evidence has substantiated the view that the hierarchical structure of goal-directed behaviour is represented by the pattern of activation along the rostral-caudal axis of the PFC, with activity in more anterior subregions linked to the processing of increasingly abstract goals (e.g., Badre, 2008; Badre & D'Esposito, 2007; Badre & Frank, 2012; Braver & Bongiolatti, 2002; Bunge, Kahn, Wallis, Miller, & Wagner, 2003; Christoff &. Gabrieli, 2000; Hazy, Frank, & O'Reilly, 2006; Fuster, 2004; Koechlin 2008; Koechlin, Ody, & Kouneiher, 2003; Koechlin & Jubault, 2006). From a developmental perspective, cognitive control has been primarily investigated behaviourally, with a focus on how children resolve competition within a particular level of a goal hierarchy. However, little is currently known about how children engage cognitive control to structure sequential behaviour in which goal attainment is linked to complex hierarchies of rules. In adults, the ability to abstract from rules and goals at various subordinate levels has been found to directly influence accuracy and response time in hierarchical learning tasks (e.g., Badre & D'Esposito, 2007). In a recent study, Amso et al. (2014) demonstrated that age-related performance effects between children (7- to 10-year-olds) and adolescents (12- to 15-year-olds) were explained by the ability to flexibly abstract from superordinate rules rather than by the number of competing alternatives within a particular response level of the task. These results suggest that updating higher-level rules in working memory is one of the main mechanisms driving developmental effects in this task. A question that remains unresolved is how the ability to consistently retrieve and maintain goal-relevant representations from working memory, in a top-down manner, develops in early childhood.

In the current study we investigated preschoolers' abilities to organize a set of sub-actions within a relatively long sequential task, and adjust top-down control according to a single higher-level goal. This sets the current task apart from more classic paradigms that examine cognitive control in children and adults by looking at how participants engage, disengage, and switch across multiple goals that compete within a particular representational layer. Frequently cognitive control in children is explored with card-sorting paradigms (e.g., DCCS: Zelazo, 2006; WCST: Grant & Berg 1948; FIST: Jacques & Zelazo, 2001), in which card sorting accuracy to a changing set of sorting criteria is measured. However, these paradigms do not address how goal hierarchies are maintained over extended periods of activity. In addition, in classic card-sorting tasks conflict resides within the parallel processing of readily observable features of the task materials. Each stimulus cues various conflicting dimensions that map onto relevant and irrelevant rules (e.g., shape vs. colour). Whether one rule or the other is currently relevant depends on the particular trial type. Therefore, card-sorting paradigms essentially measure how cognitive control is engaged and disengaged across set-shifting operations. In contrast, we sought to assess how cognitive control is sustained and how the demand for ongoing cognitive control is evaluated over the course of a sequential activity. Indeed, exerting control and evaluating the need for sustained top-down control are distinct aspects of cognitive control (e.g., Carter, et al. 2000; Botvinick et al. 2001).

Various fMRI and PET studies corroborate the view that flexible switching and rule maintenance are dissociable by delineating the topographic organisation of the prefrontal cortex (e.g., Badre & Frank, 2012; Badre & D'Esposito, 2007; Bunge, et al., 2003; Chatman, Frank, & Badre, 2014; Crone, Donohue, Honomichl, Wendelken,

& Bunge, 2006; Reverberi, Görgen, & Haynes, 2012). Collectively, these studies suggest that the maintenance of rule representations and rule switching are neurologically dissociable. Specifically, selective updating of working memory has been linked to striatal activation, whereas the maintenance of goal-relevant information in memory systems appears to be supported by frontal brain areas (e.g., Barch, Braver, Nystrom, Forman, Noll, & Cohen, 1997; Chatham & Badre, 2013, Leber, Turk-Browne, & Chun, 2008; Miller & Cohen, 2001; Ragozzino, 2007).

Using a novel ecologically valid sequential task utilising a highly familiar activity, we sought to: (1) evaluate preschool children's abilities to generate endogenously cognitive control in order to attain abstract goals, and (2) investigate whether there is a substantial developmental change during the preschool period in the way children allocate strategic control to guide action selection. In real life settings goal-directed actions are hierarchical in nature, and thus monitoring the effectiveness of complex actions requires the maintenance of goal-relevant information at different levels of abstraction while continuously updating new contextual information into working memory. In Experiment 1, we asked 3- and 5-year-olds to perform a colouring activity in which three colours had to be equally used to colour-in a line-up of animal shapes. Therefore, throughout this task, children were required to maintain representations of the abstract goal and a strategy of how to achieve it over an extended period of time. At a lower level of the hierarchy, children then mapped selected strategies onto the colouring stimuli. However, there was no external feedback provided that would have cued appropriate adjustments to the colouring activity. Thus effective goal attainment in this task was critically influenced by children's ability to evaluate their response choices in terms of the higher-level goal.

Experiment 2 extended the task by requiring the children to periodically report the overarching goal, thus ruling out the possibility that poor performance with respect to the abstract goal might be due to memory failure.

3.2. Experiment 1

3.2.1. Methods

Participants

The final sample consisted of twenty-nine 3-year-olds (range= 37-47 months; mean age= 40.4 months; SD= 3.1 months: 17 females) and 29 5-year-olds (range= 60-70 months; mean age= 64.6; SD= 3.1 months; 15 females). One additional 3-year-old and two 5-year-olds were tested, but excluded from further analysis because their response selection indicated a failure to understand the task. We return to this point in the following section. All children in this study were recruited from local nurseries and primary schools. Formal parental consents and children’s verbal approval was obtained prior to testing. The study was approved by the institutional ethics committee and conducted according to the principles of the Declaration of Helsinki.

Materials and Procedure

Each child received one sheet of paper depicting the outline of six farm animals[7] lined up horizontally (see Figure 3.1). Beneath these animal shapes, an arrow cued response direction running from the left to right side of the paper. Children also received three crayons in different colours, with the colours for each child selected at random from the crayon pack. All children were instructed to colour-in the animal shapes, following the arrow depicted beneath. They were informed that it was important not to leave any animals uncoloured. Children were also instructed to use each of their colours equally often. This colour criterion represented the overarching goal of the task and was therefore further explained. Children were first shown an equivalent picture illustrating an equal distribution of colours across colour-in shapes, which was then removed during the test session. Of note, this exemplary picture did not include any of the stimuli or colours that were available to children in this task. The example picture further illustrated that colours could be assigned to any animal shape irrespective of real-life features.

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[7] Two of the animals appeared twice in the line-up of shapes. The reason for this was to confirm that children had indeed understood the task, and thus demonstrated an attempt to reach the overarching goal, rather than selecting responses based on perceptual similarities or prior animal-colour associations (e.g., colouring all pigs pink, yielding “colour-by-shape” errors).

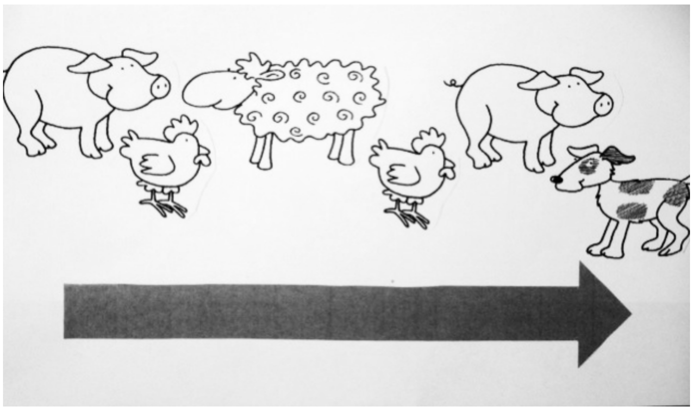

Figure 3.1. Stimuli display in the colouring task.

Importantly, none of the instructions in this task involved number concepts. In addition, the abstract concept “equally often” was further clarified prior to testing via simple examples of quantity relations using a popular preschool game in which children distribute small objects into two cups and thereafter estimated whether both cups contained equal amounts[8].

Children were also encouraged to ask questions if they had any difficulties understanding the colouring game. The starting point was set at the leftmost animal. After children had coloured in the first shape of the line-up they were reminded once that each colour should be used equally often. The task did not include feedback

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[8] Abundant evidence indicates that toddlers (e.g., Antell & Keating, 1983; Carey, 2009; Gelman, 1972; Gelman & Gallistel, 1986) and even infants (e.g., McCrink & Wynn, 2004; Wynn et al., 1992) are well capable of making numerical discriminations, suggesting that a concept of equality in the mathematical sense (as integers) is not necessary in order to judge numerical relations between small sets. In our study, children only needed minimal, if any, numerical competences for successful performance. Counting was neither requested nor required to accomplish the overarching goal based on perceptual matching mechanisms. Dividing the six shapes by three was possible but not necessary for accurate performance. Cycling colours for instance, is one strategy that led to accurate performance without the need to keep count of a single colour.

because it was designed to test specifically whether pre-school children would generate cognitive control endogenously to guide action selection.

Coding

The relative degree of control that children directed towards either the overarching goal of the task or the colouring activity per se was assessed via multiple measures. Children who met the colour criterion, i.e., those who used each of their three colours exactly twice, were coded as achieving the higher-level goal. Children who coloured-in all shapes, using one or various colours, but had done so irrespective of the colour criterion, were coded as achieving the activity but not the goal. Children who initially acted towards an accurate outcome but departed from it at a particular point in the line-up of shapes, i.e., those who grouped or cycled colours on a subset of shapes, were coded as paying attention to the overarching goal but unsuccessfully.

A second measure of interest was the number of colours used to complete this task. Although children were instructed to use all of their three colours to meet the overarching goal, subordinate goals (e.g., colouring-in all shapes left to right) could be accomplished using one or two colours only.

A third measure assessed the exact point within the series of shapes at which children first departed from acting towards an appropriate outcome (first detectable discrepancy), assuming they did not achieve the higher-level goal. As responses in this task were made in a serial order, using a total of three colours, the first point at which insufficient monitoring of the overarching goal could become apparent was the third shape in the line-up.

Finally, we assessed the type of strategy children employed. One effective strategy to satisfy the colour criterion, without leaving any shapes uncoloured, was to switch colours between every shape, cycling through the three colours (cycling approach). Alternatively, the same colour could be applied for each pair of two consecutive shapes (grouped approach). It was further possible to mix both, grouped and cycling approaches (mixed approach) while progressing through the line-up. Children who did not employ any apparent strategy were coded as approaching the task unsystematically (random).

In addition to overall performance, number of colours and strategy use, children's error correcting responses, (e.g., switching of colours mid-trial and colouring over already coloured shapes). However, children in neither age group demonstrated evidence of error correcting behaviours in this task.

3.2.2. Results

Even the youngest children in this study demonstrated an appropriate understanding of equality relations in the cup game as suggested by correctly stating whether two cups held equal amounts of items. This observation is in good agreement with a wide range of evidence for the development of a concept for numerical equivalence in children well before the age of three years (e.g., Griffin & Case, 1996; Feigenson et al., 2004; Izard et al., 2009; Izard, Streri, & Spelke, 2014; Xu & Spelke, 2000;

Starkey, Spelke, & Gelman, 1990; Wynn, 1992). All participants therefore moved on to the colouring task.

Preliminary analysis revealed no significant effects of gender so results were collapsed across males and females. Figure 3.2 illustrates the performance of preschoolers in terms of age group, strategy, and overall outcome. Chi-square test for independence revealed a significant association between Age group and Outcome, χ^2 (2, n=58) = 23.89, $p < .001$, with 5-year-olds achieving the overarching goal nearly eight times more frequently than 3-year olds (55% vs. 7%). Most 3-year-olds accomplished the activity but did not produce the higher-level goal (62% vs. 7%), although a small proportion in this age group did pay attention to this goal but unsuccessfully (31%).

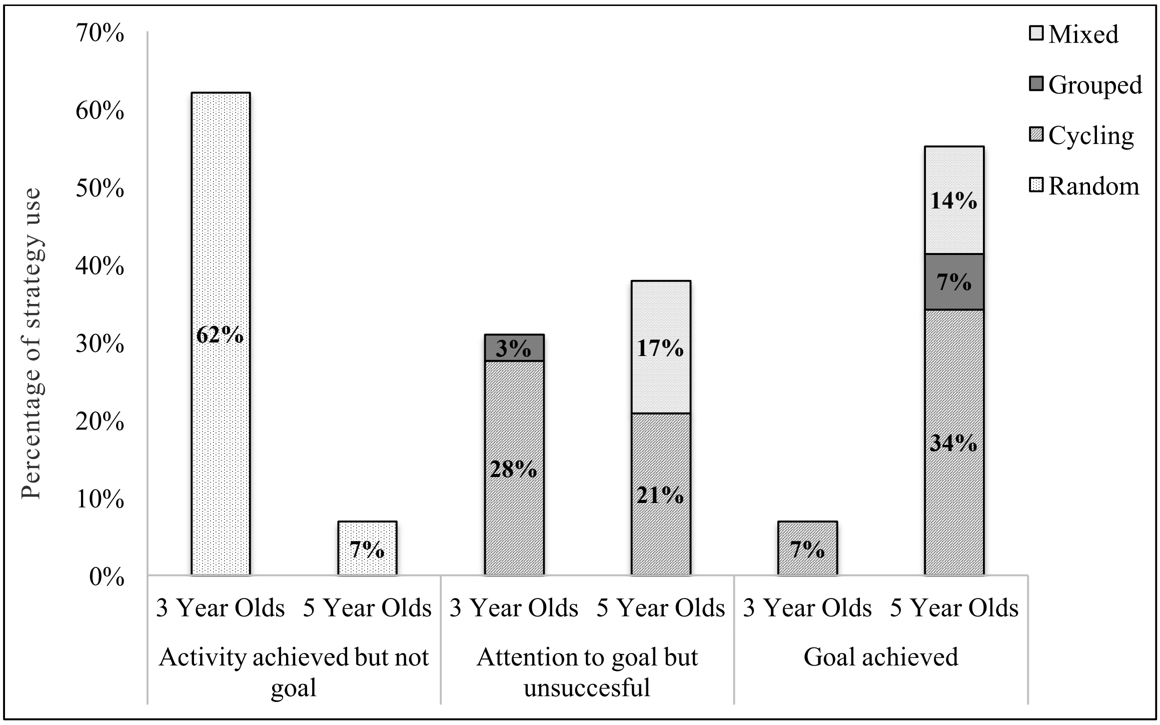

Figure 3.2. Outcome plotted by age group and strategy in Experiment 1. All preschoolers engaged in the colouring activity. Only children who reached the colour criterion were coded as achieving the overarching goal of the task. Children who acted towards the overarching goal but departed from an accurate outcome at a particular point in the sequence were classified as paying attention to the goal but unsuccessfully.

In terms of the number of different colours used to complete the task, a significant association between Number of colours and Age group was observed χ^2 (2, n=58) = 10.89, p = .004. Over half of the 3-year-olds applied a total of three colours (55%), while the rest of the children in this age group made use of either one (24%) or two (21%) colours only. In contrast, the vast majority of 5-year-olds brought all of their colours into play (94%) and only two participants in this age group approached the task using only one (3%) or two colours (3%) respectively.

In order to identify whether age affected the point within the line-up of animals at which children lost sight of the overarching goal, the first divergence from the colour criterion was analysed and compared across age groups (see Figure 3.3.). A chi-square test indicated a significant association between the first detectable Discrepancy and Age group χ^2 (4, n=58) = 18.01, p = .001. As with the previous measures, there was an overall higher level of discrepancy between the overarching goal and the actual outcome in the younger age group compared to 5-year-olds (93% vs. 45%). However, there was also a consistent pattern of younger children diverging from goal-directed response choices earlier within the sequence of shapes. Indeed, almost half the 3-year-olds in this task first deviated from goal-oriented performance when colouring-in the third shape within the serial line-up (42%). Again, it should be noted that the third shape in the line-up was the first point at which divergence was detectable in this task. A smaller percentage of 3-year-olds choose colours accurately until reaching the fourth shape in the series (17%), the fifth shape (24%), and some 3-year-olds lost sight of the overarching goal on the very last shape they coloured in (10%). In contrast, 5-year-olds who failed to reach the overarching goal did not demonstrate the same pattern as younger children in terms of the first detectable divergence. In fact, the percentage of 5-year-olds who deviated from the overarching goal on the third (10%), fourth (14%), fifth (10%) and final shape (11%) was similar.

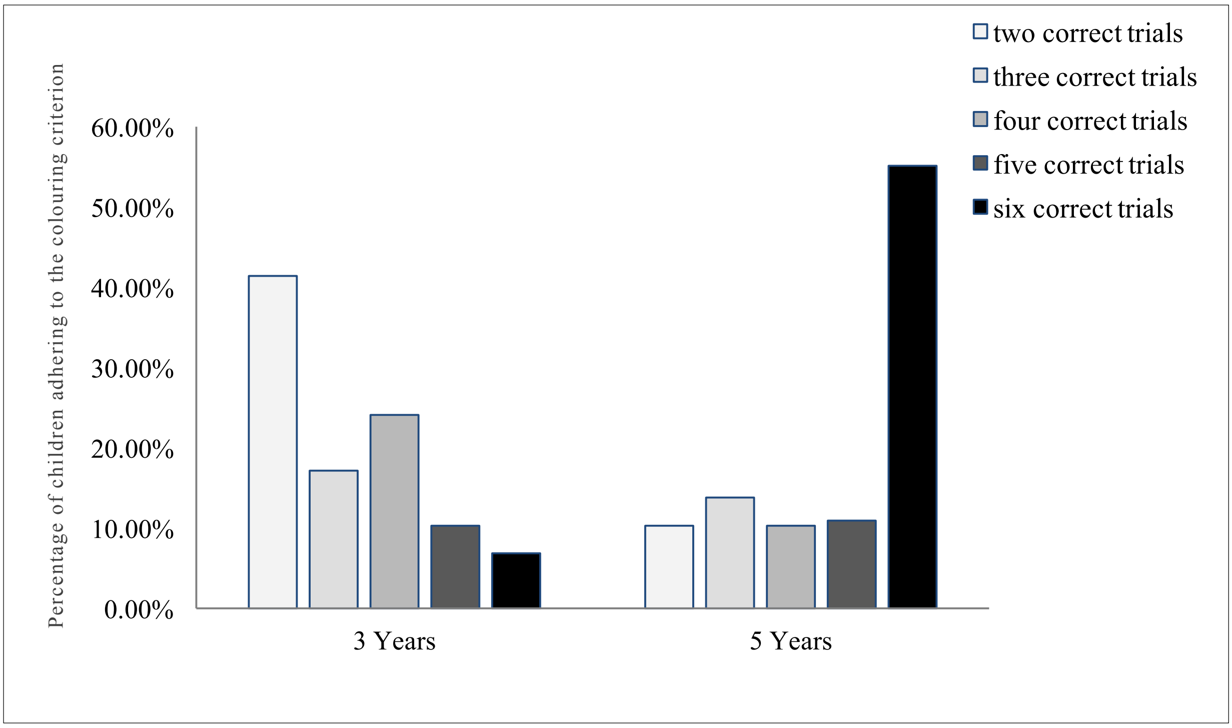

Figure 3.3. Number of correct response choices towards the overarching goal within the line-up of six shapes by age group. The third colour-in animal shape was the earliest point at which discrepancies were measurable.

A final measure concerned the type of strategies children adopted in this task. A chi-square test revealed that the association between Strategy and Age group was also significant χ^2 (3, n=58) = 23.52, p < .001. The preferred strategy of 5-year-olds involved a cycling approach (55%), though some children in this older age group acted towards the outcome using a grouped (7%) and mixed approach (31%). Only children in this age group who grouped their colours in pairs were always successful, while 62% of all 5-year-olds who cycled and 45% of those who mixed their approaches also succeeded. Thus, although successful children in this age group clearly favoured a cycling approach overall diverse and flexible strategies led to effective performance in 5-year-olds.

Conversely, fewer than half of the 3-year-olds appeared to employ any type of strategy at all (35% cycling and 3% grouped). The remaining children in this young age group approached the task seemingly acting at random (62%). The 7% of 3-year-olds who did reach the outcome made use of a cycling strategy (100%)[9].

3.2.3. Discussion

Experiment 1 set out to assess preschool children's abilities to engage cognitive control in a sequential task, in which the completion of a set of subordinate rules resulted in goal attainment at higher levels. If intermediate goals in this task were monitored sufficiently, then the demand for top-down control required to accomplish the higher-level goal in this task was decreased by constraining the task space. However, no colour in itself uniquely specified the appropriate response. No colour was more obviously associated with one strategy or another. The need to switch colours within a single trial had to be endogenously detected.

Results indicate developmental differences on all measures, with 3-year-olds demonstrating a strong focus on the colouring activity rather than the effectiveness of a goal consistent strategy. Conceivably, 3-year-olds struggled to monitor the relatively distal overarching goal in this task. The early point at which many 3-year-olds diverged from accurate response selections suggests that the overarching goal may have been neglected from the very outset of the task. In line with this argument is the observation that most 3-year-olds in this study did not employ any apparent

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[9] The number of cases in this subgroup, composed of only those children who attained the overarching goal, was low in the younger age group (7% - an equivalent of 2 cases) which in turn limits the interpretability of findings concerning the effectiveness of any one strategy over another in 3-year-olds.

strategy to produce the higher-level goal and more frequently made use of one or two colours only.

In contrast, 5-year-olds demonstrated sensitivity to higher-level goals at least at some point within the sequence. Strategy-guided acting was apparent in the performance of all but two children in this age group, with a cycling approach being the favoured and most successful strategy to effectively produce the higher-level goal. In addition to more successful planning, it is plausible that 5-year-olds implemented strategies more consistently because they were better able to consider future steps in light of past response choices than were 3-year-olds. However, the role of backtracking in sequential tasks remains to be explored by future works. Results from this experiment indicate conclusively that children in both age groups were well able to perform the most basic rule (colour-in all animals), but the vast majority of 3-year-olds did not appear to access goals at superordinate levels. As a result, most children in this age group achieved lower-level task requirements while failing to implement appropriate actions to succeed on this task.

Disregard for task requirements, frequently termed "goal neglect", has been reported in adult participants in the absence of error feedback and when multiple concurrent task requirements need to be coordinated (Duncan, Emslie, Williams, Johnson, & Freer, 1996). Goal neglect is further observed in neuropsychological patients with frontal lobe impairments (e.g., Duncan, Johnson, Swales, & Freer, 1997). Importantly, in goal neglect participants clearly understand the desired outcome but are unable to organize their actions accordingly. Duncan et al. (1996) postulate that goal neglect in frontal patients is linked to impairments to frontally distributed control networks, while in neurologically healthy individuals it is associated with task demands that exceed a participant's capacity for cognitive control (e.g., Duncan et al. 2008; Bhandari & Duncan, 2014). As discussed above, frontally distributed control mechanisms fundamentally impact the organization of goal-directed behaviours and undergo substantial development during the preschool years.

Working memory capacity and the ability to maintain goal representations activated in view of competing information has been linked with goal neglect in adults (e.g., Kane, Conway, Hambrick, & Engle, 2007; Kane & Engle, 2003) and young children (e.g., Marcovitch, Boseovski, & Knapp, 2007). The 3-year-olds' performance in our task certainly resembles preschoolers' goal-neglect elicited in tasks that require response choices to a set of bivalent stimuli (e.g., Marcovitch, Boseovski, Knapp, & Kane, 2010; Towse, Lewis, & Knowles, 2007). As others have argued, regulating cognitive control towards outcomes requires both accurate representations of the goal state and the functional availability of goal representations for top-down control (Towse, et al., 2007). Given the temporal dynamics in our sequential task, one may argue that 3-year-olds may have struggled to hold the overarching goal in active memory. To investigate this hypothesis further we conducted a second experiment asking whether preschoolers' difficulties in our task could be explained in terms of broader memory limitations.

3.3. Experiment 2

3.3.1. Methods

Participants

Twenty-nine 3-year-olds (range = 36-45 months; mean age = 40.5 months; SD = 2.64 months, 18 females) and 29 5-year-olds (range = 60-70 months; mean age = 64.4 months; SD = 3.04 months, 15 females) made up the final sample of Experiment 2. Formal consent was obtained from caregivers. Eight additional children were tested but excluded from further analysis because they had either failed to respond to the experimenter's request to express the task goal mid-sequence (five 3-year-olds and one 5-year-old) or committed colour-by-shape errors (two 5-year-olds). None of the children tested had taken part in Experiment 1.

Materials and Procedure

All testing, coding, and analyses procedures were identical to those in Experiment 1, with the exception that children were asked to recall the overarching goal at the beginning of the task and after each response selection (excluding the last shape). If a child failed to spontaneously repeat the task goal the experimenter would ask directly ("How do you need to colour-in these animals?"). Only children who answered correctly were included in the final sample of this experiment.

4.3.2. Results

All 58 children included in the final sample demonstrated a sufficient understanding of equality relations prior to testing and succeeded at directly recalling the colour criterion before making response selections. Preliminary analysis revealed no significant effects of Gender.

Figure 3.4. shows performances plotted by age group, strategy, and overall outcome. We found a significant association between Age group and Outcome as indicated by a Chi-square test for independence, χ^2 (2, n=58) = 27.64, $p < .001$. The majority of 3-year-olds either achieved the activity but failed to produce the overarching goal (55%) or demonstrated goal-directed acting for limited sections of the sequence (35%). In contrast, all 5-year-olds appeared to act in line with the appropriate outcome at least at some point within the sequence (although 34% did not succeed on all six trials).

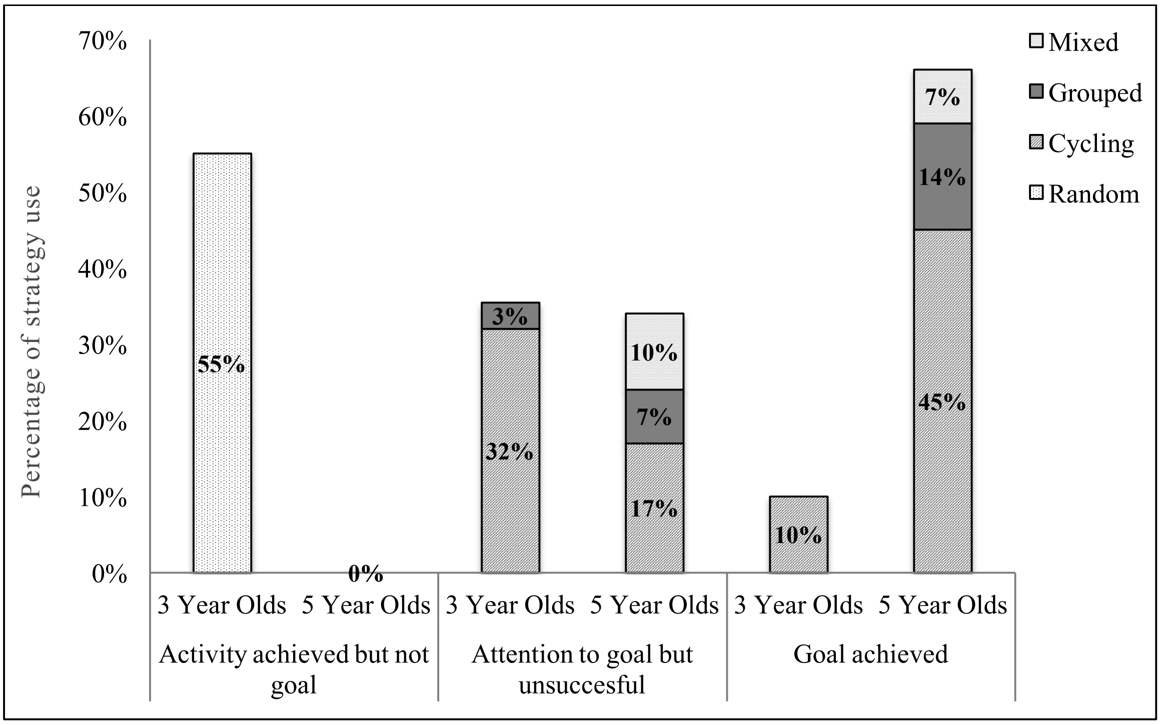

Figure 3.4. Outcome plotted by age group and strategy in Experiment 2. The colouring activity was accomplished by all participants. Children who reached the colour criterion were coded as achieving the overarching goal of the task. Performances that were directed towards accurate outcomes but failed to reach the overarching goal were coded as paying attention to the goal but unsuccessfully.

Three-year-olds' tendency to produce the activity rather than the overarching goal was further confirmed in terms of the number of colours used to accomplish the task. We observed a significant associations between Number of colours and Age group χ^2 (2, n=58) = 16.76, p <.001. All 5-year-olds utilised the full range of their colours (100%), whereas this was true for only about half the 3-year-olds in this experiment (55%). All remaining children in this younger age group applied one (14%) or two (31%) colours only.

We also analysed the first detectable divergence from the colour criterion and found a significant association between Age group and Divergence χ^2 (4, n=58) = 29.51, $p < .001$. Again, 3- but not 5-year-olds showed a strong tendency to depart from acting accurately early on within the sequence. In fact, 16 3-year-olds diverged from acting in line with the colour criterion at the earliest observable point of the sequence, while only one 5-year-old demonstrated equivalent performance (48% vs. 3%). A small proportion of 3-year-olds directed their colouring activity towards an accurate outcome and only diverted from doing so at the very last colour-in shape (14%). This final step in the line-up was the point in the sequence at which the majority of 5-year-olds who did not reach the colour criterion demonstrated divergence from an accurate performance (20%).

Finally, we analysed the strategies children choose to tackle this task. Chi-square test for independence revealed a significant association between Strategy and Age group χ^2 (3, n=58) = 25.77, $p < .001$. Again, the overall preferred strategy of 5-year-olds involved a cycling approach (62%), followed by a grouped approach (21%) and a mix of both strategies (17%). Despite the fact that only 10% of 3-year-olds succeeded on this task, almost half of the children in this age group showed evidence of cycling (42%) and 3% even attempted a grouped approach. However, the remaining children in this younger age group engaged in the activity without any evident strategy (55%).

To identify which strategy was most effectively employed, we looked at the association between Outcome and Strategy separately for 3- and 5-year-olds. Figure 3.4. illustrates the frequencies with which each strategy led to accurate task performance. As in the previous experiment, when 3-year-olds acted towards a successful outcome they did so using a cycling approach (24% of 3-year-olds using this approach were indeed successful). For 5-year-olds, the pattern of strategies is more complex than in the younger age group. The majority of 5-year-olds who cycled their colours showed accurate performance (73%). Similarly, most children in this age group who grouped their colours in sets of two shapes did accomplish the higher-level goal (67%). A comparably smaller proportion of children in this age group effectively mixed strategies without losing sight of the colour criterion (41%). Therefore, overall children in both age groups most frequently and successful made use of a cycling strategy. However, as in Experiment 1, only 5-year-olds consistently ensured goal attainment when making use of this approach. Indeed, a set of additional Chi-square tests contrasting behaviour in Experiments 1 and 2 (i.e., including Experiment as an independent variable) confirmed that there were no significant differences in the behaviour of children across the experiments.

3.3.3. Discussion

Results from this follow-up experiment replicate our initial findings and further demonstrate that children in both age groups had no apparent difficulties in recalling the task goal while simultaneously carrying out more immediate steps of the sequence. This observation strengthens our case that the colouring task poses particular challenges for preschoolers in terms of cognitive control rather than memory limitations. Building on neuropsychological research (e.g., Duncan 1986; Duncan et al., 1996; Duncan et al., 1997), it has been suggested that this type of goal neglect is linked to competing patterns of activity that represents goals and rules within the PFC to produce top-down signals for action selection (see Miller & Cohen, 2001).

As mentioned in previous sections, it should be noted that our task did not include concrete instructions or external cues about when to switch colours and what colours to switch to and therefore contrasts with other measures of cognitive control (e.g., card-sorting paradigms). Similarly, stimuli in our task did not bias responses in either a goal-compatible or incompatible manner. In line with this reasoning, it is likely that the 3-year-olds in the current study struggled to generate endogenously control mechanisms to monitor the effectiveness of their response selections because there was no direct information available in the task material that would have anchored the abstract task goal to lower level representations.

Snyder and Munakata (2010) demonstrated that endogenously generated attentional control develops later than exogenously cued control mechanisms in a switching paradigm. This study therefore supports the notion of a transition from exogenously guided to endogenous generated control mechanisms throughout development. It is our contention that developmental differences in endogenous control explain the observed pattern of results across 3-and 5-year-olds in our study. In contrast, our results do not speak to the possibility that preschoolers (especially 3-year-olds) may also have benefited more from external task-generated cues. The ability to integrate and adapt to task cues has been linked to preschoolers' performances when faced with response conflict (e.g., Holt & Deák, 2014). However, it is worth noting that neither age group significantly improved beyond the level of performance in Experiment 1 as a result of direct recall in Experiment 2.

3.4. General Discussion

Cognitive control supports action selection in goal-directed behaviour. As outlined in the introduction, acting towards complex distal goals not only requires maintaining goal representations and knowledge of procedural components in active memory, but also calls for adjustments in cognitive control if needed. Several theories provide conceptual accounts of abstract rule use and the development of cognitive flexibility (e.g., CCC, Zelazo et al., 2003; Attentional Inertia, Kirkham, Cruess, & Diamond, 2003). A remaining question is how preschoolers implement higher-level goals in sequential tasks. Clear behavioural improvements in tasks that require the regulation of attentional control are observed during early childhood, but considerably less is known about how the need to recruit and adjust cognitive control in temporally extended tasks is evaluated during this time in development. Our study provides an initial attempt to fill this gap in the literature by investigating 3- and 5-year-olds' abilities to sustain cognitive control in a sequential task in which superordinate processing determined accurate response selections at lower levels.

A differential effect of age on all measures across two experiments suggests that the 3- and 5-year-olds in this study exhibited distinct levels of effectiveness in producing the overarching goal. However, given that children in both age groups had no difficulties verbally recalling the task goal, as demonstrated in Experiment 2, performance differences are unlikely to result from a general failure to remember the goal state as such. In other words, 3-year-olds in this study failed in this task not because they lacked the representational abilities to maintain the overarching goal active in working memory, but because they failed to select actions at subordinate levels accordingly.

Despite a wealth of evidence suggesting that even toddlers are equipped with the ability to represent relatively distal future goals (e.g., Jennings, 2004) and are further capable of re-enacting familiar multi-step sequences in which specific procedural sub-actions precede and follow others (e.g., Bauer & Mandler, 1989; 1992; Bauer & Thal, 1990), the majority of 3-year-olds performed our task in accordance with automatic and stimulus-triggered actions rather than in pursuit of the overarching goal.

Given the lack of external feedback in our task, incorrect response selections were not readily apparent unless children adopted a prior strategy to facilitate goal management at intermediate levels of the hierarchy. Importantly, goals at higher levels of the sequence were both more abstract and temporally extended. In this sense, the younger children in this study demonstrated a strong tendency to direct their attention towards the most stimulus-implicit and intuitive outcome (the colouring activity). Monitoring such a focal goal is cognitively less demanding than keeping track of a distal and abstract outcome in addition to more intermediate steps of the sequence.

Alternatively, it may be argued that because of the relatively long response interval in this task, 3-year-olds performance may result from a mere failure to hold the goal state in memory. However, several points make this an unlikely explanation of the observed age differences in this study.

First, it should be noted that even the youngest participants had no difficulties recalling the task goal at any point throughout the sequence. A systematic decline in goal recall over time should be expected to parallel performance levels in terms of first observable divergence. However, while 3-year-olds departed from an accurate outcome from the earliest point within the sequence, goal recall was generally unaffected by the temporal dynamics in this task. Secondly, despite the fact that drawing parallels between task knowledge and verbal indicators can be misleading (see Munakata & Yerys, 2001), explicit verbal recall has been successfully used to assess toddlers' and preschool children's memory abilities in numerous tasks (e.g., Alloway, Gathercole, & Pickering, 2006; Bauer et al., 1998; Somerville, Wellman, & Cultice, 1983). Relatedly, Munakata and Yerys (2001) demonstrated that in a card-sorting paradigm 3-year-olds had considerable difficulty when answering questions that included conflicting task information (e.g., "Where do the red trucks go in the shape game?") but answered correctly on non-conflict trials. The authors interpret these findings within a framework of graded knowledge representation. From this viewpoint, relatively weak representations of the task space may suffice to answer non-conflict questions, but stronger representations of the rule are needed to tackle conflicting features when sorting cards and answering conflict questions. This points to a more general difficulty when faced with conflict. In our colouring task, however, neither the action measure nor the knowledge measure involved a comparable degree of conflict. In fact, our task does not bias performance in favour of any particular response (e.g., a particular strategy).

According to the conflict-monitoring hypothesis, the management of conflict can be conceived of as a negative feedback loop, composed of three sequential phases: (1) cognitive control, (2) evaluation of conflict, and (3) the intensification of cognitive control (Botvinick et al., 2001; see Chapter 1, Figure 1.2., p. 18). In relatively unpractised tasks a low level of cognitive control results in higher levels of conflict, and thus the engagement of more cognitive control. But this conflict-monitoring loop can only operate if the mismatch between the current performance and the overarching goal is detected. Inadequate evaluation of the conflict between the colouring activity and the task goal, may lead to the recruitment of insufficient top-down influences from the very outset of the task, despite preserving a good understanding of the goal state itself. The apparent random performance of most 3-year-olds in our task is therefore likely to result from a failure to detect discrepancies between the colouring activity and the higher-level goal. However, a failure to detect a mismatch between the desired and produced outcomes is not the same as being unable to hold the overarching goal in active memory. Children's direct recall of the colour criterion confirmed this hypothesis, suggesting that all preschoolers were aware of the overarching goal *per se*, yet failed to adjust actions at more sub-ordinate levels accordingly. The observation that actively representing the goal state is not sufficient to accomplish the task is in good agreement with the notion of young children's graded mental representations (e.g., Munakata, O'Reilly, & Morton, 2007; Munakata & Yerys, 2001).

Formal theories of cognitive control in conjunction with adult imaging data propose that a likely mechanism underling the evaluation of the need to adjust cognitive control resides within the anterior cingulate cortex (e.g., Botvinick, et al., 2001, Carter, et al., 1998; Carter, MacDonald, Botvinick, Ross, Stenger, Noll, & Cohen, 2000; Kim, Chung, & Kim, 2013, Shenhav, Botvinick, & Cohen, 2013). This view presupposes that the central function of cognitive control is conflict monitoring and further proposes that, at least in adults, ACC activation in rule-guided behaviour may reflect a mechanism estimating whether more or less top-down influence is needed as a function of the current level of conflict, rather than directly reflecting that cognitive control is currently exercised. Neuroimaging studies support this view by demonstrating that the strength of cognitive control engaged in tasks involving high levels of conflict is associated with increased neural activity recruited in frontal regions and ACC (e.g., Braver et al., 1997; Botvinick et al., 1999; Carter et al., 1998; 2000; Frith, Friston, Liddle, & Frackowiak, 1991; Kerns, Cohen, MacDonald, Cho, Stenger, & Carter, 2004). However, Carter et al. (2000) also demonstrated that when strategic processes were engaged, and thus control demands decreased, ACC activation declined suggesting that the observed pattern of activation specifically reflects an evaluation of the need for current control demands. While our data does not directly test this hypothesis, it is clear how the evaluation of the demand for sustained cognitive control plays a critical role in sequential behaviour.

The conflict-monitoring hypothesis therefore provides an interesting account for sequential tasks, like our colouring task, in which the demand for top-down influence in performance needs to be re-evaluated throughout the consecutive stages of the task. Precisely what the enhanced recruitment of cognitive control involves presumably depends on the particular task at hand. In the case of our colouring task one candidate would be the strengthening of goal representations and enhanced attention to strategy-compatible colours at each point of the sequence, and thus the reduction of competition from incompatible colours.

In contrast to 3-year-olds, 5-year-olds in this study endogenously detected the need to adjust top-down control in the face of conflicting information across multiple levels of abstraction. Older children overall seemed better able to retrieve goal relevant information from working memory and evaluate their actions in terms of goal attainment. In addition, it is plausible that 5-year-olds were better able to track the outcomes of their actions in terms of a particular strategy they adopted in this task. This last point becomes especially apparent when considering performances of those 3- and 5-year-olds who performed correctly in the beginning of the task and then departed from an accurate outcome in later stages of the sequence. It is clear that these children engaged in strategic action planning and even carried out initial actions accordingly. One possibility is that a failure to evaluate cognitive control demands at a particular point within the sequence resulted in a deficient regulation of actions. It is proposed that, at this point within the sequence children failed to allocate sufficient cognitive control resources to bias response selection towards proper mappings between the action output and the internal representations of superordinate goals. At the behavioural level this resulted in a mismatch between the performed outcome and intended goal, despite being able to recall the task goal itself.

Deviations from expected outcomes (e.g., reward prediction errors) are known to increase reliance on particular strategies over others (e.g., O'Reilly & Frank, 2006; Badre, Lebrecht, Pagliaccio, Long, & Scimeca, 2014). The neural mechanisms by which strategies are implemented and evaluated are not well understood. Subcortical activation in basal ganglia has been implicated in rule retrieval from memory systems and adjustments in top-down influence as a function of strategy efficiency. Specifically, tracking the efficiency of a particular retrieval strategy for goal-directed responding appears to be at least in part mediated by striatal activation (Badre, et al., 2014).

Looking at the developmental pattern of strategy use across our two experiments it appears that a cycling approach was the first strategy to be spontaneously implemented by the preschool children in our study. Despite the fact that a cycling strategy still failed to produce accurate outcomes for most 3-year-olds, 5-year-olds made use of this strategy very successfully to structure the problem space and ensure goal attainment. This observation is in good agreement with the wider problem-solving literature, reporting performance improvements during early childhood in tasks that require planning ahead and anticipating outcomes of the constructive units that make up action sequences (e.g. Jones, et al., 2003; Posner & Rothbart, 1998; Kaller, Rahm, Spreer, Mader, & Unterrainer, 2008; Welsh, et al., 1991).

Several computational models address the question of how adults manage competing sets of action strategies and decide when to create a new strategy to maximise action efficiency. Most notably, Collins and Koechlin (2012) proposed a model of human executive functions (PROBE) that predicts decision making and variations in strategy use in naturalistic situations. This recent model integrates several processes that have been implicated in the learning of complex strategies, such as task switching, expectedness of uncertainty, and reinforcement learning. Relating PROBE to individuals' performances on classic cognitive control tasks revealed that adults' monitoring capacities are limited to three to four concurrent behavioural strategies. The model further suggests that the formation of new strategies is based on the expected outcomes of currently active strategies. As such, adults infer and probe new behavioural strategies when those that are currently monitored fail to predict outcomes with sufficient reliability. Whether preschoolers form and adapt behavioural strategies through a similar mechanism of online monitoring is unclear. However, given that the internal mappings required for such a monitoring and updating system are implemented in distinct prefrontal brain regions and rely, at least in part, on information stored in long-term memory (e.g., see Collins & Koechlin, 2012 for a discussion of PROBE, its biological feasibility, and relevant neuroimaging evidence) it is likely that the control system undergoes a protracted development into adulthood.

Finally, the methodological approach taken in this manuscript offers a paradigm shift in preschool cognitive control research. Colouring-in is a naturalistic task typical of pre-school activities that can reveal a lot about planning and working memory updating within an ecologically valid context. This is arguably more than is offered by standard paradigms that rely largely on taxing the cognitive system with increasing conflict and competition using bivalent stimuli. Moreover, this type of approach negates the need to ask whether lab tasks scale up and intersect with daily behaviour since it draws directly on real-life behaviours.

In conclusion, it is the detection of conflict between response selection and higher-level goals that makes our task challenging for preschoolers. Children in both age groups demonstrated differential abilities to evaluate the demand for cognitive control in a continuous task in which perceptual cues to guide response selections were lacking. We conjecture that the ability to engage adequate cognitive control to support hierarchical action selection over extended time intervals improves during early childhood. This development is expected to impact on young children's abilities to engage in sequential tasks and to organize their actions in pursuit of increasingly abstract goals. How the behaviours observed here are linked to functional developments in other aspects of executive control remains an open question for future research.

In the next chapter we present a novel EEG paradigm that we used investigate the neurocognitive underpinnings of realistic goal perception across the preschool years and in adults. In this electrophysiological study we investigated the mechanisms that are implicated in the semantic integration of higher-level goals into a preceding event context.

CHAPTER 4

Convergent ERP and behavioural evidence of preschoolers' understanding of action goals

Understanding observed behaviour in terms of action semantics provides a structure to learn about a wide range of complex behaviours. How this ability develops across childhood is largely unknown. This study provides convergent EEG and behavioural evidence concerning the neural mechanisms underling realistic action comprehension. EEG was recorded whilst participants watched naturalistic videos of real life events, and was time-locked to the endings of complex action sequences. Prolonged midlatency event-related potentials (ERPs) were observed in response to unexpected event outcomes in both adults and two groups of preschoolers – an age over which substantial development in the control of goal-directed actions takes place. The findings of this study show that viewing a semantic violation of goal requirements elicits prolonged ERP negativities in adults, 5-year-olds, and 3-year-olds. As such, the results of this study indicate a functional role of ERP negativities in the analysis of visual events and are in good agreement with prior studies in adults. The present study suggests that even at the level of abstract goal integration strong incongruence effects are evident from an early point in development. However, while the time course of this effect was relatively comparable across development, the topographical distribution of ERP effects differed across adults and preschoolers. Linking brain activity to performance accuracies on a behavioural task further suggests that the semantic analysis of hierarchical behaviour is related to preschoolers' abilities to overtly judge actions in terms of higher-level goals.

4.1. Introduction

The notion of a strong functional link between the comprehension and production of goal-directed behaviour (e.g., Greenwald 1970, 1972; James, 1890; Lotze, 1952) is now supported by diverse and wide-ranging neuropsychological evidence (e.g., Helbig et al., 2006, 2010; Humphreys, Riddoch, Forti, & Ackroyd, 2004; Sitnikova et al., 2010). However, *how* the continuous flow of visual information is rapidly integrated into higher-level representations of meaning is largely unknown. The aim of this study was to investigate the electrophysiological underpinnings of everyday action processing across development. Specifically, we asked whether there are distinct event-related potentials (ERPs) evidenced in response to unexpected action endings that relate to how preschool children make inferences about complex goal-directed events.

One of the hallmarks of the preschool period is the ability to rapidly learn from observed behaviour and transfer this knowledge to novel situations (e.g., Whiten, Custance, Gomez, Teixidor, & Bard, 1996). Comprehension of simple and complex events is informed by past experience and is influenced by the specific context in which actions take place. In everyday environments, observers tend to entertain expectations about how observed events typically unfold given a particular action context. This context dependent view of meaning construction has received much attention from developmental researchers, and it has become apparent that even young infants seem to integrate contextual information flexibly into their understanding and prediction of action events (e.g., Gergely & Csibra, 2003; Wood et al., 2007). Indeed, in action comprehension, mutually constraining top-down and bottom-up processes shape our understanding and expectation of observed goal-directed behaviour from an early point in development (e.g., Baldwin, Baird, Saylor, & Clark, 2001; Pace, Carver, & Friend, 2013).

Recent neuroscientific evidence from adults strongly suggests a bi-directional relationship between the computation of language and action events (see Kiefer et al., 2011; Kiefer & Pulvermuller, 2012). In particular, ERP studies that typically examine the construction of meaning within the linguistic domain (e.g., N300, N400 & P600 ERP components) have recently been adapted to study the build-up of meaning in everyday action comprehension (e.g., Sitnikova et al., 2003, 2008, 2010; Reid & Striano, 2008). In particular, the N400 component, traditionally associated with the semantic integration of verbal stimuli into a preceding context (see Kutas & Hillyard, 1980a, 1980b) appears to be also evoked by action-related contextual processes. While the linguistic N400 and the action-evoked N400 share characteristics in latency and waveform, there are also important differences in the topographical distributions (see Amoruso et al., 2013 for a discussion of the parallels between the classic N400 and the action-N400).

In one of the earliest such studies, Sitnikova et al. (2003) observed robust N400-like effects over frontal and central sites as a result of presenting adult participants with video demonstrations of common actions carried out with inappropriate objects (e.g., shaving with a rolling pin). In line with this finding, Reid and Striano (2008) found increased N400-like effects over frontal, central and parietal brain region as a result of presenting subjects with unanticipated event endings compared to anticipated endings (e.g., bringing a spoon to the mouth with food vs. without food). In addition, Proverbio and Riva (2009) presented adult participants with realistic pictorial stimuli depicting a wide range of meaningful or meaningless activities, and observed enhanced frontally distributed N400-like effects in response to actions lacking an interpretable goal (pseudoactions). Moreover, in an action-sentence-compatibility paradigm (Glenberg & Kashal, 2002), Balconi and Caldiroli (2011) found frontal and central N400 effects in response to inappropriate object selection, as well as when action matching objects were used inappropriately in terms of their instrumental properties. Taken together, these findings suggest both functional similarities and differences between action-related and linguistic N400 effects. Although little is known about the neural sources of the action-N400 per se, it is likely that semantic processing of everyday actions takes place in a distributed neural network that is open to both verbal and non-verbal material (e.g., Amoruso et al., 2013).

In summary, growing neurocognitive evidence suggests that midlatency ERPs such as the action-N400 are relatively robust electrophysiological markers indexing semantic context-embedded processing of verbal and non-verbal material in adults. Similar to the action-N400, the N300 component is thought to reflect semantic processing (e.g., Barrett & Rugg, 1990; Holcomb & McPherson, 1994; McPherson & Holcomb, 1999) and is further associated with object identification (e.g., Doniger et al., 2000; Schendan & Kutas, 2002; Ganis & Kutas, 2003; Folstein et al., 2008). In addition, some previous studies identified a late posterior positivity (LPC) in response to incongruent event outcomes compared to congruent scenes (e.g., Sitnikova et al., 2003). In the next section we turn to recent developmental evidence of these action-related ERPs.

4. 1.1. Action-related ERP studies across development

Electrophysiological studies focusing on everyday actions have investigated whether adults and infants exhibit sensitivity towards violations of rationality in terms of physical laws (e.g., Jastorff, Clavagnier, Gergely, & Orban 2010), outcomes (Proverbio & Riva, 2009; Reid & Striano, 2008), and choice of means with which an action is executed (e.g., Balconi & Caldiroli, 2011; Brass, Schmitt, Spengler & Gergely, 2007; Reid, Hoehl, Grigutsch, Groendahl, Parise, & Striano, 2009; Sitnikova et al., 2003). In fact, infants' and toddlers' expectations about familiar actions have been assessed using a wide range of tasks that vary considerably in the degree to which they require higher-level representations of the presented events.

Elementary forms of rationality are likely to be based on appreciations of physical laws and the kinematics involved in, e.g., reaching over a barrier (trajectory and velocity), whereas more complex analysis of the visual input is needed when assessing the affordance of an object and the motivations behind an agent´s choice of means. Given that boundaries of lower-level information also coincide with higher-level goal attainment (e.g., Newtson & Engquist, 1976; Zacks & Tversky, 2001), it is sometimes unclear whether sensitivity to rationality violations in young toddlers and infants reflects an early understanding of the goal and means-end relations, or simply increased processing due to the perceptual salience of the non-rational event. For instance, when bringing a cup of tea to the ear rather than the mouth (see Reid et al., 2009), the deviation in path trajectory produces a perceptually salient mismatch between the expected and observed outcome. This initial detection of unexpected occurrences based on perceptual features alone may then be followed by deeper analysis of the action context, thus generating alternative explanations for the observed behaviour. This hypothesis is supported by electrophysiological evidence in adults who appear to show two spatiotemporally distinct patterns of activation in response to disruptions of novel events (Pace & Friend, 2013). Findings suggest that adults rely on an early mechanism for perceptual analysis (peaking around 50-150ms after stimulus onset) when detecting action disruptions, as well as a later mechanism (250-350ms) indicating conceptual processing of event information. It is this latter component that shares characteristics with the linguistic N400 and N300. Interestingly, when Pace et al. (2013) compared ERPs from adults to data from 24-month-old toddlers, disrupted events still elicited more negative waveforms than completed actions, but no distinct peaks were found. Although Pace et al. did not investigate action processing in terms of rationality per se, irrelevant actions can be perceived as disrupting the ongoing stream of behaviour.

In the current study, EEG was recorded while two groups of preschoolers (3- and 5-year-olds) and adults viewed video clips of common scenarios (e.g., making a cup of tea, watering a plant, and applying toothpaste to a toothbrush). All objects presented in the videos fit a broader action context (e.g., beverage preparation, household task, bathroom activities). Unexpectedness of outcomes resulted from the mismatch between the final actions with its prior event context. Changes in electrophysiological activity elicited by video stimuli provide a naturalistic measure to study the neurocognitive processes involved in young children's comprehension of realistic everyday actions.

Beyond the use of naturalistic video clips, four main characteristics set the current study apart from prior developmental works. First of all, we took into account the sequential nature of realistic events by presenting participants with event sequences composed of three subsequent sub-actions. Secondly, all events in this study convey common real-world actions, in contrast with previous developmental studies using novel and abstract events. Thirdly, we manipulated goal requirements in this study while keeping the perceptual salience comparable across conditions. Previous studies presented perceptually salient manipulations of rationality (e.g., bringing a spoon to the forehead), which made lower-level analyses of motion trajectories a likely candidate mechanism to rapidly identify the mismatch between expected and perceived action outcomes. Finally, in the current study, congruent action endings fit the preceding event sequence semantically, whereas incongruent endings do not match the event context. However, in contrast to previous works in which outcomes were presented or implied on congruent trials but were completely lacking in the non-matching condition, we present clear outcomes in both conditions. All stimuli therefore differ uniquely in terms of the congruency of outcomes with respect to the specific event context.

To investigate the development of mechanisms underlying the semantic analyses of sequential actions, we recorded adults and preschoolers ERPs in a task that required the passive viewing of various event sequences. Following this test session, 3- and 5-year-olds engaged in an additional behavioural task, in which actions had to be explicitly related to higher-level outcomes[10]. We hypothesized that incongruent event endings would elicit more negative midlatency ERPs compared to contextually matching outcomes linked to the increased semantic processing efforts provoked by nonmatching scenes. In addition, we expected that adults and preschoolers would

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[10] Only preschoolers were tested on the picture-matching task as ceiling effects of adults' performance accuracies emerged during piloting.

overall show comparable ERP latencies as a result of incongruence effects. Finally, we anticipated that young children's behavioural accuracies and reaction times (RTs) on the picture-matching task would relate to the semantic mechanisms reflected in the N300/N400 mean amplitudes.

4.2. Methods

4.2.1. Participants

Adults were recruited through the departmental database of volunteers, an electronic platform for research volunteers. Parents of preschool participants were contacted through the Babylab database. All participants were native English-speakers, had normal or corrected-to-normal vision, and a gestational age ranging from 38 - 42 weeks. The final samples constituted 12 adults (*M* = 28.7 years, *SD* = 6.2, 5 female). In total 46 preschoolers were recruited for this study, however, 15 children (nine 3-year-olds, and six 5-year-olds) were excluded from analyses due to excessive movement or fussiness. Thus, the final sample of preschoolers comprises data of 16 3-year-olds (*M* = 41.2 months, *SD* = 5.7 months, 10 female) and 15 5-year-olds (*M* = 64.8 months, *SD* = 6.1 months, 7 female). Formal consent was obtained from adults and caregivers, and preschoolers verbally agreed to take part. Adults of child participants were refunded for travel expenses and children received small gifts (*Babylab* t-shirts, stickers, bags).

4.2.2. Materials and procedure

The *EEG stimuli* consisted of video clips of three real-life events: watering flowers, making a cup of tea, and applying toothpaste to a toothbrush (Figure 4.1). Each event was comprised of three sequential actions. Actions one and two set up the specific action context of the event. Action three represented the outcome of the event, which was either (1) congruent, relative to the preceding event context, or (2) incongruent, and thus potentially semantically mismatched the observer's predictions. All participants viewed both outcomes of all events resulting in six distinct stimuli presented at random. It should be noted that *congruency* was thus dependent on the predicted overarching goal of each event, rather than whether the objects manipulated were contextually relevant or used appropriately in terms of their instrumental properties.

Stimuli were filmed with a digital camera (Canon HF R60) and were transformed into short silent clips of equal length (4.5 seconds) using a video editing software (Final Cut Pro, Apple Inc.). To overcome issues with time-locking, a blank frame was introduced before the onset of the final action. The appearance of this blank screen was similar to an occluder in the sense that it occluded the end of Action 2 and the scene reappeared at the first frame of either a congruent or incongruent outcome (critical frame). It was thus not possible to anticipate whether a trial would end in a congruent or incongruent outcome before the appearance of the critical frame. For each event sequence, blank screens were adjusted in luminance by calculating the mean luminosity between the last frame of Action 2 and the first frame of Action 3.

All actions were cantered in the middle of the scene. ERP's were then time-locked to the onset of the critical frame.

Participants were seated in a dimly lit room approximately 30 inches away from a 20-inch monitor screen. Instructions were simply to view the videos.

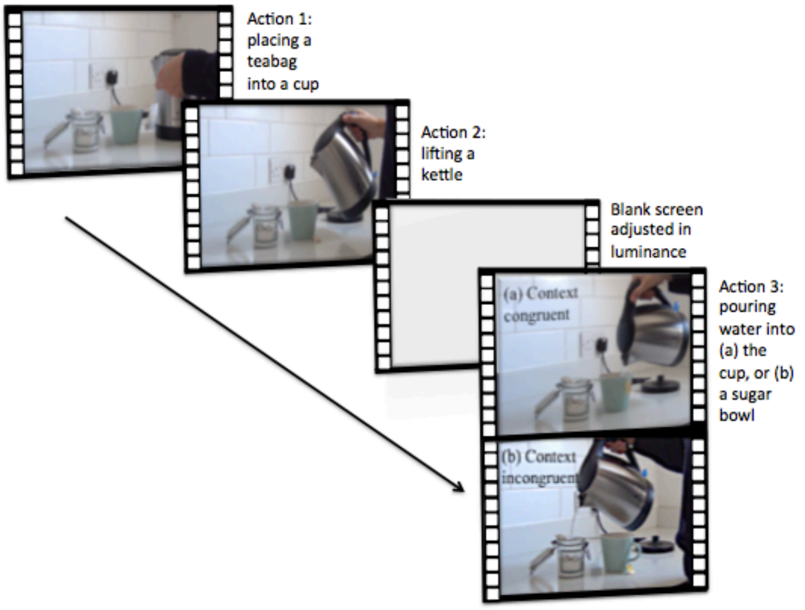

Figure 4.1. Example of event sequence presented in the EEG task. Still frames taken from video stimuli representing consecutive sub-actions of a common event sequence. (a) Example of stimuli display ending in a context congruent and (b) incongruent outcome.

Stimuli in the *behavioural task* consisted of 44 black and white picture drawings (see Figure 4.2). On each trial, a picture illustrating an action (e.g., baking) was first presented on the screen for 4 seconds. This drawing then disappeared and a second picture was presented in the centre of the screen, illustrating outcomes that either matched (e.g., cake) or mismatched (e.g., scarf) the action depicted in the preceding picture. This picture remained on the screen until the children had decided on the relatedness of each pair of drawings by means of a key press. Stimuli were presented on a 15-inch Macintosh laptop. Keys were highlighted with large colour stickers. Children were instructed to press the green key for matching and the red key for non-matching actions and action goals. Prior to testing children also received two practice trials. Reaction times and response accuracies were recorded for later analyses. All children performed a total of 22 test trials equally composed of matching and mismatching picture pairs presented at random.

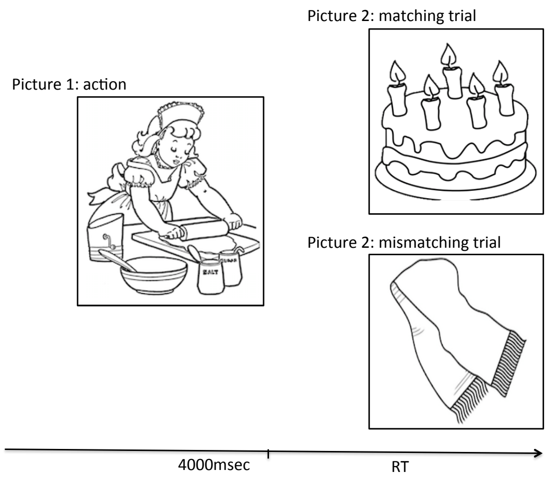

Figure 4.2. Picture-matching task. Example of pictorial stimuli used in the behavioural task. A first picture illustrated common household actions (Picture 1). Preschoolers indicated with a key press whether this action related to the outcome presented on a second picture (top right: matching trial, bottom right: mismatching trial). Response times and accuracies served as measures on this decision-making task.

2.3. ERP Recording and Analyses

All testing was video recorded and synched with the electrophysiological signal. Continuous EEG was recorded from 128 electrode Geodesic Sensornets (EGI Inc., Eugene, Oregon) at a sampling rate of 500Hz (see Figure 4.3). The continuous data was low (40Hz) and highpass (1Hz) filtered offline, segmented into 1100ms long segments (200ms before and 900ms after the onset of the critical frame), and inspected offline for artifacts. First, three different algorithms were used to detect eye movements, eye blinks, and bad channels. Moving averages of 80ms were performed for these three operations. The difference between fast and slow running averages of channel amplitudes were measured and compared to detect bad segments. Channels in which activity fell outside the 200µV range on 20% of the trials were automatically marked as bad. For vertical and horizontal eye channel deviations, amplitude differences between eye channels were calculated and compared against a voltage threshold. Amplitudes that exceeded the 140µV range were marked as blinks (high frequency noise). Amplitudes that deviated from a 55µV range were considered eye movements (low frequency drifts). All segments containing eye movements, blinks, and numerous bad channels were excluded from further data processing.

ERP segments were visually inspected for further artifacts as well as participant's visual attention and accepted or rejected on a segment-by-segment basis. On average, adults provided 30 clean attended trials (*SD* = 2.05) and preschoolers 13 (*SD* = 3.01)[11]. After bad channel replacement and re-referencing to the average electrode, the signal was baseline corrected using a 200ms baseline.

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[11] Because of technical, practical, and ethical issues in recording child data, difference in trial number are not unusual. In fact, infant and child ERPs evoked with a minimum number of trials, are frequently contrasted with ERPs obtained with considerably higher number of trials in adults (e.g., Handy, 2004). Importantly, the average numbers of trials were comparable in 3-year-olds and 5-year-olds in this study, suggesting that preschoolers' ERPs were affected by similar signal-to-noise ratios.

To assess the validity of the three event sequences in this study, segments corresponding to distinct actions were first averaged for each participant, then a grand average was computed across participants in each age group, and compared visually by overlapping the grand average from distinct actions in each condition. This visualization of distinct actions revealed that the overall pattern of ERP averages was comparable for all events. Therefore, individual actions were combined into either congruent or incongruent event sequences. Finally, a grand average with two categories (congruent / incongruent) was computed for each age group.

For the selection of time windows a strong hypothesized approach was adopted. Based on prior work using video recording of real-life actions in adults (Sitnikova et al., 2003, 2008), ERP mean amplitudes were extracted for three consecutive time windows of interest: (1) one time window corresponding to the N300 component (250-350ms post the onset of the critical frame), (2) one time window corresponding to the action-N400 component (350-600ms), and (3) one late time window corresponding to a late positive component (600-900ms). For preschoolers the midlatency time window was adjusted by 100ms (450-650ms), because prior works suggest a considerable delay in the infant and toddler action-N400[12]. In addition, an early time window corresponding to the visual N1 component (150-200ms) was analysed at frontocentral sites.

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[12] Previous works used a 600-800ms time window for 9-month-olds (e.g., Reid et al., 2009).

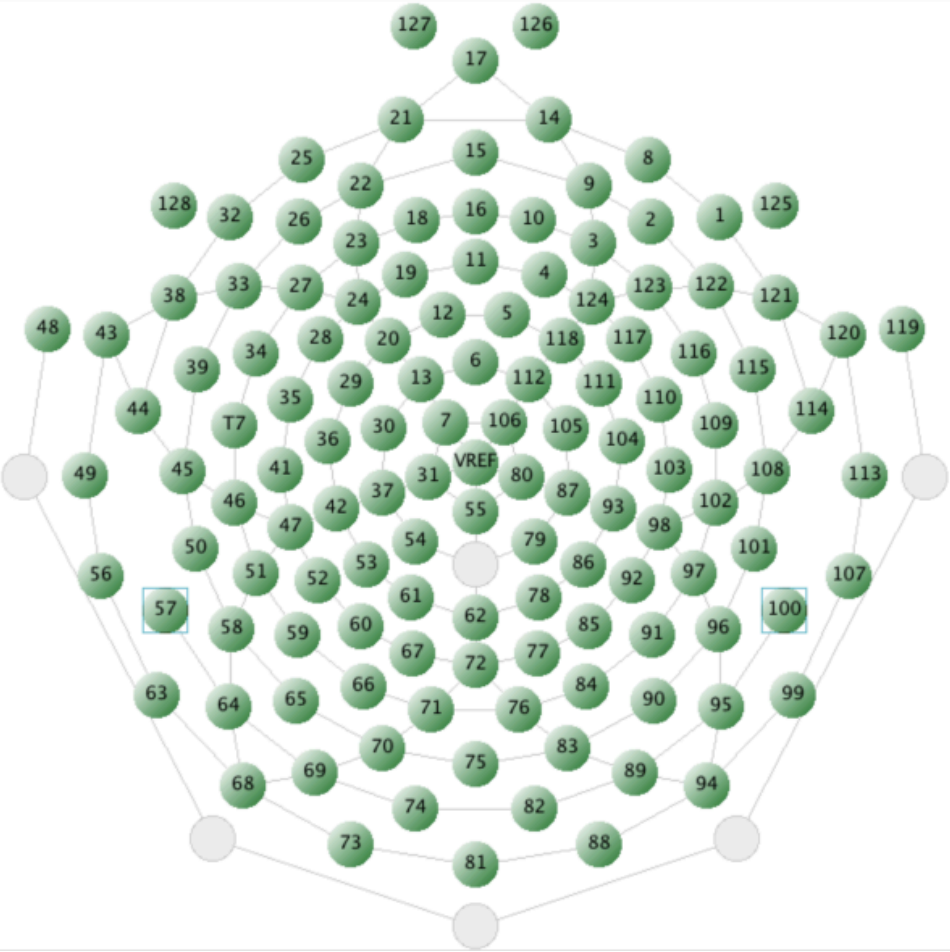

Figure 4.3. Electrode montage 128 high-density Geodesic Sensornet (EGI Inc., Eugene, Oregon).

3. Results

Prior analyses revealed no significant ERP differences elicited by the three distinct actions within each condition in adults and each group of preschoolers [13]. Because prior research of nonlinguistic action processing suggests that the construction of meaning takes place in a distributed network including frontal, lateral, and posterior sites (see Amoruso et al., 2013) planned analyses of a relatively broad scalp distribution were conducted. Mean amplitudes were averaged and statistically compared across left, midline, and right channels at fronto-central and centro-parietal scalp regions, with Condition (congruent / incongruent) and Site (left / midline / right) as within-participant factors. The results of separate analyses of variance for repeated measures are presented below. To correct for violations of the assumption of sphericity, a Greenhouse-Geisser adjustment was applied to the degrees of freedom (original df reported). Paired-sample t-tests with Bonferroni adjusted alpha levels were conducted to follow-up significant effects. Table 4.1 summarizes the results of the statistical analyses for adults and pre-schoolers respectively.

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[13] Mean amplitudes evoked by distinct actions were analyzed in a subset of 5 participants per age group. Data was extracted and analyzed using a mid-latency time window of 350-600ms post stimuli onset for adults and 450-650ms post stimuli onset for preschoolers.

Table 4.1.

Results of statistical analyses (F values) contrasting ERPs time-locked to the first frame of congruent and incongruent final actions in adults (n = 12), 3-year-olds (n = 16), and 5-year-olds (n = 15).

Age	*Region (number of electrodes)*	*Contrast*	*250-350 msec (N300)*	*350-600 msec (N400)*	*600-1000 msec (LPC)*
Adults	Fronto-	C	9.273**	22.389**	9.175**
	central	C x S	n.s.	16.470**	24.186**
	LH (24)	C	3.363**	3.315**	2.596*
	CZ (12)	C	2.798**	4.185**	2.638*
	RH (24)	C	n.s.	5.480**	6.957**
3-years-	Centro-	C	4.838*	6.665*	4.730*
olds	parietal	C x S	n.s.	6.686*	7.188**
	LH (19)	C	n.s.	n.s.	n.s.
	CZ (8)	C	2.279*	3.147**	2.503*
	RH (19)	C	2.343*	2.846**	2.914**
5-years-	Centro-	C	8.014**	17.845**	24.927**
olds	parietal	C x S	4.692*	6.922*	6.555**
	LH (19)	C	3.161**	2.511*	2.779**
	CZ (8)	C	2.918**	5.298**	5.168**
	RH (19)	C	n.s.	2.713**	4.282**

Note: LH = left hemisphere, CZ = midline region; RH = right hemisphere; C = main effect of congruency, df = 1, 11; C x S = Congruency x Site interaction, df = 2, 22 for adults. C = main effect of congruency, df = 1, 14 for 5-year-olds and df = 1, 15 for 3-year-olds; C x S = Congruency x Site interaction, df = 2, 30 for 3-year-olds and df = 2, 28 for 5-year-olds.

*p < .05, **p < .01

4.3.1. Adults

Early visual N100

Multivariate analyses did not yield significant effects for Condition within the 150ms - 200ms time window.

Early component and N300

A repeated-measures ANOVA revealed a significant effect for Condition at fronto-central scalp regions ($F(2, 22) = 9.27$, $p < .01$, $\eta_p^2 = .46$). Follow-up tests indicate that mean amplitudes were significantly more negative in response to incongruent final actions at left hemisphere ($t(11) = 3.36$, $p = .006$, $M = -3.06$, $SD = 1.59$) and midline sites ($t(11) = 3.36$, $p = .01$, $M = -3.43$, $SD = 2.82$) relative to congruent action endings (left: $M = -1.49$, $SD = 1.27$; midline: $M = -2.27$, $SD = 2.07$).

At centro-parietal regions a main effect for Condition ($F(2, 22) = 9.27$, $p < .01$, $\eta_p^2 = .46$) suggested the reverse pattern. Follow-up analyses indicated that this effect was driven by congruent endings, which evoked less positive mean amplitudes at right hemisphere ($t(11) = 3.27$, $p = .01$, $M = 1.35$, $SD = 1.47$) and midline sites ($t(11) = 4.09$, $p = .01$, $M = 2.78$, $SD = 1.92$) compared to incongruent final scenes (right: $M = 2.90$, $SD = 1.74$; midline: $M = 4.19$, $SD = 2.31$).

Midlatency component and N400

At fronto-central regions, a repeated-measures ANOVA revealed a main effect for Condition ($F(2, 22) = 22.39$, $p = .001$, $\eta_p^2 = .67$) as well as a significant interaction between Condition and Site ($F(2, 22) = 16.47$, $p = .001$, $\eta_p^2 = .77$). Planned comparisons suggest that this interaction was driven by significant differences across hemispheres. At left electrodes sites congruent outcomes elicited more negative amplitudes (*M* = -1.46, *SD* = .67) than incongruent trials (*M* = -.47, *SD* = 1.25). At right hemispheres and midline sites, however, incongruent scenes resulted in a highly significant increases in amplitude negativity (right: *t*(11) = 5.48, $p < .001$, *M* = -4.61, *SD* = 3.04; midline: *t*(11) = 4.19, $p = .002$, *M* = -3.99, *SD* = 2.85) compared to congruent actions (right: *M* = -.77, *SD* = 1.59; midline: *M* = -1.71, *SD* = 1.76). Figure 4.3a illustrates the combined mean amplitudes for fronto-central channels.

At centro-parietal scalp regions, mean amplitudes were significantly less positive in response to congruent final endings *F*(2, 22) = 14.94, $p = .003$, $\eta^2_p = .58$, (left: *t*(11) = 3.82, $p = .003$, *M* = 1.78, *SD* = 1.03; midline: *t*(11) = 3.71, $p = .003$, *M* = 2.01, *SD* = 1.35, right: *t*(11) = 3.12, $p = .01$, *M* = 1.41, *SD*= 1.18) compared to incongruent final scenes (left: *M* = 3.49, *SD* = 1.74; midline: *M* = 4.42, *SD*= 2.78, right: *M* = 2.85, *SD*= 1.42).

Late component and LPC

A significant effect for Condition (*F*(2, 22) = 9.18, $p = .01$, $\eta^2_p = .46$) as well as a Condition x Site Interaction (*F*(2, 22) = 33.39, $p < .001$, $\eta^2_p = .75$) was observed at fronto-central sites, with enhanced mean amplitude positivity evoked by congruent outcomes at right electrode sites (*t*(11) = 6.96, $p < .001$, *M* = -0.44, *SD* = 1.31) compared to incongruent final scenes (*M* = -2.97, *SD* = 1.85). No main effects or interactions were observed at centro-parietal channels.

4.3.2. 3-year-olds

Early visual N100

There was no significant difference between conditions 150ms - 200ms post onset of the critical final actions at frontocentral sites.

Early component and N300

Multivariate tests revealed that ERP mean amplitudes at centro-parietal electrode sites significantly differed in terms of Condition (*F*(2, 15) = 4.84, *p* = .04, η_p^2 = .24). However, comparing the effect of Condition across sites yielded significant results (given the conservative alpha levels) at midline (*t*(15) = 2.28, *p* = .03) and right hemisphere electrodes (*t*(15) = 2.34, *p* = .03). Mean values in this time window indicate that incongruent outcomes evoked overall larger mean amplitude negativity (left: *M* = -2.47, *SD* = 6.59; midline: *M* = 2.11, *SD* = 6.63, right: *M* = -1.45, *SD* = 5.66) than congruent final actions (left: *M* = 0.68, *SD* = 5.33; midline: *M* = 6.49, *SD* = 6.26, right: *M* = 2.25, *SD* = 5.31).

Midlatency component and N400

In the time window corresponding to the action-N400, mean amplitudes measured at centro-parietal scalp regions significantly differed as a function of Condition, *F*(2, 15) = 6.66, *p* = .02, η_p^2 = .31 (Figure 4.3b). In addition, analyses revealed a significant interaction between Condition and Site *F*(2, 30) = 6.69, *p* = .01, η_p^2 = .31. Follow-up analyses yielded significant effects only at midline (*t*(15) = 3.14, *p* = .007) and right hemisphere sites (*t*(15) = 2.84, *p* = .01), with incongruent action endings eliciting more ERP negativity (midline: *M* = 1.01, *SD* = 7.53, right: *M* = -1.59, *SD* = 6.23) than congruent outcomes (midline: *M* = 7.35, *SD* = 7.92, right: *M* = 3.39, *SD* = 6.88).

Late component and LPC

In the 600-900ms epoch, congruous final actions evoked a significant mean amplitudes positivity across centro-posterior sites, as suggested by a significant interaction effect between Condition and Site, *F*(2, 30) = 7.19, *p* = .006, η^2_p = .32. There was also a significant main effect for Condition, *F*(2, 15) = 4.73, *p* = .04, η^2_p = .24. Follow-up analyse indicated midline (*t*(15) = 2.51, *p* = .02) and right-lateralization (*t*(15) = 2.91, *p* = .01) of this late positivity in response to congruent action endings (midline: *M* = 4.31, *SD* = 4.51, right: *M* = 2.24, *SD* = 4.08) compared to incongruous final actions (midline: *M* = 0.03, *SD* = 6.67, right: *M* = -1.72, *SD* = 4.53).

4.3.3. 5-year-olds

Early visual N100

No significant effects were observed in the early perceptual/sensory time-window at frontocentral sites.

Early component and N300

A significant effect for Condition was observed at centro-parietal regions in the N300 time-window (*F*(2, 14) = 8.01, *p* = .01, η^2_p = .36). Follow-up comparisons revealed that incongruent action endings evoked significantly more negative mean amplitudes at midline (*t*(14) = 2.91, *p* = .01, *M* = 5.75, *SD* = 1.31) and left (*t*(14) = 3.16, *p* = .007, *M* = -0.13, *SD* = 4.56) electrode sites than final actions that were congruent in terms of the preceding action context (midline: *M* = 11.57, *SD* = 9.95, left: *M* = 2.61, *SD* = 4.01). No significant differences were observed at fronto-central brain regions.

Midlatency component and N400

In the midlatency time window (Figure 4.3c), a significant effect was observed at centro-parietal channels for Condition (*F*(2, 14) = 17.84, $p = .001$, $\eta^2_p = .56$) as well as a significant interaction between Condition and Site (*F*(2, 28) = 6.92, $p = .009$, $\eta^2_p = .31$). Further analyses revealed overall a higher degree of mean amplitude negativity in response to incongruent outcomes (left: *M* = 2.11, *SD* = 4.20; midline: *M* = 8.49, *SD* = 7.89, right: *M* = 5.85, *SD* = 5.49) than congruent final scenes (left: *M* = 4.09, *SD* = 4.63; midline: *M* = 13.55, *SD* = 7.58, right: *M* = 8.52, *SD* = 4.52). This difference in mean amplitude reached statistical significance at left (*t*(14) = 2.51, $p = .02$), midline (*t*(14) = 5.29, $p < .001$) and right electrode sites (*t*(14) = 2.71, $p = .01$).

Late component and LPC

There was a significant effect for Condition (*F*(2, 14) = 24.92, $p < .001$, $\eta^2_p = .64$) as well as a significant interaction effect between Condition and Site (*F*(2, 14) = 6.55, $p = .007$, $\eta^2_p = .32$) at centro-parietal scalp regions. Planned comparison indicated that congruent action outcomes elicited significantly more positive mean amplitudes at all electrode sites (left: *M* = 3.22, *SD* = 2.97; midline: *M* = 8.78, *SD* = 4.78, right: *M* = 6.31, *SD* = 3.03) relative to incongruent final scenes (left: *M* = 0.93, *SD* = 3.46; midline: *M* = 3.38, *SD* = 4.95, right: *M* = 2.87, *SD*= 3.02)

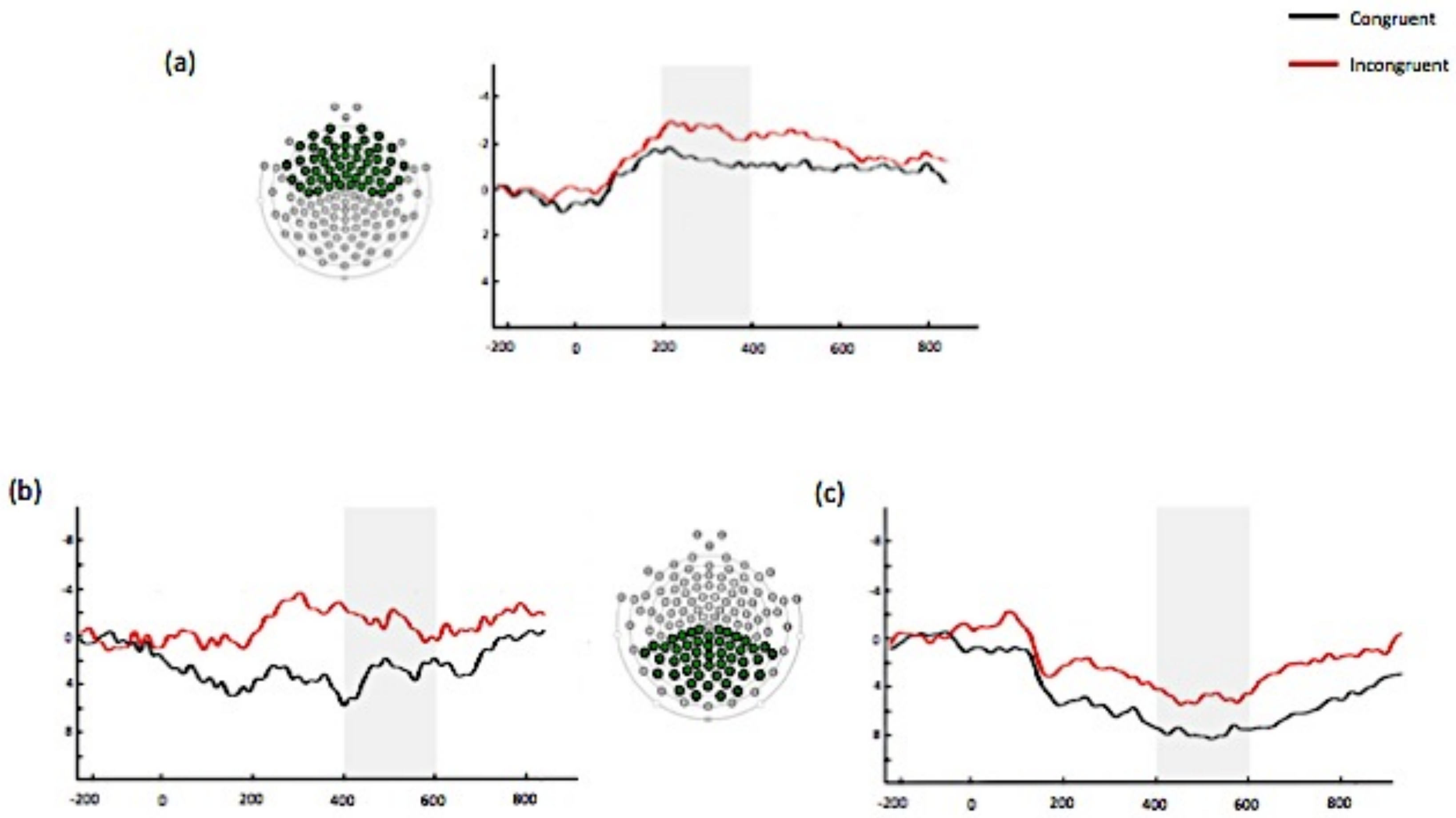

Figure 4.4. Combined mean amplitudes at (a) fronto-central channels in adults, and centro-parietal channels in (b) 3- and (c) 5-year-olds. Graphs represent b activity recorded at multiple electrode sites in response to the presentation of congruent and incongruent critical frames and 200ms preceding these events. Highlighted areas (grey) correspond to the N400 time-windows for adults and preschoolers.

4.3.4. Behavioural results

Behavioural performance on the picture-matching task was assessed in terms of accuracy levels (number of correct responses) and reaction times across age groups, and within groups as a function of condition and overall performance level. In what follows, separate sets of analyses for overall accuracy and reaction time measures will be discussed. Thereafter, behavioural results will be integrated to provide a comprehensive overview of performance on this task and in each group of participants. Finally, behavioural results will be linked with results from ERP measures and the theoretical importance of this relationship will be discussed.

4.3.4.1. Overall accuracy

To assess group differences on the picture-matching task in terms of Accuracy (the mean count of correct trials) and Reaction time, an initial multivariate analysis of variance was conducted controlling for high vs. low performances levels (below median score / above median score). The cut-off between low and high scores (Performance level) was 18 accurate trials/22 for 3-year-olds and 20 accurate trials/22 for 5-year-olds. Splitting the data into low (n = 15) and high (n = 16) scores based on group medians permitted comparisons of measures while taking into account broader developmental trends (e.g., high performing 3-year-olds tend to have mean accuracies of nine correct trials in each condition, as do low performing 5-year-olds).

Preliminary assumption testing was conducted to assess homogeneity of variance-covariance matrices, multicollinearity, normality, linearity, univariate and multivariate outliers. Bonferroni adjusted alpha levels of .025 were used for all separate analyses.

Results indicated no serious violations of multivariate assumptions. A statistically significant main effect for Age, $F(2, 26) = 6.01$, $p = .001$, $\eta^2_p = .41$, with 5-year-olds achieving overall higher Accuracy scores ($M = 20.13$, $SD = 1.36$) than 3-year-olds ($M = 17.13$, $SD = 2.83$) was observed. Table 4.2 summarizes the mean values across high and low Performance levels in both age groups. Follow-up univariate tests revealed that the only difference to reach significance between groups was the number of correctly performed trials in the matching condition ($F(1, 27) = 10.55$, $p = .003$, $\eta^2_p = .28$). No significant effects for Age were observed on non-matching trials. Within groups, inspection of the Accuracy means confirmed that the overall lowest scores were obtained by low-performing 3-year-olds in response to matching trials ($M = 6.56$, $SD = 2.61$), while high-performing 3-year-olds reached comparable scores across matching ($M = 9.43$, $SD = .79$) and non-matching trials ($M = 9.71$, $SD = .95$).

The observation that group differences in Accuracy were driven by performance on matching trials was further supported by a simple effect of Performance level, $F(2, 26) = 11.04$, $p < .001$, $\eta^2_p = .46$. When performance levels were considered separately, only matching trials yielded statistically significant differences ($F(1, 27) = 11.67$, $p = .001$, $\eta^2_p = .20$), suggesting that mean scores were relatively comparable across low- and high-performers on non-matching trials but substantially differed in the matching condition.

Table 4.2.

Performance accuracy on the picture-matching task

	Age	Performance Level	Mean	SD	N
Accuracy on matching trials	3-year-olds	below median accuracy	6.56	2.60	9
		above median accuracy	9.43	.78	7
	5-year-olds	below median accuracy	9.33	.81	6
		above median accuracy	10.33	.70	9
	Total	below median accuracy	7.67	2.46	15
		above median accuracy	9.94	.85	16
Accuracy on non-matching trials	3-year-olds	below median accuracy	9.00	2.23	9
		above median accuracy	9.71	.95	7
	5-year-olds	below median accuracy	9.50	.83	6
		above median accuracy	10.78	.44	9
	Total	below median accuracy	9.20	1.78	15
		above median accuracy	10.31	.87	16

Note: Descriptive statistics for Accuracy across Conditions and Performance levels. Performance levels represent high and low scores in each age group. Low and high performance levels correspond to scores below and above the median accuracy values respectively. The cut-off between performance levels was a score of 18 correct responses in 3-year-olds and 20 correct responses in 5-year-olds. The maximum of correct responses is 11 on matching and non-matching trials, corresponding to a total of 22 trials on the picture-matching task. SD = standard deviation.

4.3.4.2. Reaction times

Initial visual inspection for outliers resulted in the exclusion of one participant in each age group. For follow-up tests, an adjusted alpha level of .025 was used. First, reaction time mean scores were grouped and compared in terms of Condition (matching / non-matching) and Age (3 years / 5 years), yielding a significant effect of Age (F (1, 26) = 10.13, p = .004, η^2_p = .28). Mean scores indicate that overall 5-year-olds showed faster reaction times (M = 2.12 sec., SD = .42 sec.) than 3-year-olds (M = 2.90 sec., SD = .82 sec.). Follow-up univariate tests controlling for Performance level [14] revealed that within age groups, children with low Performance levels demonstrated significantly slower RTs (3-year-olds: M = 3.47 sec., SD = .73 sec.; 5-year-olds: M = 2.36 sec., SD = .36 sec.) than high performers (3-year-olds: M = 2.13 sec., SD = .41 sec.; 5-year-olds: M = 1.89 sec., SD = .31 sec.), F (1, 26) = 13.66, p > .001, η^2_p = .34. In contrast, no significant effect was observed when taking into account the correctness of responses within each condition (i.e., whether a correct or incorrect response was made within matching / non-matching trials). Thus, this analysis suggests that children who achieved high levels of overall accuracy had faster RTs, but there was no indication that reaction times differed in respect to trials that then resulted in correct and incorrect responses. In other words, those children who performed better on the task overall, were also faster to execute their response choices irrespective of whether this selection then resulted in a correct or incorrect outcome. Table 4.3 summarises RTs in terms of Condition and Accuracy.

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[14] Performance levels were defined by the same median cut-off used for Accuracy analyses (18 and 20 correct trials for 3- and 5-year-olds respectively).

Table 4.3.

Descriptive Statistics: reaction times and accuracy on the picture-matching task for 3- and 5-year-olds (N = 29).

	3-year-olds (n = 16)			5-year-olds (n = 15)		
Variables	**M**	**SD**	**Range**	**M**	**SD**	**Range**
Mean RTs all correctly answered trials	2.85	.87	1.68 - 4.45	2.08	.41	1.54 – 2.77
Mean RTs all incorrectly answered trials	2.98	.81	1.85 – 4.37	2.47	.63	1.62 – 4.09
Mean RTs correctly answered congruent trials	2.92	1.05	1.47 – 4.78	2.05	.36	1.45 – 2.83
Mean RTs incorrectly answered congruent trials	2.87	.85	1.66 – 4.34	2.39	.54	1.62 – 3.55
Mean RTs correctly answered incongruent trials	2.78	.83	1.67 – 4.92	2.11	.48	1.63 – 3.04
Mean RTs incorrectly answered incongruent trials	2.94	.88	1.94 – 4.82	2.72	1.03	1.79 – 4.64
Number of correctly answered congruent trials	7.81	2.45	2 - 10	9.93	.88	8 - 11
Number of correctly answered incongruent trials	9.75	2.79	4 - 11	10.27	.88	9 - 11
Overall accuracy	17.13	2.82	10 - 20	20.13	1.36	18 - 22

Note: Summary of behavioural measures in the picture-matching task (22 trials). RT = reaction time; *M* = mean; *SD* =standard deviation; Range = minimum and maximum value.

4.3.5. Relating ERPs and behavioural results

To determine how change within the midlatency time-window relates to changes in behavioural performance, electrical activity measured over selected electrode sites was regressed to behavioural accuracy on the picture-matching task.

Performance accuracy in relation to electrophysiological activity

A regression model was applied to investigate the relationship between brain activity and performance accuracy on the picture-matching task. Mean amplitudes that correlated sufficiently with behavioural performances ($r > .2$) were entered into a linear regression model. This resulted in a total of 9 predictor variables: left parietal congruent (LP_C), centroparietal congruent (CP_C), right parietal congruent (RP_C), left frontal congruent (LF_C), frontoparietal congruent (CZ_C), right frontal congruent (RF_C), left frontal incongruent (LF_I), central incongruent (CZ_I), and right frontal incongruent (RF_I). Accuracy is represented in scores out of 22 trials (11 per condition). All independent variables in this model were coded as voltage in microvolts (µV).

Preliminary analyses revealed no violations of normality, linearity, homoscedasticity, or multicollinearity assumptions as indicated by collinearity statistics. Overall the model yielded a significant regression equation ($F(9, 21) = 2.69$, $p < .02$) with an adjusted R-squared [15] value of .34 ($R^2 = .53$). Individual coefficients and effect sizes are summarized in Table 4.4. Standardized coefficients suggest that mean amplitudes in LP_C ($\beta = -1.13$, $p = .002$) and CP_C ($\beta = 1.33$, $p = .004$) made the strongest contributions in explaining Accuracy levels. Semipartial correlation coefficients indicate that LP_C uniquely accounted for 28% of the variance in Accuracy followed by 22% contribution from CP_C.

Table 4.4

Summary of regression analyses for ERP activity predicting Accuracy on the color-matching task across 3- and 5-year –olds (N = 31)

	Accuracy across 3 –and 5-year-olds		
Variable	***B***	***SE B***	***β***
LP_C	-.44	.12	-1.13**
CP_C	-.43	.13	-1.33**
RP_C	-.15	.11	-.36
LF_C	.08	.11	.18
CZ_C	.17	.19	.36
RF_C	-.14	.22	-.27
LF_I	.13	.14	.35
CZ_I	-.06	.15	-.17
RF_I	.13	.12	.33
R^2	.53		
Adjusted R^2	.34		
F	2.69*		

Note: Performance level was dichotomized as low (< median) vs. high (> median) performance in each age group. LP_C = left parietal congruent; CP_C = centroparietal congruent; RP_C = right parietal congruent; LF_C = left frontal congruent; CZ_C = frontocentral congruent; RF_C = right frontal congruent; LF_I = left frontal incongruent; CZ_I = central incongruent; RF_I = right frontal incongruent. Event related activities at relevant sites were centered at their averaged mean amplitudes 450-640ms post stimuli onset. *B* = unstandardized beta coefficient; *β* = standardized beta coefficient; *SE = standard error;* R^2 = explained variation/ total variation. *$p < .05$. **$p <$

4.4. Discussion of ERP & behavioural data

Complex actions are situated in a context of hierarchical action-goal relationships. The comprehension of sequential behaviour is, thus, guided by the likelihood of related actions occurring. In this sense, associative weights between sub-actions shape our expectations about upcoming events, and are modulated by specific action contexts (e.g., Wurm & Schubotz, 2012). In this study, we manipulated the congruency of final sub-actions to match or mismatch a preceding action context. Guided by prior research in adults, we identified several consecutive ERP components that are considered to be of functional significance in the semantic analyses of verbal material, gestures, and actions (i.e., N300 / N400).

The absence of significant differences across conditions within the N1 time-window suggests that comparable levels of attentional resources were engaged at the onset of congruent and incongruent final scenes. A lack of such early effects further suggests that final actions did not significantly differ on low level features of the visual stimuli. Differential activation in adults' and preschoolers' grand averages across congruent and incongruent trials was visible 250ms following stimuli onset. However, these congruency effects differed spatially for adults and preschoolers. Across participants, average waveforms contained significant deflections at ~ 300ms and ~ 400ms post-stimuli onset and were more negative for incongruent actions than congruent actions. This observation suggests that the overall time-course involved in the cognitive processes underlying semantic integration of actions into a greater event context might be similar for congruent and incongruent actions.

Finally, significant interaction effects as a function of congruency at fronto-central regions in adults and centro-parietal sites in preschoolers, suggest prolonged processing of the dynamic visual stimuli used in this study. While congruent actions evoked prolonged waveforms that were significantly more positive than waveforms elicited by incongruent actions, we did not observe a clear positive peak that would relate to the LPC component reported in previous studies (600ms - 900ms at fronto-central regions; e.g., Sitnikova et al., 2003). In the next sections, we first discuss adults' ERP results and then turn our focus to preschoolers' brain activity observed in this study.

ERP findings in adults

A negative peak was evident at approximately 280ms after the onset of the critical frame. This peak was significantly more negative for incongruent actions than congruent final actions. The latency of this effect shares similarities with the adult N300 component identified in several prior studies using familiar and novel actions (e.g., Pace, Carver, & Friend, 2013). Sitnikova et al. (2008) observed fronto-central N300 effects (~250ms post stimuli onset) at anterior electrode sites in response to incongruent final actions of real-life video stimuli like those presented in the current study. The N300 component thus appears to reflect modality-dependent conceptual aspects of non-verbal stimulus processing (e.g., West & Holcomb, 2002).

A second negative peak was present at about 390ms following incongruent actions. The reduced latency and more frontal distribution of the action-N400 component compared to the linguistic N400 (typically peaking approximately 400ms post-stimulus onset at centro-parietal sites, Kutas & Federmeier, 2011) is in good agreement with prior electrophysiological research in adults using video stimuli of real-life actions and pictures (e.g., Sitnikova et al., 2003, 2008; Reid & Striano, 2009).

In terms of the wider topographical distribution of the evoked effects, there is good consensus that brain activity in prefrontal networks is widely implicated in relational reasoning and the integration of multiple associated representations into higher-order mental representations (e.g., Waltz, Knowlton, Holyoak, Boone, Mishki, Santos, Thomas, & Miller, 1999). Moreover, widespread distributions of fronto-central activity within the N400 time-window have been implicated in the processing of discourse-level semantic coherency of stories conveyed by picture stimuli (e.g., West & Holcomb, 2002).

ERP findings in preschoolers

Average waveforms contained visible deflections that were more negative for incongruent than congruent final scenes. Incongruent actions elicited a prolonged negative waveform that reached a maximum within 300ms post-stimuli onset over centro-parietal sites. A peak was present in both age groups approximately 250 to 350ms after the onset of incongruent final actions. The latency of this effect thus compares to the N300 component observed in adults. The maximum of this effect was located over midline regions in both age groups. Widespread negativities over centro-parietal regions indicated further effects of congruence within the putative developmental N400 time-window (450 - 650ms following stimuli onset).

Neural activity in parietal and temporal regions is commonly present in the perception of biological motion (e.g., Allison et al., 2000; Grossman et al., 2000). Parietal brain regions also appear to be particularly implicated in the production of standard hand actions such as reaching and grasping (e.g., Jeannerod, Arbib, Rizzolatti & Sakata, 1995). Further evidence suggests that networks within the parietal cortex are critically involved in both observing purposeful hand movements (e.g., Bonda, Petrides, Ostry & Evans, 1996) and imagining hand actions (e.g., Gerardin, Sirigu, Lehéricy et al., 2000). Thus, posterior brain regions appear fundamental in the processing of sensorimotor experience and the translation of somatosensory information into adequate formats for action planning (e.g., Kilner, 2011). Left postero-lateral brain regions have especially been related to the analysis of more schematic aspects of the dynamic relations between agents and objects in goal-direct actions (e.g., Bedny, Caramazza, Grossman, Pascual-Leone & Saxe, 2008; Grossman, Koenig, DeVita et al., 2002).

There is good consensus that ERPs are not only delayed in infants and young children compared to adults, but that components of similar functional significance appear to have a greater duration, smaller amplitude, and may at times even be inverted in polarity (e.g., Pang & Taylor, 2000; Pascalis, de Haan, & Nelson, 2002). It is possible that large amplitude waveforms with low frequencies overlap or mask less mature components at fronto-central sites (e.g., Ceponiene, Rinne, & Naatanen, 2002). Alternatively, it is also plausible that a topographical shift occurs as maturing neural generators become increasingly (or decreasingly) activated during the semantic analyses of goal-related information. In the same vein, it has been speculated that neural generators of opposed orientations that differentially contribute to ERP components, give rise to polarity inversions throughout development (e.g., Thierry, 2005). The cause and time-course of inversion and topographical shifts affecting specific components is yet to be investigated in longitudinal studies.

Because any evidence regarding the preschoolers' N300 / N400 components is currently lacking, relating the current results to infant and adult ERP findings is by no means straightforward. Comparative research suggests that the overall time-course of distinct ERP components appears to be similar in infants and adults (e.g., de Haan, Pascalis, & Johnson, 2002; Pascalis, de Haan, & Nelson, 2002). However, inter-individual variability and variation within age groups is far greater in infants and preschoolers than in adults (e.g., Kushnerenko, Ceponiene, Balan, Fellman, & Naatanen, 2002; Morr, Shafer, Kreuzer, & Kurtzberg, 2002). At present, we do not have sufficient developmental evidence that would allow the use of source localization procedures, and thus developing strong predictions concerning the neural generators implicated in the action-N400 is premature.

Evaluation of the regression model suggests that 34% of the variance in Accuracy on the picture-matching task is explained by activation in response to congruent and incongruent event endings. Standardized Beta coefficients suggest that the strongest unique contributions to explaining overall accuracy levels originated from centroparietal and left parietal electrode sites. This observation strengthens the notion of a substantial relationship between brain activity in posterior brain regions and cognitive mechanisms involved in the semantic processing of goal-directed action. Results indicate that on average a 2-point increase in the overall accuracy on the picture-matching task was associated with a 1µV decrease in centroparietal electrodes. It thus appears that, in particular, parietal areas play a role in the semantic analyses of goal-directed actions and that activity in these regions can be linked to how 3- and 5-year-olds relate outcomes to actions. While this observation is in line with the theoretical predictions of this study, the question remains whether developmental effects and individual differences in the ability to judge goal requirements of specific action contexts significantly add to the relationships identified by this model. Given the small sample size in this study, it was not feasible to build a series of separate models for 3- and 5-year-olds, which would have allowed a deeper investigation of the relationship between behavioural scores and brain activity in terms of developmental effects. It should also be noted that the two strongest predictor variables (LP_C, CP_C) reflect activity that was recorded in adjacent electrodes during congruent trials. Given the relatively low spatial resolution of EEG methods, the role of individual channels should be interpreted with caution. Thus, significant contributions from LP_C and CP_C amplitudes to the model should be viewed as a more general involvement of centroposterior sites that reached statistical significance in these particular channels [16].

5. General Discussion

Results suggest that both adults and preschoolers processed the incongruence of final actions by means of perceptual processes (reflected at early stages) and conceptual processes (reflected in midlatency ERP components). The simultaneous processing of actions that takes place at multiple levels has been observed in prior studies with adults and infants (e.g., Hard, Recchia, & Tversky, 2011; Pace, Carver, & Friend, 2013). It has been suggested that the observed mid-latency components could well be described in terms of a N300 / N400 complex evoked by dynamic visual events (e.g., Amoruso et al., 2013). Results of this study, thus, are consistent with the notion of a functional link between the N300 and N400 in the semantic analyses of goal-directed sequential actions as a conceptual whole. More evidence is needed to identify whether

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[16] Some degree of left lateralization in the observed mid-latency effect is certainly feasible and in good agreement with previous studies investigating action comprehension in adults (Ibáñez & Manes, 2012; Ibáñez, Melloni, Huepe, Helgiu, Rivera-Rei et al., 2012; Cardona, Dos Santos, Blenkmann, Aravena et al., 2013).

the N300 and N400 components relate to specific processing stages or whether they, in fact, reflect a functional complex.

A decrease of peak latencies with ongoing development (e.g., Mills, Coffey-Corina, & Neville, 1997; Kushnerenko et al., 2002) is thought to be linked to maturational changes in myelination (e.g., Thierry, 2005). Structural changes in the brain, specialization of neural populations, and axonal myelination may explain the observed differences in the topographical distribution of adults' and infants' ERPs. However, at the moment, one cannot exclude the possibility that the observed effects originate from different neural generators in children and adults, and thus reflect altogether distinct ERP components.

An alternative explanation is that adults in this study were overall more sensitive to the observation of goal-requirements than preschoolers. There is good evidence that sensitivity to the realized goals of prehensile actions is reflected by activity in frontally distributed networks. Numerous prior works substantiate the role of the premotor / prefrontal cortex in the processing of goal-directed actions (e.g., Catterjee, 2001; Grézes & Decety, 2001; Giovannetti, Schwartz & Buxbaum 2007; Jeannerod, 1997; Kemmerer, Rudrauf, Manzel & Tranel, 2012). In particular, left hemisphere premotor and prefrontal areas have been implicated in the higher-level visuomotor processing of actions that involve manual object manipulation (e.g., Chao & Martin, 2000). Moreover, activity within the inferior section of the prefrontal cortex appears to be distinctly evoked by the perception of hand-object interactions, rather than in response to the kinematic motion involved in manual actions (e.g., Johnson-Frey, Maloof, Newman-Norlund, & Farrar, 2003).

One may speculate that the topographical differences in the N300 / N400 distribution across adults and preschoolers may originate from differences in the semantic analyses of the contextually inappropriate actions. As such, adults may have focused on relating higher-level goals into a coherent abstract representation of the event (indicated by a frontally distributed N400-like component), whereas preschoolers cantered the focus of the semantic analyses on more concrete action-related requirements (reflected in a posterior N400-like component). This is not to say that preschoolers did not perceive the observed events in terms of higher-level goals. However, it may well be that the representational content of conflict detection on incongruent trials differed for adults and preschoolers. This hypothesis assumes that adults and preschoolers primarily differed not in respect to the degree to which semantic processes were engaged but rather at the levels of abstraction at which semantic integration took place. In other words, while adults may have detected conflict in terms of higher-level goal violations, children may have been more sensitive to violations of concrete action-object relationships.

While previous studies suggest that preschoolers at times struggle to structure sequential behaviour in respect to hierarchically organized action-outcome relations (e.g., Freier, Cooper, & Mareschal 2015a, 2015b), there is currently no developmental evidence relating posterior midlatency negativities to the semantic analyses of naturalistic sequences of actions. However, it should be noted that Reid et al. (2009) observed parietal N400-like effects in 9-month-olds in response to pictorial stimuli. These authors argued that effects at frontal sites were likely masked by a large Nc component, which was evident in both the expected and unexpected condition. While this ontogenetically unique Nc component may indeed represent a precursor to the later developing N400 component, Reid et al. found N400-like ERPs at posterior sites only in the unexpected action condition. Therefore, the observed midlatency negativities elicited by unexpected actions may in fact be more localized to centro-posterior regions in infants than these authors proposed. Interestingly, in this study prolonged ERP differences between conditions were suggested to reflect the degree to which low-frequency neuronal activity is in phase. However, in Reid et al.'s study only the expected condition (bringing a spoon to the mouth) was goal-directed, whereas the unexpected condition (bringing a spoon to the ear) did not achieve a discernable goal, rendering this action not only unexpected but also lacking a detectable outcome.

The regression model suggests that the observed relationship in preschoolers between ERP mean amplitudes and levels of accuracy on the picture-matching task is (1) associated with electrical potentials in response to congruent final scenes, and (2) driven by performance on matching trials. While this finding may initially seem counterintuitive to the predictions derived from the action-N400 literature, it indicates that the ERP and behavioural measures in this study are in good agreement. On the one hand, children in both age groups overall committed more errors on matching compared to non-matching trials. On the other hand, insufficient or incomplete semantic processing is linked to decreased ERP negativities within the midlatency time window, while an increase in semantic processing demands is associated with N400-like effects.

ERP mean amplitudes in this study suggest that children in both age groups showed increased negativities on incongruent trials. Despite the fact that midlatency ERP negativity appears to be critically implicated in the processing of goal violations, some level of semantic integration is still needed to process outcomes on congruent trials. Reduced electrical potentials in responses to congruent trials might suggest that generally lower levels of integrative mechanisms are engaged as long as no obvious mismatch between the predicted and actual outcome is detected. If, however, predictions are violated, then semantic processing demands rapidly increase, resulting in an increase in the engagement of semantic processing networks and midlatency negativities such as the action-N400. A relatively low engagement of semantic mechanisms on congruent trials may well be mirrored by behavioural performance on the picture-matching task in the form of errors and prepotent responses on matching trials, leaving performance measures on non-matching trials relatively unaffected.

In conclusion, we report the first electrophysiological investigations of action processing in preschoolers, a time of great change in children's control of goal-directed action sequences (Freier et al., 20015a, 2015b). We find that adults and preschoolers appear to engage similar cognitive mechanisms in the semantic processing of action sequences as suggested by comparable latencies of the N300 and action-N400 components. However, the distinct topographical distributions of these effects suggest that the neural systems that give rise to semantic integration change over the course of childhood. The semantic analyses of dynamic sequential events appear to implicate higher-level cognitive operations that are mediated by frontal, temporal, and parietal brain regions. Results of this study therefore corroborate the view that both perceptual and conceptual mechanisms operate together in the semantic processing of sequential goal-directed actions by 3 years of age. The extent to which these mechanisms are engaged in the detection of conflict between actions and a greater event context appears to undergo marked development from preschool to adulthood.

Our findings thus provide a first step into investigating the implicit brain responses of preschoolers that underlie semantic integration of higher-level goal-directed actions in terms of a preceding event context and in relation to behavioural performance on a decision-making task. What mechanisms are generated in order to resolve the conflict caused by goal violations remains one of many open questions concerning the comprehension of complex intentional behaviour. For instance, it is unclear how lower-level event specific information influences the detection of higher-level goals. Recent works with adults suggest that sensitivity to kinematic patterns of movement may provide additional information regarding an agents' intentions (e.g., Ansuini, Cavallo, Bertone, & Becchio, 2014). In the next chapters we turn the to question of whether covert cognitive states are reflected in adult and young children's production of goal-directed actions. We present novel evidence suggesting that the kinematic parameters of children's reach-to-grasp actions are affected by interferences caused by the evaluation of distractor objects.

CHAPTER 5

Interference effects in reach-to-grasp action across development

5.1. Introduction

While early cognitive theories assumed that decision-making is preceded by perceptual inputs and followed by motor outputs, current models built on neuropsychological evidence that links perception, cognition, and action through interactive and parallel processes (e.g., Song & Nakayama, 2009 for a review). For instance, wide-ranging evidence suggests that sensorimotor experience gathered during bodily actions calibrates perception (e.g. Stefanucci & Geuss, 2009) and thus serves the development of numerous cognitive skills (e.g., Brockmole, Davoli, Abrams, & Witt, 2013). At the same time, competing cognitive states affect the motor pattern of goal-directed behaviour, shaping the temporal evolution of action kinematics. In this chapter we will focus on the flow of cognitive states into the planning of motor outputs. One way of measuring the temporal dynamics of internal processes is to capture the continuity in movement as it unfolds in real time.

5.1.1. The planning of prehension

In the introduction chapter we discussed the link between action and perception, as two interrelated domains that, together, provide the temporal and spatial constraints that give rise to goal-directed behaviour (e.g., von Hofsten, 1987; 2007). In everyday behaviour numerous potential actions compete for selection, and goal-directed actions are, therefore, highly selective (e.g., Tipper, Lortie, & Baylis, 1992). Numerous lines of research have contributed to the view that from an early point in development humans are equipped with selective processes that allow them to tackle the tremendous amounts of perceptual information arriving from our external surroundings (e.g., Kane & Engle, 2002 for a review). However, this does not mean that action selection is unaffected by the presence of irrelevant perceptual input (e.g., Keulen, Adam, Fischer, Kuipers, & Jolles, 2004).

Until now we have considered action planning in terms of the cognitive abilities required to plan, structure, and control actions in relation to higher-level goals. However, selective processes are also engendered through action requirements that influence the kinematic patterns of movement. In this chapter we shift our focus to the influence of schematic structure on reach-to-grasp actions.

Goal-directed actions are characterised by prehensile actions. From around 4 months of age infants gather experience in the reaching and grasping of objects (e.g., Coluccini, Maini, Martelloni, Sgandurra, & Cioni, 2005; Corbetta, & Snapp-Childs, 2008; Newell, Scully, McDonald, & Baillargeon, 1989). While seemingly effortless, the mechanisms underlying these actions require the transformation of visual features of objects into appropriate hand configurations and, thus, the ability to update the position of body segments in respect to the object's position, shape, weight, and affordance. In addition, attentional selective mechanisms need to be in place. For example, when choosing an apple from a bowl of various fruits, many possibilities for reaching and grasping are presented. Fully specified action plans prior to the movement onset would suggest that only apple-related sensory information shapes the reaching and grasping kinematics. However, in reality movements are initiated without such detailed plans of the precise pattern of motion involved (e.g., Wilson & Golonka, 2013). As such, precise motion parameters are left unspecified for later adaptation. In fact, in the example above, the other fruits, of different shapes, sizes, and weights might cause a substantial amount of interference to the kinematic pattern of the reach-to-grasp action. Such effects are referred to as *distractor interference* by Tipper and colleagues (e.g., Tipper, Lortie, & Baylis, 1992).

The current study assessed the role of interference effects triggered by several distractor objects across development. Specifically, we asked whether the strengths of interference effects relate to the perceptual and semantic attributes of various distractor objects. Using optical motion capture methods, this study constitutes the first investigation of interference effects upon kinematic parameters of a reach-to-grasp action in children.

Before discussing the impact of distractor objects on reaching and grasping, the following section will provide a brief description of prehensile movement. More detailed accounts concerning the precise motor pattern underlying reach-to-grasp actions are beyond the scope of this study and are provided elsewhere (e.g., Smeeta & Brenner, 1999; Wang & Stelmach, 1999).

5.1.2. Reach-to-grasp action dynamics

While generally considered together, reaching and grasping constitute separate movement components of prehensile actions (e.g., Jeannerod, 1986; Jervis, Bennett, Thomas, Lim, & Castiello, 1999). During the reach component, the arm is moved towards the object and fingers are postured in preparation for object contact. During grasping, fingers are positioned to accommodate the size, shape, and use of the object. At this stage, force is applied to execute a stable grasp and maintain it. For instance, during the execution of a power grip, the fingers are flexed to form a clamp against the palm, incorporating all digits and a large palmar surface area. In contrast, a precision grip is characterised by the opposition of the thumb to the index finger and implicates the pads of the digits for a delicate grasp. However, in goal-directed behaviour the selection of the most appropriate grasp depends on both the object features as well as the purpose of the prehensile action (e.g., Napier, 1956).

Human movement science, comprehensibly demonstrated that the spatiotemporal patterns of reach and grasp components are shaped by the anatomical pattern of prehension, specified by object features and affordances (e.g., Jeannerod, 1986; Napier, 1956). For instance, the spatial and temporal dynamics of the reach-to-grasp action during the execution of a power grip are different from those required during precision grips (see Figure 5.1). However, it is the timing of these components that has been extensively related to attentional selection during movement execution. For instance, once the movement towards a target object is initiated, the posture of the hand and the configuration of the digits are adjusted to pre-shape the object, leading to a maximum grip aperture at around 60-80% of the overall movement time (e.g., Jeannerod, 1986). Evaluating objects in terms of the positioning of the hands and fingers (e.g., volumetric object representation) necessitates mechanisms of selective attention (e.g., Castiello, 1999).

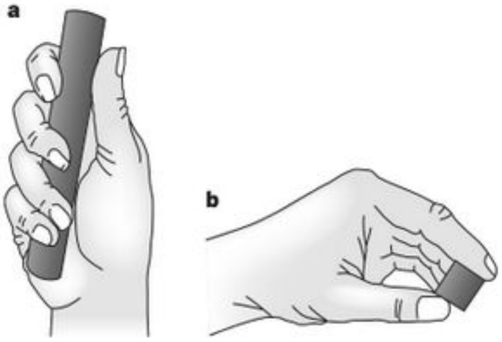

Figure 5.1. Prehensile actions: (a) power grip, and (b) precision grip. Source: Castiello (2005).

Studying movement from a kinematic perspective can provide detailed descriptions of the position and displacement (e.g., angular, linear) of the limbs, hands, and fingers during reach-to-grasp actions. Kinematic parameters (e.g., peak velocities, accelerations, decelerations), thus, provides insight into the relationships between different segments of the body and the organisation of movement in relation to the external environment.

5.1.3. Interference effects in reach-to-grasp action

Various studies with adults have used a range of techniques to examine the spatiotemporal representation of prehensile actions (e.g., Jervis, Bennett, Thomas, Lim, & Castiello, 1999; Tipper, Howard, & Houghton, 1998; Tipper, Howard, &

Jackson, 1997; Tipper, Lortie, & Baylis, 1992). While participants have little or no awareness of motion patterns involved in reach-to-grasp actions, they nevertheless show systematic differences in the kinematic parameters of the movement as a function of object category and position (e.g., Jervis, Bennett, Thomas, Lim, & Castiello, 1999; Tipper et al. 1992).

In one of the earliest investigations of distractor interference, Tipper et al. (1992) presented adult participants with a selective reaching task, involving a board containing several buttons and adjacent lights. Participants were instructed to press the button that displayed a red light and ignore buttons with yellow lights (distractor objects). The results of this study suggested that distractor objects caused significant degrees of interference (greater response times) that further depended on the starting position of the hand. Because the position of distractor objects relative to the hand appeared to critically affect the reaching kinematics, Tipper and colleagues argued that selective spatial attention in reaching actions is situated in an action-based frame of reference (e.g., Tipper, Lortie, & Baylis, 1992; Tipper, Howards, & Houghton, 1998). Subsequent works referred to this finding in terms of a visuomotor processing hypothesis, in which interference is triggered by visuomotor competition from distractor objects (e.g., Meegan & Tipper, 1999). This assumption is based on the notion that at the neural level, reach-to-grasp actions are spatiotopically represented in terms of the location of the object in respect to the current location and configuration of the hand. Within the constraints of a behavioural goal, the movement patterns afforded by multiple objects are encoded in parallel. However, the action-centred frame of reference, allows action-based inhibitory mechanisms to mediate the selection of the target object among competing distractors (e.g., Tipper, Howards, &

Houghton, 1998). Tipper et al.'s account further argues that shorter reach distances cause larger interference effects from distractors at this location. Interestingly, according to this view distractors presented at near locations appear to have a visuomotor processing advantage compared to distractors that are located further away (see also Keulen, Adam, Fischer, Kuipers, & Jolles, 2004).

Tipper et al.'s original paradigm was replicated and advanced several times with adults, suggesting that not only the relative location to the hand but also the size and shape of the objects appear to impact on the reaching kinematics in reach-to-grasp action (e.g., Jervis, Bennett, Thomas, Lim, & Castiello, 1999; Keulen, Adam, Fischer, Kuipers, & Jolle, 2002; Pratt & Abrams, 1994). It has further been established that the proximity between target and distractor objects crucially impacts on interference effects, because not only does the general location of the target-distractor area need to be specified, but also the exact location of the target relative to distractors (e.g., Keulen, Adam, Fischer, Kuipers, & Jolle, 2002). Thus, it appears that an environment-centred frame of reference is implicated at least at a later stage in the selection process.

Finally, it should be noted that there is a considerable amount of controversy regarding the interpretation of interference effects. For instance, Castiello et al. (1996) presented adults with a more ecologically valid task that required the grasping of a piece of fruit to perform a task. The results of this study did not suggest interference effects in the kinematic profiles of adults. In fact, findings from various experiments suggest that the passive processing of distractor objects does not influence selection *for* action (e.g., Castiello, 1996; Jackson, Jackson, & Rosicky, 1995). This observation challenges the assumption that distractor objects provoke interference effects as a result of competition in the processing of actions. As a result, the authors proposed that selecting among competing motor plans, constrained by the shapes and sizes of objects, may not cause interference at all.

This hypothesis was then followed up in a motion capture study by Jervis and colleagues (1999), in which the kinematics of the reach-to-grasp action were contrasted across the presentation of different types of object categories (semantically related vs. semantically unrelated). Participants reached for an apple that was either presented alone, or with a compatible/ incompatible distractor object. Compatibility in this task referred to object properties that identified objects as belonging to the same semantic category, as opposed to objects that were perceptually and semantically unrelated. The results of this study indicated significant differences in the kinematic patterns of grasps as a function of semantic compatibility. Specifically, Jervis et al (1999) observed a consistent trend for faster velocities in the incompatible distractor condition compared to the no distractor condition. In other words, while the overall movement times did not vary across conditions, the acceleration of the finger opening during grasping occurs earlier in the presence of a semantically unrelated distractor object than when no distractor object was present. Thus, the categorical relationship between the target and the distractor object influenced the organisation of the grasping movement (e.g., opening rate of the fingers, time of maximum grip aperture). Significant differences were also evident in terms of the relative times to peak acceleration and velocity, with incompatible distractor objects leading to earlier occurrences than the no distractor and compatible distractors conditions.

It should be noted, however, that the target object in this study was an apple, while the distractor object was a box. Despite the fact that these two objects belong to different semantic categories, they also substantially differ in shape, and thus grip affordance. Therefore, Jervis et al. ran an additional experiment to control for the possibility that interference effects were in fact perceptual in nature (presenting a ball as distractor) and found no significant effects. In addition, the general results of this study further corroborate the argument that the presence of interference effects is determined by the amount of visual exposure that participants have prior to movement onset. Tipper et al. (1997) had first noticed that when participants observed the object placement, competing information form the distractor objects was effectively overcome prior to reaching onset.

In summary, research with adults suggests that action interference effects are caused by simultaneous presentation of a target and distractor object and the resulting conflict between processing demands. One possibility is that multiple motor plans that are considered during the selection of the reach-to-grasp action compete and, thus, produce interference (perceptual hypothesis). An alternative account postulates that the semantic relationship between the target and the distractor objects generates conflict that results in increased processing demands (semantic hypothesis). In respect to the development of selective attention in reach-to-grasp actions, there is currently no comprehensive account of how the perceptual experience is constrained to control goal-directed actions during the childhood years. Moreover, there is currently no evidence suggesting that children demonstrate similar effects of planning interference as a result of simultaneous presentation of targets and distractors.

While most investigations of interference effects have been carried out with response time measures (e.g., Tipper, Lortie, & Baylis, 1992) or digitized computer interfaces (e.g., Keulen, Adam, Fischer, Kuipers, & Jolle, 2004; Tipper, Weaver, Jerreat, & Burak, 1994), the use of these methods limits the volume of kinematic measurements that can be obtained. In addition, mapping devices that require cursor movements pose additional mapping issues that, particularly in young children, may only be overcome through extensive training. Using optical motion capture methods allows us to translate natural movement into a 3D recreation of the action with a high temporal resolution and sub-millimetre accuracy. As outlined in the introduction chapter, motion-capture techniques provide a promising means to bridge motor and conceptual action processing through detailed analyses of kinematic parameters. Therefore, in the current study we used motion capture methods to tap planning related processes that implicitly impacted on the kinematic output during a reach-to-grasp action.

The first aim of his study was to investigate whether simultaneous presentation of multiple objects produces interference effects in children's reach-to-grasp actions across development. Some lines of evidence suggest that interference effects are exacerbated in populations with fewer inhibitory attentional resources, such as young children and adults with Alzheimer's disease (e.g., Ambron, Della Sala, & McIntosh, 2012; Ambron, McIntosh, Allaria, & Della Sala, 2009). The second aim of this study was to explorer the role of perceptual and conceptual processing demands and their influences on adults' and children's reaching kinematics. To address these questions, we built on the reaching paradigm used by Jervis et al. (1999) discussed above. Across various perceptual and semantic distractor conditions, 6-, 9-, 12-year-olds, and adults reached for a central target object while aiming to ignore task irrelevant distractor object.

Investigating interference effects across childhood can provide new insight regarding the planning and online control of goal-directed actions in natural environments. In Chapter 2 we presented a study in which preschoolers were asked to carry out a naturalistic goal-directed action sequence, while disregarding distractors that were located in close spatial proximity to the target objects. The results in this study suggested that the ability to structure the familiar sequence hierarchically depended on whether children had observed an agent performing distractor actions (a misleading demonstration). However, the pattern of results in the misleading demonstration condition also suggested that, older preschoolers were better able to select appropriate objects only from among distractors than were younger preschoolers. Investigating the attentional mechanisms underling action selection can, therefore, enhance our understanding of advances in planning abilities across childhood.

As discussed in Chapter 1, the preschool period constitutes a time in development during which action-related executive control mechanisms are increasingly engaged (e.g., Jones et al., 2003). However, it has also been suggested that executive inhibition undergoes protracted development across childhood (e.g., Carlson & Moses, 2001; Davidson et al., 2006; Diamond & Taylor, 1996; Luria, 1959; Simpson & Riggs, 2007). Arguably, the development of executive inhibition is inseparable from the development of selective attention. It was, thus, anticipated that younger children in this study would demonstrate the highest levels of interference effects while also demonstrating longer movement durations overall than older participants.

Guided by prior kinematic experiments of reach-to-grasp actions, we presented four groups of children and adults with several distractor conditions that differed in terms of their semantic and perceptual relatedness to the target object (a red apple). We reasoned that, if interference effects in this paradigm result, as argued by Jervis et al., from the level of competition between objects of different semantic categories, the processing of multiple semantic categories should cause increased interference effects. If, however, interference effects are caused by insufficient inhibition of perceptual attributes related to grasp apprehension, as proposed by Tipper and colleagues, the presentation of distractors that afford different hand configurations should provoke strong interference effects, irrespective of semantic relatedness. What these accounts appear to have in common is that processing competition generates cognitive interference. Following this logic we contrasted seven distractor conditions in this study (see Figure 5.2.):

(1) no distractor object condition (ND),
(2) perceptually compatible / semantically incompatible condition (PC/SC),
(3) moderate perceptually compatible / semantically incompatible condition (mPC/SI)
(4) increased perceptually compatible / semantically incompatible condition (iPC/SI)
(5) moderate perceptually incompatible / semantically compatible condition (mPI/SC)
(6) increased perceptually incompatible / semantically compatible condition (iPI/SC)
(7) perceptually incompatible / semantically incompatible condition (PI/SI)

The conditions in this study, thus, differed in terms of their semantic and perceptual compatibility between the distractor and target, as well as in the overall number of distractors that were simultaneously presented (set size). Given the lack of prior evidence regarding kinematic interference effects across development, we did not make any specific predictions of the level of interference in each condition.

5.2 Methods

Participants

Due to excessive marker occlusion two adults, six 6-year-olds, and four 9-year-olds had to be excluded from the final sample. A further three 6-year-olds and one 12-year-old were also excluded because of a consistent failure to bring the reaching hand back to the starting location at the onset of each trial. Seventy-three participants (9 left handed / 64 right handed), naïve to the purpose of the study, were included in the final sample. Age groups were composed of 19 6-year-olds (*M* = 6.6 year, *SD* = 0.3 years; female = 9), 23 9-year-olds (*M* = 9.4 years, *SD* = 0.3; female = 13), and 19 12-year-olds (*M* = 12.6 years , *SD* = 0.5 years; female = 7). A total of 11 adult participants took part (*M* = 29.4 years, *SD* = 4.4 years; female = 8). All participants had normal or corrected-to-normal vision. All participants were tested individually. Formal consent was obtained from caregivers and children verbally agreed to participants. The study was granted ethical approval from the College Ethics Committee and all experimental sessions were conducted in accordance with the Helsinki declaration. All participants received travel reimbursement and children were given small gifts for taking part.

Material

Stimuli in this study consisted of three round objects with equal diameters (6cm) that belonged to different semantic categories (apples, a tennis ball, a tea ball infuser), as well as three common objects that varied in shape, size, and semantic relatedness (banana, grape, scissors). Prior to testing, children and adults were asked to identify all objects. Figure 5.2. illustrates the experimental setup in this study. Retroreflective markers for optical motion-capture were placed on the participants' dominant hand.

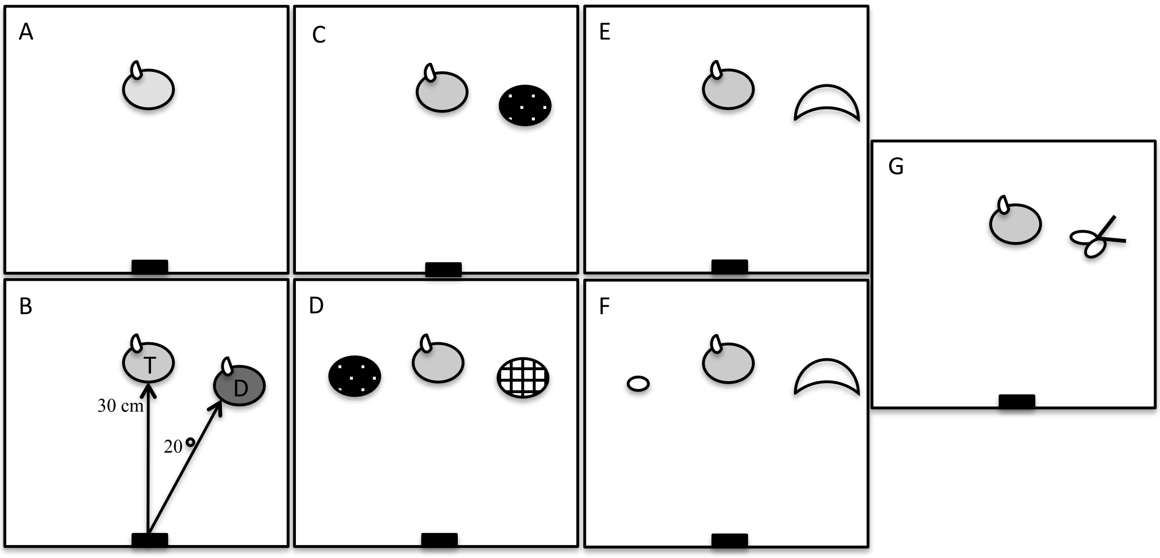

Figure 5.2. Stimuli displayed across conditions. (A) The target object alone in the centre of the table (grey apple), 30cm away from the starting position of the hand (black square), represented the no distractor condition (ND). Participants were further presented with (B) a perceptually compatible – semantically compatible distractor condition (PC/SC) displaying two apples; a (C) moderate and an (D) increased version of a perceptually compatible - semantically incompatible distractor condition (mPC/SI, iPC/SI), presenting the target apple together with a tennis ball and tea infuser of equal diameter. In a (E) moderate and an (F) increased version of the perceptually incompatible - semantically compatible distractor condition (mPI/SC, iPI/SC), the target was presented with either one (banana) or two (banana & grape) pieces of fruit. Finally, we added a (G) perpetually incompatible – semantically incompatible distractor condition (PI/SI) in which the distractor was a pair of scissors.

Procedure

The experiment was carried out under normal lighting conditions. The participants sat on table (50cm x 50cm) with their dominant hand placed in front of them. Figure 5.3 illustrates the participants' position in relation to the experimental setup. A straight line on the table surface marked the starting position for trial. All participants were instructed that their reaching hand had to be placed at this starting position with the three middle digits touching, but never crossing, the line. Hand placement was further practiced before testing. The target object was then displayed in the centre of the table, aligning with the midline of the participants' bodies and the starting position of the hand (30cm away). Participants were instructed to reach for the apple with a movement that felt natural, to pick it up, and to place it back on the table. Further instructions specified that participants had to ignore all other objects presented to the left and right sides of the central apple. For children, instructions emphasized that only the apple had to be lifted and that none of the other objects mattered in this task. All participants also received three practice trials before the first test trial commenced.

The experimental conditions were each composed of 10 trials with exception of the no distractor condition, which was presented 30 times. This resulted in a total of 90 randomly presented trials. At the beginning of each trial, the experimenter reminded participants that the reaching hand had to be placed at the starting position, and only when this was confirmed was a new test trial begun. In order to minimise visual processing time before reaching onset, the experimenter placed a screen on the table to conceal the placement of the stimuli from the participants' view. The lifting of the screen marked the onset of each trial. Participants' reach-to-grasp actions were tracked and recorded with an optical motion-capture camera system.

Marker placement and Motion recording

Spherical passive retroreflective markers (4 mm diameter) were attached to four points on the participants' hands, using skin-safe double-sided adhesive tape. The first three points were the same as in the original experiment by Jervis et al. (1999): (i) on the wrist — radial styloid process (ii) on the index finger — dorsal side of the tip of the second finger (iii) on the thumb — dorsal side of the tip of the index finger. A fourth marker position, (iv) placed on the first knuckle of the index finger — dorsal side of the second metacarpophalangeal joint, was chosen based on previous motion-capture research in children (e.g., Coluccini, Maini, Martelloni, Sgandurra, &, Cioni, 2007; Jaspers, Feys, Bruyninckx, Harlaar, Molenaers, &, Desloovere, 2011). In addition, a single marker was attached to the target object and all distractors.

Movements were recorded using a five-camera optical marker-based motion capture system (4 Oqus 1 cameras to record markers, 1 Oqus 210c camera for synchronized colour video recording, all from Qualisys Inc., Sweden). Each camera was equipped with an LED strobe emitting light in the near-infrared light spectrum (~ 800nm wavelength). The sampling rate was set to 100 Hz. The four marker-recording cameras were placed in a quarter-circular fashion on tripods around the table, between 1 m and 1.5 m from the closest edge of the table and 0.3 m to 1 m apart. The cameras were vertically inclined at a height between 0.8 m and 1.1 m relative to the table-working surface. Figure 5.3 illustrates the camera placement in this study.

The calibrated measurement volume was approximately 1.5 m long × 1 m wide × 1 m high. Calibration was performed using a wand with two markers attached to the wand 299.3 mm apart. An L-shaped frame equipped with four markers (one marker at the junction; one marker at 200 mm distance from the junction marker on the short side; two markers at 90 mm and 300 mm distances from the junction marker on the long side; all markers were coplanar) was placed on the table during calibration as static reference and coordinate system origin.

The recording was controlled using the Qualisys Track Manager (QTM) software package (version 2.9). Each testing session was recorded continuously. This yielded one measurement file per participant containing all trials from the respective session.

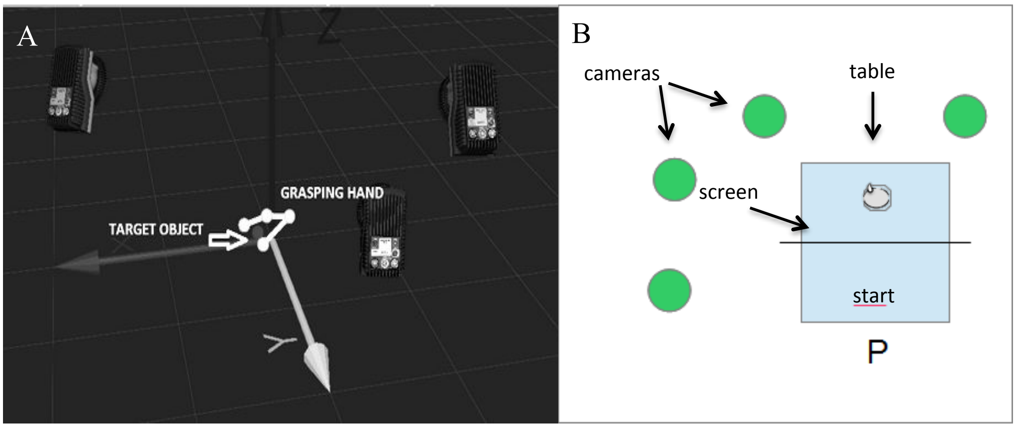

Figure 5.3. (A) Experimental setup and camera placement from the left side. Retroflective markers (white) are depicted in relation to the target object (grey). (B) Experimental setup and camera placement from above (P = participants position; the target object is presented on a marked position in the centre of the table).

Coding

The QTM software package was used to calculate the three-dimensional reconstruction of the marker positions. Each successful trial was then assessed visually to manually record the frame at which one of three events occurred: (i) start of the reach component (ii) end of the reach component, and (iii) end of the grasp component (end of the movement). The start of the reaching component was coded as the instant at which the hand was lifted off the table surface (reflected in an acceleration of the velocity curve). The end of the reach component was coded as the point at which the arm was maximally extended. From this instant to the point at which the participant's fingers had closed around the object, the movement interval was coded as part of the grasp component. Three independent coders checked the recorded video sessions for correct placements of the participants' hands at the onset of each trial. Coders also screened the reconstructed motion capture data for signal failures as suggested by discontinuous velocity curves. All coders received training of the manual coding procedure until Krippendorff's Alpha coefficient of inter-coder reliability was 0.90 or higher. Trials with signal failures (due to marker occlusion) were eliminated, as were trials in which the participant's hand was misplaced at the onset of the reach. After coding and data processing, the average numbers of included trials that participants contributed were: 53 coded trials in 6-year-olds; 58 average coded trials in 9-year-olds; and 74 average coded trials in 12-year-olds. Adults contributed on average 73 coded trials in this task.

Processing of kinematic data

The kinematic data was first smoothed using a second-order lowpass Butterworth filter (10 Hz cutoff frequency) and then processed in MATLAB (version R2015s). Movement perpendicular to the table workspace was ignored. Only the two-dimensional motion parallel to the table workspace was assessed. For each successful trial the following kinematic parameters were calculated: (a) movement duration (from the reach start event to the end of the grasp), (b) time to peak velocity, (c) occurrence of peak velocity (in percentage of movement duration), (d) time to peak acceleration, (e) occurrence of peak acceleration (in percentage of movement duration), (f) time to peak deceleration, (g) and occurrence of peak deceleration (in percentage of movement duration). All kinematic parameters were derived from the position data of the knuckle markers. The parameters were individually computed for reach and grasp components. Kinematic analyses in relative terms[17] allowed the evaluation of temporal occurrences of kinematic events at different percentages of the total movement across conditions and age groups.

For statistical analyses, cases including extreme values (values within the 1st and 99th percentile of the distribution) were excluded. Mean values of the kinematic parameters were first computed and introduced in a mixed multivariate analysis of variance. Thereafter, planned comparison analyses (Turkey HSD) were conducted to contrast the specific hypotheses that interference effects are linked to Set size (no distractor / 1 distractor / 2 distractors), Semantic compatibility (no distractor / semantically compatible / semantically incompatible) or Perceptual compatibility (no distractor / perceptually compatible / perceptually incompatible). Bonferroni adjusted alpha levels (.017) were used for multiple comparisons. Because of the large volume of parametric measures and factors in this study, results are presents separately, considering first the overall movement analyses, followed by individual analyses for the reach and grasp components.

5.3. Results

Assumption testing suggested no serious violations of normality, univariate and multivariate outliers, multicollinearity, and homogeneity of variance-covariance matrices. Pillai's trace was chosen to ensure robustness of the statistical test despite unequal sample sizes in this study. Preliminary analyses did not yield significant results in terms of gender or handedness.

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[17] Expressing kinematic parameters as a percentage of the total movement duration provides a useful measure of the temporal dynamics of events (Jervis et al., 1999).

Overall Movement

An initial multivariate test was conducted to analyse absolute kinematic measures (Movement duration, Peak velocity, Peak acceleration, Peak deceleration) across the complete reach-to-grasp action. This analysis included Age (6 years / 9 years / 12 years / adults) as between-subjects variable and Condition (ND, PC/SC, mPC/SI, iPC/SI, mPI/SC, iPI/SC, PI/SI) as within-subjects variable. Table 5.1 presents mean values of kinematic parameters and as percentage of total movement duration. Mean values of movement duration across Conditions and Age groups are summarised in Table 5.2. The results revealed a statistically significant effect for Age, F (4, 415) = 11.41, p < .001; η_p^2 = .13. Follow-up univariate analyses indicated that this effect was significant in terms of Movement duration F(3, 418) = 39.55, p < .001; η_p^2 = .22, Peak velocity, F(3, 418) = 7.11, p < .001; η_p^2 = .05, Peak acceleration F(3, 418) = 11.26, p < .001; η_p^2 = .08, and Peak deceleration, F(3, 418) = 8.45, p < .001; η_p^2 = .06. Inspection of mean values confirmed overall increases in reach-to-grasp velocity with age (see Table 5.1).

Table 5.1. Mean values of kinematic parameters in ms and as percentage of total movement duration (N = 73).

	Kinematic parameter	**Reach-to-Grasp**		**Reach Component**		**Grasp Component**	
		M	*SD*	*M*	*SD*	*M*	*SD*
6-year-olds	Movement duration (ms)	920	219	752	196	168	59
	Time to peak velocity (ms)	351	121	351	121	765	21
	%	39	9	39	9	83	5
	Time to peak acceleration (ms)	199	123	189	98	865	20
	%	21	8	21	8	95	3
	Time to peak deceleration (ms)	499	158	473	131	899	214
	%	56	10	53	10	98	3
9-year-olds	Movement duration (ms)	835	142	694	127	141	48
	Time to peak velocity (ms)	348	73	348	73	702	132
	%	42	7	42	7	84	5
	Time to peak acceleration (ms)	201	79	198	74	791	131
	%	24	8	24	8	95	3
	Time to peak deceleration (ms)	469	96	468	92	822	138
	%	58	10	58	10	96	2
12-year-olds	Movement duration (ms)	764	121	653	104	111	29
	Time to peak velocity (ms)	334	64	334	64	661	108
	%	43	4	43	4	86	3
	Time to peak acceleration (ms)	183	54	183	54	729	110
	%	24	5	24	5	96	2
	Time to peak deceleration (ms)	449	81	446	78	754	116
	%	59	6	59	6	99	1
Adults	Movement duration (ms)	679	86	574	69	105	30
	Time to peak velocity (ms)	295	41	295	41	575	70
	%	43	4	44	4	85	3
	Time to peak acceleration (ms)	131	39	131	39	665	83
	%	19	6	19	6	98	2
	Time to peak deceleration (ms)	424	61	424	61	656	85
	%	62	6	62	6	99	1

Table 5.2. Mean reach-to-grasp (total movement) durations per condition collapsed across age groups (N = 73).

Age	Condition	*M*	*SD*
6-year-olds	(A) NO, No distractor	797 ms	123 ms
	(B) PC/SC, No semantic or perceptual competition	906 ms	187 ms
	(C) mPC/SI, Moderate semantic competition	865 ms	139 ms
	(D) iPC/SI, Increased semantic competition	974 ms	233 ms
	(E) mPI/SC, Moderate perceptual competition	922 ms	181 ms
	(F) iPI/SC, Increased perceptual competition	1071 ms	338 ms
	(G) PI/SI, Semantic and perceptual competition	899 ms	191 ms
9-year-olds	(A) NO, No distractor	771 ms	124 ms
	(B) PC/SC, No semantic or perceptual competition	834 ms	146 ms
	(C) mPC/SI, Moderate semantic competition	842 ms	141 ms
	(D) iPC/SI, Increased semantic competition	861 ms	157 ms
	(E) mPI/SC, Moderate perceptual competition	841 ms	156 ms
	(F) iPI/SC, Increased perceptual competition	891 ms	137 ms
	(G) PI/SI, Semantic and perceptual competition	809 ms	115 ms
12-year-olds	(A) NO, No distractor	712 ms	97 ms
	(B) PC/SC, No semantic or perceptual competition	794 ms	127 ms
	(C) mPC/SI, Moderate semantic competition	759 ms	108 ms
	(D) iPC/SI, Increased semantic competition	802 ms	149 ms
	(E) mPI/SC, Moderate perceptual competition	764 ms	135 ms
	(F) iPI/SC, Increased perceptual competition	777ms	107 ms
	(G) PI/SI, Semantic and perceptual competition	738 ms	108 ms
Adults	(A) NO, No distractor	671 ms	116 ms
	(B) PC/SC, No semantic or perceptual competition	659 ms	62 ms
	(C) mPC/SI, Moderate semantic competition	671 ms	56 ms
	(D) iPC/SI, Increased semantic competition	672 ms	51 ms
	(E) mPI/SC, Moderate perceptual competition	688 ms	102 ms
	(F) iPI/SC, Increased perceptual competition	708 ms	92 ms
	(G) PI/SI, Semantic and perceptual competition	684 ms	104 ms

No multivariate effects were observed for Condition, however, univariate tests suggested a main effect for Condition in terms of Movement duration, F(6, 418) = 3.71, p = .001; η_p^2 = .05. For planned comparison analyses Conditions were collapsed across Age. Post-hoc analyses revealed significant effects for Set size, in terms of Movement duration, F (2, 434) = 10.18, p < .001; η_p^2 = .05, with significant differences in mean scores between no distractor (*M* = 746 ms, *SD* = 122 ms) and both 1 distractor (*M* = 810 ms, *SD* = 156 ms) and 2 distractors (*M* = 868 ms, *SD* = 117 ms), and between 1 distractors (*M* = 810 ms, *SD* = 156 ms) and 2 distractors (*M* = 868 ms, *SD* = 175 ms). Table 5.3 summarises all mean values (Movement Duration) and Figure 5.4 illustrates mean values of Movement duration as a factor of Set Size. Contrasting movement duration in terms of Semantic compatibility also yielded a significant effect, F (2, 434) = 6.51, p = .02; η_p^2 = .03, however post-hoc analyses revealed that the only differences to reach significance were between no distractor (*M* = 746 ms, *SD* = 122 ms) and semantically compatible (*M* = 841 ms, *SD* = 193 ms), and no distractor (*M* = 746 ms, *SD* = 122 ms) and semantically incompatible (*M* = 817 ms, *SD* = 164 ms). Similarly, movement durations differed in terms of Perceptual compatibility F (2, 434) = 5.89, p = .003; η_p^2 = .03, with no distractors (*M* = 746 ms, *SD* = 122ms) leading to significantly lower movement durations compared to the perceptual compatible (*M* = 826 ms, *SD* = 166 ms) and the perceptual incompatible (*M* = 823 ms, *SD* = 192 ms) conditions. No significant differences were observed between perceptually compatible and perceptually incompatible distractor conditions. We also did not observe a significant interaction between Age and Condition. However, this interaction approached significance when contrasting movement durations in the youngest age group with adult mean values (F (2, 174) = 2.88, p = .059; η_p^2 = .03).

Further analyses were conducted to investigate the temporal occurrence of kinematic parameters in respect to the overall movement. Multivariate analyses of relative kinematic measures (Occurrence of peak velocity, Occurrence of peak acceleration, Occurrence of peak deceleration) yielded a significant effect of Age, $F(3, 416) = 10.63$, $p < .001$; $\eta_p^2 = .07$. The significance of this result was confirmed by univariate tests, indicating effects across all measures: Occurrence of peak velocity, $F(3, 418) = 13.29$, $p < .001$; $\eta_p^2 = .09$, Occurrence of peak acceleration, $F(3, 418) = 9.29$, $p < .001$; $\eta_p^2 = .06$, and Occurrence of peak deceleration, $F(3, 418) = 7.39$, $p < .001$; $\eta_p^2 = .05$. Mean values of relative kinematic parameters suggest a trend of increases in relative movement times with age (Table 5.1).

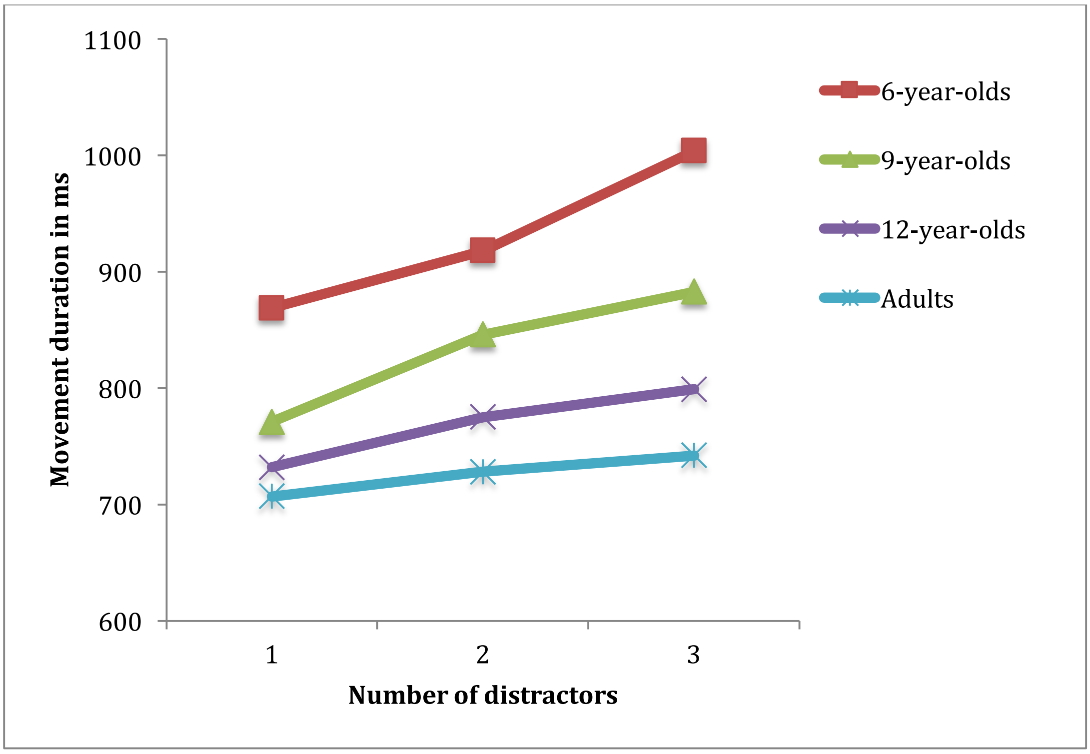

Figure 5.4. Overall movement duration as a factor of set size

Reach Component

Another set of analyses concerned the reach component across Age and Condition. Table 5.4 summarises all mean values for reaching duration (Reach duration). As with previous results there was a multivariate effect for Age, F (4, 415) = 9.05, $p < .001$; $\eta_p^2 = .08$, that was statistically significant for all kinematic measures: Movement duration F(3, 418) = 25.04, $p < .001$; $\eta_p^2 = .15$, Peak velocity, F(3, 418) = 7.09, $p < .001$; $\eta_p^2 = .05$, Peak acceleration F(3, 418) = 12.42, $p < .001$; $\eta_p^2 = .08$, and Peak deceleration, F(3, 418) = 4.85, p = .002; $\eta_p^2 = .03$. Univariate analyses collapsed across age further indicated a significant effect for Condition in terms of Movement duration F(6, 418) = 4.11, p = .001; $\eta_p^2 = .05$.

Follow-up tests of Movement duration (reaching duration) across conditions, yielded a main effect for Set size, F(2, 466) = 7.53, p = .002; $\eta_p^2 = .03$, with statistically significant increases in reaching durations in response to 2 distractors (*M* = 724 ms, *SD* = 187 ms) compared to 1 distractor (*M* = 676 ms , *SD* = 132 ms) and No distractor (*M* = 623 ms , *SD* = 101 ms), as well as in response to 1 distractor (*M* = 676 ms , *SD* = 132 ms) compared to No distractor (*M* = 623 ms , *SD* = 101 ms). In the same way, there were significant effects for Movement duration in respect to Semantic compatibility F (2, 434) = 5.66, p = .004; $\eta_p^2 = .03$, and Perceptual compatibility F (2, 434) = 5.45, p = .005; $\eta_p^2 = .02$. Post-hoc analyses revealed significant differences between no distractor and semantically compatible, no distractor and semantically incompatible, as well as between no distractor and perceptually compatible and no distractor and perceptual incompatible. In turn, contrasting Movement duration across Semantic and Perceptual compatibilities did not suggest significant differences.

The same pattern of results was observed for relative reaching times, with an effect for Age, F (4, 416) = 12.52, p < .001; η_p^2 = .08, that was driven by all relative kinematic measures: Occurrence of peak velocity, F(3, 418) = 13.26, p < .001; η_p^2 = .09, Occurrence of peak acceleration, F(3, 418) = 10.44, p < .001; η_p^2 = .07, and Occurrence of peak deceleration, F(3, 418) = 18.44, p < .001, η_p^2 = .12 (see Table 5.1 for mean values of relative kinematic parameters during reaching).

Grasp component

Here again, multivariate analyses of the kinematic measures revealed a statistical significant effect for Age, F (4, 415) = 14.73, p < .001; η_p^2 = .12. Follow-up analyses indicated that this effect was highly significant in terms of Movement duration F(3, 418) = 41.99, p < .001; η_p^2 = .23, Peak velocity, F(3, 418) = 25.68, p < .001; η_p^2 = .16, Peak acceleration F(3, 418) = 32.23, p < .001; η_p^2 = .19, and Peak deceleration, F(3, 418) = 35.86, p < .001; η_p^2 = .21 (see Table 5.1 for all mean values of the grasp component).

In addition, univariate analyses revealed a significant effect for Set size in terms of Peak velocity, F(2, 434) = 9.47, p < .001; η_p^2 = .04, with significant increases in response to No distractor (*M* = 627 ms, *SD* = 102 ms) compared to 2 distractors (*M*= 734 ms, *SD* = 193 ms), and further significant increases from 1 distractor (*M* = 684 ms, *SD* = 138 ms) to 2 distractors (*M* = 734 ms, *SD* = 193 ms). Planned comparisons also suggested similar differences in terms of Peak acceleration during grasping, F(2, 434) = 10.48, p < .001; η_p^2 = .05. In fact, a significant increase in time to peak acceleration was observed from the No distractor (*M* = 712 ms, *SD* = 109 ms) condition, to conditions with 2 distractors (*M* = 824 ms, *SD* = 198 ms), and from 1 distractor (*M* = 769 ms, *SD* = 143 ms) to 2 distractors (*M* = 824 ms, *SD* = 198 ms). Finally, there were further significant differences in terms of Peak deceleration, F(2, 434) = 10.37, p < .001; η_p^2 = .05, in the sense that the time required to Peak deceleration during grasping significantly increased from No distractor (*M* = 736 ms, *SD* = 117 ms) to 2 distractors (*M* = 854 ms, *SD* = 209 ms) and from 1 distractor(*M* = 797 ms, *SD* = 149 ms) to 2 distractors (*M* = 854 ms, *SD* = 209 ms).

In respect to Semantic compatibility, Peak velocity, F(2, 434) = 5.86, p = .003; η_p^2 = .03, Peak acceleration, F(2, 434) = 6.26, p = .002; η_p^2 = .03., and Peak deceleration, F(2, 434) = 6.39, p = .002; η_p^2 = .03, all yielded significant results, with significant increases in terms of peak times between No distractor and Semantically compatible and No distractor and Semantically incompatible conditions (Table 5.3. displays all mean values). The same pattern of results was observed for Perceptual compatibility, with significant effects for grasping Peak velocity, F(2, 434) = 5.66, p = .004; η_p^2 = .03, Peak acceleration, F(2, 434) = 5.94, p = .003; η_p^2 = .03., and Peak deceleration, F(2, 434) = 5.91, p = .003; η_p^2 = .03. Post-hoc tests again confirmed that these results were driven by significant differences of mean values between No distractor and Perceptual compatible/ Perceptual incompatible conditions (see Table 5.3 for mean values and standard deviations).

Table 5.3. Mean values of post-hoc comparison (Turkey HSD) collapsed across age groups (N = 73).

	Condition	Movement duration		Reach duration		Time to grasp peak velocity		Time to grasp peak acceleration		Time to grasp peak deceleration	
Age		*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Set Size	No distractor	746 ms	122 ms	623 ms	101 ms	627 ms	102 ms	712ms	109 ms	736 ms	117 ms
	1 distractor	810 ms	156 ms	676 ms	132 ms	684 ms	138 ms	769 ms	143 ms	797 ms	149 ms
	2 distractors	868 ms	175 ms	724 ms	187 ms	734 ms	193 ms	824 ms	198 ms	854 ms	209 ms
Semantic Compatibility	No distractor	746 ms	122 ms	663 ms	101 ms	627 ms	102 ms	712 ms	109 ms	736 ms	117 ms
	Semantically compatible	841 ms	193 ms	701 ms	165 ms	709 ms	171 ms	798 ms	179 ms	827 ms	187 ms
	Semantically incompatible	817 ms	164 ms	683 ms	141 ms	691 ms	147 ms	777 ms	148 ms	804 ms	157 ms
Perceptual Compatibility	No distractor	746 ms	122 ms	652 ms	101 ms	627 ms	102 ms	712 ms	109 ms	736 ms	117 ms
	Perceptually compatible	826 ms	166 ms	688 ms	141 ms	697 ms	148 ms	782 ms	149 ms	812 ms	159 ms
	Perceptually incompatible	823 ms	192 ms	696 ms	166 ms	704 ms	171 ms	792 ms	178 ms	819 ms	186 ms

Finally, a significant effects for Age was again confirmed in terms of relative grasping times, F (3, 416) = 11.62, $p < .001$; $\eta_p^2 = .08$. Separate analyses of kinematic measures during the grasp component suggested that this effect reached statistical significance across all measures: Occurrence of peak velocity, F(3, 418) = 14.99, $p < .001$; $\eta_p^2 = .11$, Occurrence of peak acceleration, F(3, 418) = 17.89, $p < .001$; $\eta_p^2 = .11$, and Occurrence of peak deceleration, F(3, 418) = 15.45, $p < .001$, $\eta_p^2 = .10$. Table 5.1 summarises mean values during the grasp component as percentage of the overall movement duration. No other main effects or interactions were observed.

5.4. Discussion

Human goal-directed action is highly selective and directed towards objects within a three-dimensional environment. Investigating kinematic parameters such as motion velocity, acceleration, and deceleration is one step forward in answering the question of why movement has the form it does. As outlined in the introduction, the discrete motion segments of complex actions are not solely shaped by the passive dynamics of our bodies. Movements that make up complex events are connected in a way that requires considerable planning and cognitive control. From an embodied cognition perspective, motion kinematics emerge in real time from the interactions between the properties of the body, cognitive-level selective processes, and the environment (e.g., Wilson & Golonka, 2013). Capturing motion allows us to indirectly measure these interacting resources that are distributed across the brain and body as motion unfolds.

It has been suggested that the processing of simultaneously presented objects interferes with reach-to-grasp actions as a results of automatic processing of even the task-irrelevant properties of the distractor (e.g., see Castiello 1996 for a review). As discussed in the introduction section, there has been some controversy as to what object property dimensions (e.g., perceptual features, semantic category) induce the processing interference identified in the kinematic pattern of adults' prehensile actions. Evidence concerning similar effects in children's reach-to-grasp actions has thus far been lacking. The current study provides the first kinematic investigation of interference effects across development.

As expected, results suggest overall reduced movement durations with age. Reach-to-grasp kinematic patterns have been observed to gradually reflect adult-like characteristics over the course of childhood (e.g., Coluccini, Maini, Martelloni, Sgandurra, & Cioni, 2005). Specifically, we observed substantial decreases in movement duration and the time required to reach peak velocity, peak acceleration and peak deceleration with age. Age differences in duration and velocity were reflected in both the reach and grasp component of the movement. In relative terms, analyses of kinematic measures revealed an increase in times to peak velocity, acceleration, and deceleration across age groups, with younger participants demonstrating peak occurrences earlier across reaching and grasping than older participants. Despite a suggested trend for prolonged movement durations as a function of set size in the youngest age group, we did not observe a significant interaction effect between age groups and distractor conditions. This observation suggested that the influence of distractor objects was relatively comparable across the four age groups in this study.

The results of this study indicate that interference effects were reflected in some kinematic measures (i.e., movement duration, peak velocity, peak acceleration/ peak deceleration) but not in others (occurrence of peaks within the total movement). In addition, results suggest similar influences on participants' kinematic profiles across the reach and grasp components of the action. However, overall, we also observed stronger effects in the grasp component. This observation is compatible with Jervis et al.'s (1999) finding of interference in grasping but not reaching kinematics.

Considering both reaching and grasping together suggested prolonged movement durations in the increased perceptually incompatible - semantically compatible, as well as in the increased perceptually compatible - semantically incompatible distractor condition. Given that these conditions involved two distractor objects that featured opposite perceptual and semantic attributes it is unlikely that interference effects in this study arise from perceptual or semantic competition. In turn, the fastest movement velocities were observed in the no distractor condition followed by reach-to-grasp actions in the PI/SI distractor condition. Thus, it appears that interference effects were primarily related to the number of distractor objects that were presented simultaneously, irrespective of their semantic and perceptual relatedness to the target. Similarly, when considering the reach and grasp components separately, the times to kinematic peak measures were highest overall when participants encountered more than a single distractor object. In contrast, the presentation of a single distractor object that was incompatible to the target caused moderate inference effects (prolonged movement durations). A distractor that was both perceptually and semantically incompatible to the target, however, resulted in movement durations and velocities that were comparable to those observed in the no distractor condition.

As others have argued, selective attention requires inhibitory mechanisms to effectively suppress the influence of distracting information (e.g., Tipper, Howard, & Houghton, 1998). In a related point, it has been observed that strongly salient distractors trigger higher levels of suppression during goal-directed actions, and therefore lower levels of interference than less salient distractors (e.g., Moher, Anderson, & Song, 2015). This finding, while counterintuitive, relates to the argument that efficiency and accuracy on a reaching task may well be enhanced when the perceptual information is highly conflicting. As such, enhanced conflict on a task results in the recruitment of higher levels of cognitive control (e.g., Botvinick et al. 2001; see Chapter 1, Figure 1.2 for a schematic depiction of conflict monitoring). Indeed, in the current study a highly salient distractor, that was both perceptually and semantically incompatible with the target object, did not induce interference effects in the kinematic parameters of the reach-to-grasp action. However, the observed movement durations and peak velocities suggest no more than a small processing advantages for salient distractors (PI/SI) compared to distractors that were perceptually and semantically compatible with the target object (PC/SC).

While the observation of a gradient in movement duration as a function of the set size is compatible with the notion that interference effects are triggered by processing competition, our results suggest that the nature of this competition may not be limited to either semantic or perceptual object properties. It is likely that, during action selection, distractor objects are considered in more than a single dimension depending on the event context and the behavioural goal of the action. However, in the present study, participants' actions were not related to a particular higher-level goal or event context. An outstanding question, therefore, concerns whether objects of behavioural relevance also trigger interference effects in children's reach-to-grasp actions. For instance, evidence with adults suggests that object manipulation (e.g., during tool use) enhances visual perception, alters distance judgments, and prolongs the allocation of attention during reaching actions (e.g., see Brockenmole, Davoli, Abrams, & Witt, 2013 for a review). Similarly, movement kinematics are influenced by an agent's intentions (e.g., Becchio et al., 2010; Marteniuk et al., 1987). Recently, it has been suggested that adults are sensitive to kinematic patterns when observing an agent's action and are further able to use this information to discriminate people's intentions (e.g., Ansuine, Cavallo, Bertone, & Becchio, 2014). This line of research again highlights the strong link between action perception and production that is discussed in Chapter 1. Kinematic evidence strengthens this notion by demonstrating that covert mental states can be inferred by means of overt motor behaviour. Future research will explorer the ontogeny of this sensitivity in respect to the ability to represent hierarchical action structures. For instance, there is currently no evidence regarding the influence of kinematic information on young children's abilities to interpret an agents' intentions. Likewise, it is plausible that kinematic patterns uniquely contribute to the detection of structure in perceived sequential events and thus relevant additional information in agents' actions.

These findings support an embodied view of the spatial representation that is influenced by internally specified goals. In a related sense, it is certainly plausible that the distance between the reaching hand and the target object influences the level of interference effects in young children. Developmental research suggests that visual and tactile exploration of objects within the peripersonal space is a crucial ingredient in young infants' representation of the interface between bodily and external space (e.g., Bremner, 1978; Bremner & Cowie, 2013; Bremner, Mareschal, Lloyd-Fox, & Spence, 2008). This early ability to incorporate information about spatial location in respect to the position of the body is likely to aid the locating of objects that are placed in close proximity to the body.

The influence of distractor objects has been investigated in studies concerned with motor distractibility. Most notably, Ambron, Della Sala, & McIntosh (2012) noted increased shifts towards distractor objects in preschoolers that also demonstrated closing-in behaviours compared to adults and preschoolers without closing-in tendencies. Closing-in refers to the moving towards or overlapping of graphical representations (e.g., images of shapes) when asked to copy. This phenomenon observed in young children and adults with dementia has been critically associated with attentional impairments (e.g., Ambron, McIntosh, et al., 2009). Ambron et al. (2012) argued that the kinematics of copying in this study was fundamentally affected by manual attraction through the exogenous capture of attention by distractors. The evidence on closing-in behaviours is consistent with Tipper et al.'s (1998) argument that the presentation of distractors entails attention to the location of the distractors and preparation of movement towards this location.

Most notably, while participants did not know in advance which distractor objects they would face on each trial, the target object itself and its location never changed. Despite the high predictability of the target action, various kinematic parameters in this study reflected interference effects. In adults and children of different ages, the presence of distractors triggered processing competition that was overcome through mechanisms of selective spatial attention. The observation that movement kinematics in a prehensile action are affected by competing visual input suggests that a considerable part of motor planning is carried out on-line, both in children and adults. Furthermore, this flexibility in selective processes holds important advantages for action planning in real life event contexts. Despite hard-won event knowledge, one cannot always know in advance the type of motor pattern and level of motor control that a given action will require. What inference effects, therefore, indirectly reflect is the highly adaptive ability to adjust action performance through adjustments in attentional selection.

In conclusion, the results of this study suggest moderate interference effects in the kinematic parameters of a reach-to-grasp action as a result of processing competition between the target and distractor object across development. Our results further suggest that the degree to which movement durations and peak velocities were affected by interference effects is mediated by set size. When selecting a target object among multiple competing distractors, mechanisms of selective spatial attentions come into play to configure appropriate action plans. Interference effects thus support the notion of a close link between action and perception that together constraints and shape goal-directed behaviour. The bases through which children gradually overcome processing conflict through top-down spatial attention are yet to be explored (although see Botvinick & Cohen, 2001 for a accounts of conflict monitoring in adults).

The aim of the next chapter is to reflect on how the individual studies in this project relate to each other as well as to the wider action research. This final section will also discuss the general limitations of the tasks used in this work. The chapter concludes setting future perspectives and a brief discussion of why further investigations should build on the evidence generated in this project.

CHAPTER 6

What does it mean?

All goal-directed actions require active mental representations of goal states and are, thus, at least partially planned prior to movement initiation. While planning of complex behaviours entails abstractions at multiple levels of the goal hierarchy, even simple motor acts are planned in terms of their anticipated action effects (e.g., Hauf & Prinz 2005; Wood & Neil, 2007; Sommerville & Woodward, 2005). The foregoing chapters discussed empirical evidence concerning preschoolers' abilities to process hierarchical goal structure when perceiving and planning goal-directed events.

Both the comprehension of observed actions and the execution of goal-directed behaviour are fundamentally informed by anticipations of action effects. However, disambiguating goals in relation to specific contexts, detecting coherence among discrete actions, and discerning the intentions of others is not straightforward. Low-level structure detection may constitute an early mechanism by which action observation gradually develops towards more fine grained and meaningful analysis of the observed behaviour. In **Study 1** (*'The planning and execution of natural sequential actions in the preschool years',* Chapter 2) we ask how internal intentions interact with external opportunities during the planning of a realistic action sequence. The findings from two behavioural experiments with 3- and 5- year-olds suggest the presence of a developmental change in the ability to structure observed actions in terms of goal hierarchies.

In Chapter 2 we discussed the links between internally specified goals and external opportunities during the planning of a naturalistic action sequence. The results of two behavioural experiments suggested considerable developmental change in learning from observed behaviour between the ages of 3 and 5 years. One aim of this first study was to investigate preschoolers' tendencies to incorporate modelled actions into their own subsequent performance. We presented preschoolers with a familiar event sequence that was composed of actions that could be linked to specific goals, as well as actions that did not appear to serve the overarching goal of the sequence in an interpretable way. In contrast to previous over-imitation studies, our results strongly suggest that preschoolers' planning was perceptually informed by both a prior demonstration and the presence of external cues in this task. Importantly, while 3-year-olds demonstrated overall a high susceptibility for over-imitation behaviour as a result of a single misleading demonstration, this tendency was overcome when procedural components of the sequence were spatially cued. We concluded Chapter 2 with a discussion of preschoolers' planning abilities in relation to the role of prior event knowledge and reflected on the notion of graded goal representations in children (e.g., Munakata. O'Reilly, & Morton, 2007; Munakata & Yerys, 2001). As part of this first study we observed that young preschoolers expected sub-actions that followed each other to form part of the same goal-directed sequence.

These observations are in good agreement with the findings from our first study in the sense that young preschoolers particularly strongly relied on the available perceptual cues to make inferences about causes and effects; actions and outcomes. Thus, together, the results of the first two studies in this project provide strong evidence that with age preschoolers increasingly interpret events in terms of higher-level goals. However, what these studies also suggest is that bottom-up knowledge critically influences how preschoolers plan subsequent interventions.

The argument that preschoolers' higher-level action planning is greatly informed by bottom-up processes has important considerations for real-life learning situations. As discussed in Chapter 1, naturalistic events tend to comprise multiple sequential actions that contribute to temporally delayed and spatially distal outcomes. Therefore, providing greater perceptual support to structure the hierarchical relations underlying events may effectively scaffold preschoolers' learning in sequential tasks. However, sensitivity to the underlying event structure is unlikely to singlehandedly account for young children's increasing abilities to pursue higher-level goals. As argued in Chapter 3, naturalistic goal-directed behaviours require the engagement and maintenance of appropriate levels of cognitive control over relatively extended intervals of time. For instance, sequential actions that span multiple levels of abstraction are likely to demand high levels of cognitive control (e.g., Amso, Haas, McShane, & Badre, 2014). In the introduction Chapter, as well as in Chapter 3, we summarised various lines of developmental evidence suggesting that self-regulatory processes, involved in the ability to maintain, modify, and delay distal goals undergo important changes during the preschool years and continue to improve thereafter (e.g., Anderson, 1998; Brydges, Reid, Fox, & Anderson & Reidy, 2012; Diamond 2002; Giedd & Rapoport 2010; Levin et al. 1991; Luria, 1974; Posner & Rothbart, 1998; Yakovlev & Lecours, 1967; Welsh, Pennington, & Groisser, 1991).

During the preschool period, children show increasing abilities to use abstract action knowledge to pursue complex goals. This advance in action parsing and planning abilities is paralleled by increasing abilities to evaluate and adapt action plans in relation to complex goal hierarchies. Once action plans are formed, performance monitoring, mediated by neural networks within frontal and parietal brain regions, comes into play.

Study 2 (*'Preschool children's control of action outcomes'*, Chapter 3) explores preschoolers' strategic action planning oriented towards distal goals, and asks how this ability relates to mechanisms of cognitive control. Here, results suggest that the ability to maintain top-down control and adjust behavioural responses at multiple levels of abstraction undergoes a marked improvement from 3 to 5 years of age.

In Study 2 (Chapter 3), we investigated the degree to which 3- and 5-year-olds endogenously detect the need to adjust top-down control in the face of conflicting information across two experiments. Using a novel sequential colouring task, we assessed preschoolers' abilities to implement strategic action planning to reach goals at sub- and superordinate levels of the goal hierarchy. Given the lack of external feedback in this task, incorrect response selections were not readily apparent unless children evaluated outcomes at multiple levels of abstraction. The results of this study suggest that young preschoolers in particular demonstrate a strong tendency to direct their attention towards stimulus-implicit and intuitive outcomes (the colouring activity in this task). In Chapter 3 we interpret this observation in relation to the cognitive demands required for monitoring a distal and abstract outcome in addition to more intermediate steps of the sequence.

The findings of Study 2 compliment Studies 1 in highlighting that 3- and 5-year-olds demonstrate differential abilities to evaluate the demand for cognitive control in complex sequential tasks. Collectively, the behavioural findings described in the first three studies of this project (Chapters 2, 3, and 4), thus support the view that the ability to engage adequate cognitive control to support hierarchical action selection over space and time improves during early childhood. However, these studies do not directly inform about the mechanisms that drive young children's comprehension of higher-level goals.

Neuropsychological evidence with adults suggests that the human action network is likely to implicate frontal, parietal and temporal brain regions. To date almost nothing it known about the neural underpinnings that mediate advances in action comprehension and planning abilities during the preschool period. Using electrophysiological measures, **Study 3** (*'Convergent ERP and behavioural evidence of preschoolers' understanding of action goals'*, Chapter 4) set out to investigate the neurocognitive mechanisms implicated in the perception of higher-level goals. The findings of this event-related potential (ERP) study highlight the functional importance of mid-latency components during the semantic integration of action outcomes into a preceding event context. Convergent behavioural data on a picture-matching task revealed associations between preschoolers' ERP patterns and their abilities to explicitly judge whether actions are contextually linked to specific outcomes.

Study 3 (Chapter 4) investigated the development of the neurocognitive underpinnings during goal perception across the preschool years and in adults. Using a novel ERP paradigm we studied the integration of higher-level goals into a preceding event context. We presented 3-year-olds, 5-year-olds, and adults with dynamic scenes of everyday goal-directed actions in which final actions either matched or mismatched the overall event context. The distinct patterns of brain activity evoked in this study suggest that observing context compatible actions activates representations of expected outcomes. In contrast, context incompatible actions were unexpected for both adults and preschoolers. The attempt to embed incongruent final actions into the preceding action context yielded significant conflict as indicated by mid-latency ERP components. In addition, the preschoolers in this study carried out a behavioural task in which outcomes and actions had to be judged based on their semantic relatedness. This convergent behavioural experiment revealed associations between 3-and 5-year-olds' ERP patterns and their abilities to judge explicitly whether actions were contextually linked to higher-level goals. The findings of this study indicate that, like adults, preschoolers processed the incongruence of final actions by means of perceptual (reflected at early processing stages) as well as conceptual inferences (reflected in N400 ERP activity). This observation is in good agreement with findings form Study 3 as it suggests that the processing of actions takes place simultaneously at multiple levels of analyses. This finding is further supported by evidence from other ERP studies in adults and infants (e.g., Hard, Recchia, & Tversky, 2011; Pace, Carver, & Friend, 2013). However, there were also important differences between adults and preschoolers in the topographical distribution of mid-latency components. For instance, an N400-like component was frontally distributed in adults but had a posterior component in preschoolers.

Chapter 4 concluded with a discussion of the ERP and behavioural results in relation to the development of semantic networks within frontal, parietal, and temporal cortices. In addition, we put forth the hypothesis that adults may have focused on relating higher-level goals into a coherent abstract representation of the event (indicated by a frontally distributed N400-like component), whereas preschoolers based semantic analyses on more concrete action-related requirements (reflected in a posterior N400-like component). We further argued that the mechanisms that gave rise to the detection of incongruence may well differ for adults and preschoolers. While, at the present, the functional importance of the N300/N400 distribution remains speculative, the comparable latencies of ERP components in Study 4 support the argument that preschoolers and adults engage similar cognitive mechanisms in the semantic processing of action sequences. In addition, the findings of this study suggest that both perceptual and conceptual mechanisms operate together in the semantic analyses of sequential goal-directed actions. This ERP study further ties in with the behavioural findings from Studies 1 and 2 because it again underlines the importance of evaluative processes that drive the detection of conflict within the context of specific events. In the final study of this thesis we revisited this point in connection with the role of selective attention in the planning of goal-directed actions.

Finally, an important objective of this thesis was to provide new insight concerning the development of action cognition by investigating fundamental action-related processes at multiple levels. Thus, **Study 4** (*'Interference effects in reach-to-grasp action across development'*, Chapter 5) explores cognitive interference on action planning at the level of raw movement as indicated by specific kinematic parameters of reach and grasp actions. Results from this motion-capture experiment reflect developmental effects in the influences of planning related processes, which are far-reaching and traceable at the stage of motor output.

The context of many everyday-behaviours is characterised by tremendous amounts of competing sensory input. Selective attention guides the allocation of appropriate levels of attentional control to regulate actions in a highly adaptive goal-directed manner. Therefore, attentional mechanisms provide functional links between conflict and control, and thus between perception and action. Taking on a bottom-up perspective we investigated the role of interference effects in reaching-kinematics triggered by competing visual input. Using motion-capture methods we presented four age groups of children (6-12 years) and adults with a reach-to-grasp paradigm. This study provided the first developmental investigation of planning related processes that are traceable at the stage of the motor output. The results of

Study 4 (Chapter 5) suggest that the kinematic parameters of children's reach-to-grasp actions are indeed affected by interference effects caused by the evaluation of distractor objects. We further observed that the level of interference reflected in reaching and grasping kinematics was mediated by stimulus set size. Moreover, while the magnitude of interference effects was age depended, the kinematic patterns were similar across development. In Chapter 6 we discussed the implications of these findings in the context of selective spatial attention. As with the previous studies of this project, the outcomes of this kinematic experiment support the notion of a close link between action and perception that together constrain and shape the planning and execution of goal-directed behaviour. Study 5 adds to the findings discussed in the previous sections by demonstrating that bottom-up and top-down interactions are evident not just in cognitive terms (Study 1 & 2)) and neurocognitive mechanisms (Study 3), but even at the stage of motor output.

Taken together the findings of this project suggest that the preschool years are a period during which basic action-outcome contingencies become transformed into increasingly complex means of goal pursuit. Moreover, important advances in cognitive control and causal reasoning drive developmental effects in implementing strategic action planning. In addition, we observed developmental effects in the ability to monitor actions at lower and higher-levels of abstraction between the ages of 3 and 5 years.

A popular view in psychological science postulates that real-world cognitive mechanisms operate, first and foremost, to guide situation-appropriate behaviour (e.g., Wilson, 2002). The idea that cognition is situated (i.e., taking place in the context of a task in which actions are carried out while receiving sensorimotor feedback) has been advanced to the point of making the claim that, at the representational level, planned action and perceived events are essentially the same (e.g., Theory of Event Coding, Hommel et al. 2001). Similarly, action-oriented predictive coding theories unify action, perception, and cognition into cascades of predictions that span across all levels of the action hierarchy; from motor commands, through to anticipated sensory effects, all the way up to higher-level goals (see Clark, 2013 for a review). According to this view, "thinking, predicting, and doing are all part of the same unfolding of sequences moving down the cortical hierarchy" (Hawkins & Blakeslee 2004, p. 158). In a related sense, embodied cognition accounts and ideomotor perspectives stress the role of active agency in knowledge acquisition. The notion that goals are acquired through action experience is relevant especially in an educational context. For instance, the idea that children learn best through *reflective activities* (e.g., Greeno, 1998), commonly referred to as "learning-by-doing", is an integral part of current educational practices. As such, being the agent of an action, as well as adopting a first person's perspective when observing others, benefits knowledge acquisition of the relationships between goals, actions, and outcomes (e.g., Gianelli, Farnè, Salemme, Jeannerod, & Roy, 2011).

However, accounts of *how* higher-level action representations are acquired and updated over the course of development are currently missing. Collectively, the findings of the current project underscore that the development of action cognition during early childhood is characterised by advances in interacting perceptual and conceptual processes.

Children observe many goal-directed events on a daily basis. Some of these are unfamiliar or at least not well understood. The foregoing chapters have discussed preschoolers' abilities to perceive and interpret goal hierarchies, and how learned action-outcome relations are used to plan and control complex goal-directed behaviours. We reviewed existing evidence of how internal descriptions of sequential events are achieved based on perceptual and conceptual processes and how these processes compare to infant and adult cognition. We have also argued that the parsing of higher-level goals is largely context dependent and critically influenced by prior knowledge.

A key argument of the four studies carried out in this project is that action comprehension and execution is achieved through the anticipation of outcomes. In fact, goal representations themselves appear to drive selective processes at multiple levels of the action hierarchy (e.g., see Grafton & Hamilton, 2007 for a review). As discussed in Chapters 1, 2, and 3, there is a large volume of studies suggesting that infants are capable of perceiving simple action-effect contingencies. Together, the findings of the current project suggest that the preschool period is a time during which children begin to demonstrate good abilities to represent goals simultaneously at lower and higher levels of abstraction. To investigate the early developmental trajectories of action-related cognitive and neural processes, this project has employed multiple methodologies and has used a range of novel tasks that were specifically designed to achieve greater ecological validity than the existing cognitive measures.

Collectively, the developmental effects we observed across the studies in this project substantiate the view that the preschool period is a time of dramatic developmental change in terms of the comprehension, planning, and regulation of goal-directed actions. Taken together the findings of five studies suggest that during the preschool years basic action-outcome contingencies become transformed into increasingly complex means of goal-pursuit. By the end of preschool, children show remarkable abilities to use abstract action knowledge in order to pursue complex goals. Nevertheless, numerous unresolved questions remain in our understanding of action cognition during this critical time in development. The studies presented in this thesis are limited in the sense that they only provide cross-sectional evidence of the developmental changes that take place. More detailed analyses of age-dependent effects are needed to define the developmental trajectories that characterise the preschool period. Relatedly, given the large amount of within-subject variability during this time in development (see Chapter 1 for a discussion of this issue), retesting children may reveal considerable fluctuations in planning and monitoring abilities. The question then begs the question of asking what factors predict low and high levels of performance, and where does within-subject variability on planning and decision-making tasks come from.

In the current project we did not follow up participants, nor did we obtain other indices that would have potentially informed us about children's general cognitive performance (e.g., nursery reports, school assessments). It should also be noted that a drawback of attempting to use more ecologically valid tasks is that these tasks are novel and, thus, not yet validated with different groups of subjects. Therefore, it is possible that our results are affected by extraneous factors such as parental education, preschool attendance, home enrichment factors, and socioeconomic background. While the same argument has been made in connection to well-validated standardised tasks (e.g., Noble, Norman, & Farah, 2005), it is nonetheless important to investigate the impact of such factors on the performance measures we used in this project. Finally, we did not explicitly address how planning and monitoring abilities relate to preschoolers' remarkable improvements in other cognitive domains (e.g., social cognition). Integrating action-related processes into a larger picture of cognitive, motoric, and social advances is likely to reveal relationships that go beyond the development of action cognition.

While this project sought to shed light onto the cognitive processes and neural mechanisms that underlie preschoolers' advances in the processing of higher-level goals, the studies discussed in the foregoing chapters provide only a first step into this direction. Therefore, this project is only an initial investigation of critical action-related processes that, thus far, have only been studied in infants, older children, and adults. Addressing this gap in the developmental literature is important because planning and monitoring abilities form the basis for a myriad of academic and social achievements later in life (e.g., Mischel, et al., 2011). For example, a recent meta-analysis spanning 75 individual studies revealed that the academic success of children significantly correlates with individual performances on cognitive control tasks (Allan, Hume, Allan, Farrington, & Lonigan, 2014). In fact, children's academic success during the first grade of elementary school significantly predicts academic achievements in later years (e.g., Entwistle & Hayduk, 1988). It thus appears that inter-individual differences in planning abilities and regulatory processes are laid out early in life. Educational interventions during the preschool period may more effectively target learning deficits from the earliest point of formal education and thus before severe academic delays emerge.

One examples of how educational practices may benefit from the evidence put forth in this project concerns the role of cognitive control for planning and adaptive decision making. Future research should aim to identify the links between inter-individual differences in learning and how strongly children weigh bottom-up and top-down information. As discussed in this thesis, we do not currently understand how young children shift from perceptually driven action planning to more abstract forms of event processing. Future investigations of how planning strategies emerge and evolve to bridge multiple levels of abstraction will provide critical insight regarding the origins of low and high performance levels on sequential tasks, such as those used in the current project. Educational practices may also benefit from scientific evidence concerning how children begin to rely on top-down knowledge while ignoring misleading and counterfactual information. To tackle this question future studies should seek to identify under what circumstances novel information is integrated into existing event representations. Finally, research in this direction may greatly advance our understanding regarding the mechanisms that allow for adaptive planning as a result of performance feedback. To date there are no studies linking inter-individual differences in the processing of action errors to learning rates and cognitive profiles. In summary, understanding the parallel processes that emerge in connection to action-related abilities is likely to generate promising interventions that will promote learning from a bottom-up and top-down perspective.

REFERENCES

Allan, N.P., Hume, L.E., Allan, D.M., Farrington, A.L., Lonigan, C.J. (2014). Relations between Inhibitory Control and the Development of Academic Skills in Preschool and Kindergarten: A Meta-Analysis. *Developmental Psychology, 10,* 2368-2379.

Allison T, et al. (2000). Social perception from visual cues: role of the STS region. *Trends Cognitive Science, 4,* 267–278.

Alloway, T.P., Pickering, S.J., & Gathercole, S.E. (2006). Verbal and Visuospatial Short-Term and Working Memory in Children: Are They Separable? *Child Development, 77*, 1698-1716.

Ambron, E., Della Sala, S., & McIntosh, R.D. (2012). Closing-in behaviour and motor distractibility. *Neuropsychologia, 50,* 419-425.

Ambron, E., McIntosh, R.D., Allaria, F., & Della Sala, S. (2009). A large-scale retrospective study of closing-in behaviour in Alzheimer's disease. *Journal of the International Neuropsychological Society, 15*, 787-792.

Amoruso, L., Gelormini, C., Aboitiz, F., González, M.A., Manes, F., Cardona, F. & Ibanez, A. (2013). N400 ERPs for action: building meaning in context. *Frontiers in Human Neuroscience,* Doi: 10.3389/fnhum.2013.00057.

Amso, D., Haas, S., McShane, L., & Badre, D. (2014). Working memory updating and the development of rule-guided behaviour. *Cognition, 133 (1),* 201-210.

Anderson V. (1998). Assessing executive functions in children: biological, psychological, and developmental considerations. *Neuropsychological Rehabilitation, 8,* 319–349.

Anderson, P.J., & Reidy, N. (2012). Assessing executive functions in preschoolers. *Neuropsychological Review, 22*, 345-360.

Ansuini, Cavallo, Bertone, & Becchio, C. (2014). The visible face of intention: why kinematics matters. *Frontiers in Psychology, 5*, 815.

Antell, S. E., & Keating, D. P. (1983). Perception of numerical invariance in neonates. *Child Development, 54*, 695–701.

Asch, S.E. (1952). *Social Psychology.* New York: Prentice- Hall.

Badre, D. (2008). Cognitive control, hierarchy, and the rostro-caudal organization of the frontal lobes. *Trends in Cognitive Neuroscience, 12(5),* 193-200.

Badre, D. & D'Esposito, M. (2007). FMRI evidence for a hierarchical organization of the prefrontal cortex. *Journal of Cognitive Neuroscience, 19 (12),* 1–18.

Badre, D., & Frank, M.J. (2012). Mechanisms of hierarchical reinforcement learning in cortico-striatal circuits 2: evidence from fMRI. *Cerebral Cortex, 22,* 527-536.

Badre, D., Lebrecht, S., Pagliaccio, D., Long, N.M., & Scimeca, J.M. (2014). Ventral striatum and the evaluation of memory retrieval strategies. *Journal of Cognitive Neuroscience, 26 (9),* 1928-1948.

Badre, D. & Wagner, A.D. (2007). Left ventrolateral prefrontal cortex and the cognitive control of memory. *Neuropsychologia, 45,* 2883-2901.

Baird, J., & Baldwin, D. A. (2001). Making sense of human behavior: Action parsing and intentional inference. In B. F. Malle, L. J. Moses, & D. A. Baldwin (Eds.), *Intentions and intentionality: Foundations of social cognition.* Cambridge, MA: MIT Press.

Balconi, M. & Caldiroli, C. (2011). Semantic violation effect on object-related action comprehension. N400-like event-related potentials for unusual and incorrect use. *Neuroscience, 197,* 191–199.

Baldwin, D. A., Andersson, A., Saffran, J. R., & Meyer, M. (2008). Segmenting dynamic human action via statistical structure. *Cognition, 106 (3),* 1382–1407.

Baldwin, D. A., Baird, J. A., Saylor, M. M., & Clark, M. A. (2001). Infants parse dynamic action. *Child Development, 72*, 708–717.

Barch, D.M., Braver, T.S., Nystrom, L.E., Forman, S.D., Noll, D.C., & Cohen, J.D. (1997). Dissociating working memory from task difficulty in human prefrontal cortex. *Neuropsychologia 35*, 1373–1380.

Barker, R. G., & Wright, H. F. (1954). *Midwest and its children: The psychological ecology of an American town.* Evanston, IL: Row, Peterson.

Barrett, S. E., & Rugg, M. D. (1990*).* Event-related potentials and the phonological matching of picture names*. Brain and language, 38 (3),* 424-437.

Bates, A., Carlson-Luden,V., Bretherton, I. (1980). Perceptual aspects of tool using in infancy. *Infant Behaviour and Development 3*, 127-140.

Bauer, P.J. (2005). Developments in declarative memory - decreasing susceptibility to storage failure over the second year of life. *Psychological Science, 16 (1),* 41-47.

Bauer, P.J. (2007). Recall in infancy: A neurodevelopmental account. *Current Directions in Psychological Science, 16,* 142-146.

Bauer, P.J., & Fivush, R. (1992). Constructing event representations: building a foundation of variation and enabling relations. *Cognitive Development, 7,* 381-401.

Bauer, P.J., & Mandler, J. M. (1989). One thing follows another. Effects of temporal structure on 1-to 2-year-olds‘ recall of events. *Developmental Psychology, 25*, 197-206.

Bauer, P.J., & Mandler, J. M. (1992). Putting the horse before the cart: the use of temporal order in recall of events by one-year-old children. *Developmental Psychology, 28 (3),* 441-452.

Bauer, P.J., Kroupina, M.G., Schwade, J.A., Dropik, P.L., & Wewerka, S.S. (1998). If memory serves, will language? Later verbal accessibility of early memories. *Development and Psychopathology, 10,* 655-679.

Bauer, P.J., & Thal, D.J. (1990). Scripts or Scraps: Reconsidering the development of sequential understanding. *Journal of Experimental Child Psychology, 50*, 287-304.

Beccio, C., Sartori, L., & Castiello, U. (2010). Towards you: the social side of actions. *Current Directions in Psychological Science, 19,* 183-188.

Bedny M, Caramazza A., Grossman E., Pascual-Leone A. & Saxe R. (2008) Concepts are more than percepts: The case of action verbs. *Journal of Neuroscience, 28 (44),* 11347-11353.

Bekkering, H., Wohlschläger, A., & Gattis, M. (2000). Imitation of gestures in children is goal-directed. *Quarterly Journal of Experimental Psychology Section A Human Experimental Psychology, 53,* 153-164.

Bell, J.A., & Livesey, P.J. (1985). Cue significance and response regulation in 3- to 6-year old-children's learning of multiple choice discrimination tasks. *Developmental Psychobiology, 18,* 229–245.

Bhandari, A., & Duncan, J. (2014). Goal neglect and knowledge chunking in the construction of novel behaviour. *Cognition 130 (1),* 11-30

Binkofski, F., Buccino, G., Posse, S., Seitz, R. J., Rizzolatti, G. & Freund, H.J. (1999). A frontoparietal circuit for object manipulation in man: evidence from an fMRI-study. *European Journal of Neuroscience, 11,* 3276–3286.

Bonawitz, E.B., Ferranti, D., Saxe, R., Gopnik, A., Meltzoff, A.N., Woodward, J., & Schulz, L.E. (2010). Just do it? Investigating the gap between prediction and action in toddlers causal inferences. *Cognition, 115,* 104–117.

Bonda, E., Petrides, M., Ostry, D. & Evans, A. (1996). Specific involvement of human parietal systems and the amygdala in the perception of biological motion. *Journal of Neuroscience, 16*, 3737–3744.

Bortoletto, M., Mattingley, J. B., & Cunnington, R. (2011). Action intentions modulate visual processing during action perception. *Neuropsychologia, 49 (7),* 2097-2104.

Botvinick, M.M., Braver, T.S., Barch, D.M., Carter, C.S., & Cohen, J.D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108 (3),* 624-652.

Botvinick, M.M. & Toussaint, M. (2012). Planning as inference. *Trends in Cognitive Science*, *16 (10),* 485-488.

Bracci, S., Cavina-Pratesi, C., Ietswaart, M., Caramazza, A. & Peelen, M. (2012). Closely overlapping responses to tools and hands in left lateral occipitotemporal cortex. *Journal of Neurophysiology, 107 (5),* 1443-1456.

Brass, M., Schmitt, R. M., Spengler, S., & Gergely, G. (2007). Investigating action understanding: inferential processes versus action simulation. *Current Biology, 17,* 2117–2121.

Braver, T.S. (2012). The variable nature of cognitive control: a dual mechanisms framework. *Trends in Cognitive Science, 16,* 106-113.

Braver, T.S., & Bongiolatti, S.R. (2002). The role of frontopolar cortex in subgoal processing during working memory. *Neuroimage, 15,* 523-536.

Braver, T.S., Cohen, J.D., Nystrom, L., Jonides, J., Smith, E., & Noll, D.C. (1997). A parametric study of prefrontal cortex involvement in human working memory. *Neuroimage, 5,* 49-62.

Bremner, J.G. (1978). Egocentric versus allocentric spatial coding in nine-month-old infants: Factors influencing the choice of code. *Developmental Psychology. 14,* 4, 346-355.

Bremner, A. J., & Cowie, D. (2013). Developmental origins of the hand in the mind, and the role of the hands in the development of the mind. In. Z. Radman (Ed.), *The hand: An organ of the mind. What the manual tells the mental* (pp. 27-55). Cambridge, MA: MIT Press.

Bremner, A. J., Mareschal, D., Lloyd-Fox, S., & Spence, C. (2008). Spatial localization of touch in the first year of life: early influence of a visual spatial code and the development of remapping across changes in limb position. *Journal of Experimental Psychology: General,* 137, 149-162.

Brockmole, J. R., Davoli, C. C., Abrams, R. A., & Witt, J. K. (2013). The world within reach: Effects of hand posture and tool-use on visual cognition. *Current Directions in Psychological Science, 22,* 38-44.

Brownell, C.A., (1988). Combinatorial skills: Converging developments over the second year. *Child Development, 59,* 675-685.

Brugger, A., Lariviere, L.A., Mumme, D.L., & Bushnell, E.W. (2007). Doing the right thing: infants' selection of actions to imitate from observed event sequences. *Child Development, 78,* 806-824.

Brydges, C.R., Reid, C.L., Fox, A.M., & Anderson, M. (2012). A unitary executive function predicts intelligence in children. *Intelligence, 40,* 458-469.

Buchsbaum, D., Griffiths, T.L., Plunkett, D., Gopnik, A., & Baldwin, D. (2015). Inferring action structure and causal relationships in continuous sequences of human action. *Cognitive Psychology, 76,* 30-77.

Bullock, M., & Gelman, R. (1979). Preschool children's assumptions about cause and effect: Temporal ordering. *Child Development, 50,* 89-96.

Bullock, M., Gelman, R., & Baillargeon, R. (1982). The development of causal reasoning. In W. J. Friedman (Ed.), *The developmental psychology of time* (pp. 209-254). NY: Academic.

Bullock, M., & Lütkenhaus, P. (1988). The development of volitional behaviours in the toddler years. *Child Development, 59*, 664–674.

Bunge, S.A., Kahn, I., Wallis, J.D., Miller, E.K., & Wagner, A.D. (2003). Neural circuits subserving the retrieval and maintenance of abstract rules. *Journal of Neurophysiology, 90,* 3419-3428.

Bush, G., Luu, P. & Posner, M.I. (2000). Cognitive and emotional influences in the anterior cingulated cortex. *Trends in Cognitive Science, 4 (6*), 215-222.

Buttelmann, D., Zmyj, N., Daum, M.M., & Carpenter, M. (2013). Selective imitation of in-group over out-group members in 14-month-old infants. *Child Development, 84,* 422–428.

Byrne, R.W., & Russon, A.E. (1998). Learning by imitation: a hierarchical approach. *Behavioral and Brain Science, 21 (5),* 667-721.

Cappa, S. F., Perani, D., Schnur, T., Tettamanti, M. & Fazio, F. (1998). The effects of semantic category and knowledge type on lexical-semantic access: a PET study. *Neuroimage, 8,* 350–359.

Carey, S. (2009). *The origin of concepts.* Oxford University Press, USA.

Carlson, S.M. & Moses, L.G.(2001). Individual differences in inhibitory control and children's theory of mind. *Child Development, 72*, 1032-1053.

Carter, C.S., Braver, T.S., Barch, D.M., Botvinick, M.M., Noll, D, Cohen, J.D. (1998) Anterior cingulate cortex, error detection, and the online monitoring of performance. *Science, 280*, 747–49.

Carter, C.S., MacDonald, A.M., Botvinick, M., Ross, L.L., Stenger, V.A., Noll, D., & Cohen, J.D. (2000). Parsing executive processes: strategic vs. evaluative functions of the anterior cingulate cortex. *Proceedings of the National Academy of Science of the United States of America, 97,* 1944-1948.

Casey, B.J., Trainor,R., Giedd, J., Vauss, Y., Vaituzis, C.K., Hamburger, S., Kozuch, P. & Rapoport, J.L. (1997). The role of the anterior cingulate in automatic and controlled processes: A developmental neuroanatomical study. *Developmental Psychobiology 30 (1),* 61–69.

Castiello, U. (1998). Attentional coding for three-dimensional objects and two-dimensional shapes. Differential interference effects. *Experimental Brain Research, 123,* 289-297.

Castiello, U. (1999). Mechanism of selection for the control of hand action. *Trends in Cognitive Sciences, 3,* 264-271.

Castiello, U. (2005). The neuroscience of grasping. *Nature Reviews Neuroscience, 6,* 726-736.

Center on the Developing Child at Harvard University (2011). Building the Brain's *"Air Traffic Control" System: How Early Experiences Shape the Development of Executive Function: Working Paper No. 11.* Retrieved from www.developingchild.harvard.edu.

Ceponiene, R., Rinne, T., & Naatanen, R. (2002). Maturation of cortical sound processing as indexed by event-related potentials. *Clinical Neurophysiology 113,* 870–882.

Chao, L. L., & Martin, A. (2000). Representation of manipulable man-made objects in the dorsal stream. *Neuroimage, 12*, 478–484.

Chatham, C.H. & Badre, D. (2013). Working memory management and predictive utility. *Frontiers in Behavioural Neuroscience, 7 (83*), 1-12.

Chatman, C.H., Frank, M.J., & Badre, D. (2014) Corticostriatal output gating during selection from working memory. *Neuron, 81 (4),* 930–942.

Chatterjee, A. (2001). Language and space: Some interactions. *Trends in Cognitive Sciences, 5,* 55–61.

Chaytor, N., Schmitter-Edgecombe, M. & Burr, R. (2006). Improving the ecological validity of executive functioning assessment. *Archives of Clinical Neuropsychology, 21*, 217-227.

Chen, Y., Keen, R., Rosander, K., Von Hofsten, C. (2010). Movement planning reflects skill level and age change in toddlers. *Child Development, 81(6),* 1846-1858.

Chen, Z. & Siegler, R. (2000). Across the great divide: bridging the gap between understanding of toddlers' and other children's thinking. *Monographs of Society of Research in Child Development, 65 (2),* 1-96.

Christoff, K. & Gabrieli, J.D.E. (2000). The frontopolar cortex and human cognition: evidence for a rostrocaudal hierarchical organization within the human prefrontal cortex. *Psychobiology, 28,* 168–186.

Chugani, H.T., Phelps, M.E. & Mazziotta, J.C. (1987). Positron emission tomography study of human brain functional development. *Annals of Neurology, 22*, 487-497.

Clark, A. (2013) Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behavioural and Brain Science, 36,* 1-73.

Claxton, L.J., Mc Carty, M.E., Keen, R. (2009). Self-directed action affects planning in tool-use tasks with toddlers. *Infant Behaviour and Development, 32,* 230-233.

Cohen, L.B., & Oakes, L.M. (1993). How infants perceive a simple causal event. *Developmental Psychology, 29 (3),* 421-433.

Colling, A. & Koechlin, E. (2012). Reasoning, learning, and creativity: frontal lobe function and human decision-making. *PLoS Biology, 10 (3),* Article e10011293.

Coluccini, M., Maini, E.S., Martelloni, C., Sgandurra, G. &, Cioni, G. (2007). Kinematic characterization of functional reach to grasp in normal and in motor disabled children. *Gait and Posture, 25,* 493–501.

Cooper, R.P., Ruh, N., & Mareschal, D. (2014). The goal circuit model: A hierarchical multi-route model of the acquisition and control of routine sequential action in humans. *Cognitive Science, 38*, 244-274.

Cooper, R.P., & Shallice, T. (2000). Contention Scheduling and the control of routine activities. *Cognitive Neuropsychology, 17,* 297–338.

Cooper, R. P. & Shallice, T. (2006). Hierarchical schemas and goals in the control of sequential behavior. *Psychological Review, 113*, 887-916.

Corbetta, D., & Snapp-Childs, W. (2008). Seeing and touching: the role of sensory-motor experience on the development of infant reaching. *Infant Behaviour and Development, 32,* 44-58.

Crone, E.A., Donohue, S.E., Honomichl, R., Wendelken, C., & Bunge, S.A. (2006). Brain regions mediating flexible rule use during development. *Journal of Neuroscience, 26*, 11239-11247.

Csibra G., Bíró S., Koos O., Gergely G. (2003). One-year-old infants use teleological representations of actions productively. *Cognitive Science, 27,* 111–113

Csibra, G., & Gergely, G. (2009). Natural pedagogy. *Trends in Cognitive Science, 13,* 148-153.

Csibra, G., & Gergely, G. (2011). Natural pedagogy as evolutionary adaptation. *Philosophical Transactions of the Royal Society B: Biological Science, 366*, 1149-1157.

Cisbra, G., Gergely, G., Bíró, S., Koos, O., & Brockbank, M. (1999). Goal attribution without agency cues: The perception of 'pure reason' in infancy. *Cognition, 72,* 237–267.

Damasio, A. R., & Damasio, H. (1994). Cortical systems for retrieval of concrete knowledge: The convergence zone framework. In C. Koch (Ed.), *Large-scale neuronal theories of the brain* (pp. 61–74). Cambridge, MA: MIT Press.

Damasio, A. R., Damasio, H., Tranel, D. & Brandt, J.P. (1990). The neural regionalization of knowledge access: Preliminary evidence. *Quantitative Biology, 55,* 1039–1047.

Daum, M.M., Vuori, M.T., Prinz, W., & Aschersleben, G. (2009). Inferring the size of a goal object from an actor's grasping movement in 6- and 9-month-old infants. *Developmental Science, 12 (6),* 854-862.

Davidson M.C., Amso D., Anderson L.C., and Diamond, A. (2006) .Development of cognitive control and executive functions from 4 to 13 years: evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia, 44 (11),* 2037-2078.

DeLoache, J.S., Sugarman, S., & Brown, A.L. (1985). The development of error correction strategies in young children's manipulative play. *Child Development, 56*, 928-939.

DeLoache, J.S., Uttal, D.H., & Rosengren, K.S. (2004). Scale errors offer evidence for a perception-action dissociation early in life. *Science, 304,* 1047-1029.

Desimone R, Duncan J. 1995. Neural mechanisms of selective visual attention. *Annual Review of Neuroscience, 18*, 193–222.

Diamond A. (2002). Normal development of prefrontal cortex from birth to young adulthood: Cognitive functions, anatomy, and biochemistry. In: Stuss, D.T. & Knight, R.T. (Eds.) *Principles of frontal lobe function.* London, UK: Oxford University Press, pp. 466–50.

Diamond, A., & Taylor, C. (1996). Development of an aspect of executive control: Development of the abilities to remember what I said and to "Do as I say, not as I do." *Developmental Psychobiology, 29,* 315–334.

Di Pellegrino, G., Fadiga, L., Fogassi, L., Gallese, V. & Rizzolatti, G. (1992). Understanding motor events: A neurophysiological study. *Experimental Brain, 91,* 176–180.

Doniger, G. M., Foxe, J. J., Murray, M. M., Higgins, B. A., Snodgrass, J. G., Schroeder, C. E., et al. (2000). Activation timecourse of ventral visual stream object-recognition areas: high density electrical mapping of perceptual closure processes. *Journal of Cognitive Neuroscience, 12,* 615–621.

Dumoulin, S. O., Bittar, R. G., Kabani, N. J., Baker, C. L., Le Goualher, G., Pike, G. B. & Evans, A. C. (2000). A new anatomical landmark for reliable identification of human area V5/MT: A quantitative analysis of sulcal patterning. *Cerebral Cortex, 10,* 454–463.

Duncan, J. (1986). Disorganization of behaviour after frontal lobe damage. *Cognitive Neuropsychology, 3*, 271-290.

Duncan, J., Emslie, H., Williams, Johnson, R., & Freer, C. (1996). Intelligence and the frontal lobe: The organisation of goal-directed behaviour. *Cognitive Psychology, 30*, 257-303.

Duncan, J., Johnson, R., Swales, M. & Freer, C. (1997). Frontal Lobe Deficits after Head Injury: Unity and Diversity of Function. *Cognitive Neuropsychology, 14* (5), 713-741.

Duncan, J., Parr, A., Woolgar, A., Thompson, R., Bright, P., Cox, S., Bishop, S., Nimmo-Smith, I. (2008). Goal neglect and Spearman's g: competing parts of a complex task. *Journal of Experimental Psychology: General 137(1),* 131-48.

Entwistle, D.R. & Hayduk, L.A. (1988). Lasting effect of elementary school. *Sociology of Education, 61,* 147-159.

Espy, K.A., Kaufmann, P.M., McDiarmid, M.D., & Glisky, M.L. (1999). Executive functioning in preschool children: performance on A-not-B and other delay responses format tasks. *Brain and Cognition, 41*, 178-199.

Fadiga, L., Fogassi, L., Gallese, V. & Rizzolatti, G. (2000). Visuomotor neurons: Ambiguity of the discharge or “motor” perception? *International Journal of Psychophysiology, 35,* 165–177.

Feigenson, L., Dehaene, S., & Spelke, E.S. (2004). Core systems of numbers. *Trends in Cognitive Sciences, 8 (7),* 307–314.

Fivush, R., & Mandler, J.M. (1985). Developmental changes in the understanding of temporal sequence. *Child Development, 56 (6),* 1437-1446.

Folstein, J.R., Van Petten, C., & Rose, S.A. (2008). Novelty and conflict in the categorization of complex stimuli. *Psychophysiology 45*, 467–479.

Freier, L., Cooper, P.R., & Mareschal, D. (in press). Preschool children's control of action outcomes. *Developmental Science.*

Freier, L., Cooper, P.R., & Mareschal, D. (2015). The planning and execution of natural sequential actions in the preschool years. *Cognition, 144,* 58-66.

Friedrich, M. & Friederici,A.D. (2004). N400-like Semantic Incongruity Effect in 19-Month-Olds: Processing Known Words in Picture Contexts. *Journal of Cognitive Neuroscience*, 16 (8), 1465-1477.

Friedrich, M. & Friederici,A.D. (2006). Early N400 development and later language acquisition. *Psychophysiology, 43 (1),* 1-12.

Frith, C.D., Friston, K.J., Liddle, P.F., & Frackowiak, R.S.J. (1991). Willed actions and the prefrontal cortex in man: a study with PET. *Proceedings of the Royal Society of London, Series B, 244*, 241-246.

Fuster, J.M. (2004). Upper processing stages of the perception-action cycle. *Trends in Cognitive Science, 8,* 143–145.

Gainotti, G. & Silveri, M. C. (1996). Cognitive and anatomical locus of lesion in a patient with a category specific semantic impairment for living beings. *Cognitive Neuropsychology, 13,* 357–389.

Ganis, G., & Kutas, M. (2003). An electrophysiological study of scene effects on object identification. *Cognitive Brain Research 16,* 123–144.

Gelman, R. (1972). The nature and development of early number concepts. In H.W. Reese (Ed.), *Advances in child development*, Academic Press, New York, pp. 115–167.

Gelman, R., & Gallistel, C.R. (1986). *The child's understanding of numbers*. Harvard University Press, Cambridge, MA.

Gergely, G. (2001). The obscure object of desire- 'nearly but clearly not, like me': contingency preference in normal children versus children with autism. *Bulletin of the Menninger Clinic, 65*, 411-426.

Gergely, G., Bekkering, H., & Kiraly, I. (2002). Rational imitation in preverbal infants. *Nature, 414,* 755.

Gergely, G. & Csibra, G, (2003). Teleological reasoning in infancy: the naïve theory of rational action. *Trends in Cognitive Science, 7*, 287-292.

Gergely G., Nasady Z., Csibra G., Bíró S (1995). Taking the intentional stance at 12 months of age. *Cognition, 56*, 165–193.

Gerardin, E., Sirigu, A., Lehéricy, S., Poline, J.-B., Gaymard, B., Marsault, C., Agid, Y. & Le Bihan, D. (2000). Partially overlapping neural networks for real and imagined hand movements. *Cerebral Cortex, 10,* 1093–1104.

Gerstadt, C.L., Hong, Y.J., & Diamond, A. (1994). The relationship between cognition and action: performance of children 3.5 – 7 years old on a stroop-like day-night test. *Cognition, 53*, 129-153.

Gianelli, C., Farnè, A., Salemme, R., Jeannerod, M., & Roy, A.C. (2011). The agent is right: when motor embodied cognition is space-dependent. *PLoS One, 6 (9*), e25036.

Giedd, J.N., & Rapoport, J.L. (2010). Structural MRI of paediatric brain development: what have we learned and where are we going? *Neuron, 67,* 728-734.

Giovannetti, T., Schwartz, M.F. & Buxbaum, L.J. (2007). The coffee challenge: a new method for the study of everyday action errors. *Journal of Clinical and Experimental Neuropsychology, 29 (7)*, 690-705.

Gibson, J.J. (1966). *The senses considered as perceptual systems.* Boston, MA: Houghton Mifflin.

Gibson, J.J. (1979). *The ecological approach to visual perception.* Boston, MA: Houghton Mifflin.

Glenberg, A. M. (1997). What memory is for. *Behavioral & Brain Sciences, 20*, 1-55.

Glenberg, A.M., & Kaschak, M.P.(2002). Grounding language in action. *Psychonomic Bulletin and Review, 9(3),* 558-565.

Gogtay, N., Giedd, J.N., Lusk, L., Hayashi, K.M., Greenstein, D., Vaituzis, C., Nugent, T.F., Herman, D.H., Clasen, L.S., Toga, A.W., Rapoport, J.L., & Thompson, P.M. (2004). Dynamic mapping of human cortical development during childhood through early adulthood. *Proceedings of the National Academy of Science, 101,* 8174-8179.

Gold, D.A. & Park, N.W. (2009) The effect of dividing attention on the encoding and performance of novel naturalistic actions. *Psychological Research, 73,* 336-349.

Gollwitzer, P.M. (1999). Implementation intentions: Strong effects of simple plans. *American Psychologist, 54*, 493-503.

Grafton S.T. Embodied cognition and the simulation of action to understand others (2009). *Annals of the New York Academy of Sciences, 1156*, 97–117.

Grafton, S. T., Arbib, M. A., Fadiga, L. & Rizzolatti, G. (1996). Localization of grasp representations in humans by PET: 2. Observation compared with imagination. *Experimental Brain Research, 112*, 103–111.

Grafton S. T., & de Hamilton C. A. F. (2007). Evidence for a distributed hierarchy of action representation in the brain. *Human Movement Science, 26*, 590–616.

Grant, D.A., & Berg, E.A. (1948). A behavioural analysis of degree of reinforcement and ease of shifting to new responses in a Weigl-type card sorting problem. *Journal of Experimental Psychology, 38,* 404–411.

Greeno, J. G. (1998). The situativity of knowing, learning, and research. *American Psychologist, 53,* 5–26.

Greenwald, A.G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideomotor mechanism. *Psychological Review, 77*, 73-99.

Greenwald, A.G. (1972). On doing two things at once: Time sharing as a function of ideomotor compatibility. *Journal of Experimental Psychology, 94*, 52-57.

Grézes, J. & Decety, J. (2001). Functional anatomy of execution, mental simulation, observation, and verbal generation of action: a meta-analysis. *Human Brain Mapping, 12,* 1-9.

Grezes J, Costes N, & Decety J. (1998). Top-down effect of strategy on the peception of human biological motion: A PET investigation. *Cognitive Neuropsychology, 15,* 553–582.

Griffin, S., & Case, R. (1996). *Number worlds: Kindergarten level.* Durham, NH: Number Worlds Alliance.

Grossman E.D. & Blake R. (2001). Brain activity evoked by inverted and imagined biological motion. *Vision Research, 41*, 1475–1482.

Grossman, M., Koenig, P., DeVita, C., Glosser, G., Alsop, D., Detre, J., & Gee, J. (2002). Neural representation of verb meaning: an fMRI study. *Human Brain Mapping, 15,* 124-134.

de Haan, M., Pascalis, O., & Johnson, M.H. (2002). Specialization of neural mechanisms underlying face recognition in human infants. *Journal of Cognitive Neuroscience, 14,* 199–209.

Haazebroek P., Van Dantzig S., & Hommel B. (2013). How task goals mediate the interplay between perception and action. *Frontiers in Psychology, 4, 247*. doi: 10.3389/fpsyg. 2013.00247

Handy, T.C. (2004). *Event-related potentials: a methods handbook.* Todd C. Handy (ed). Cambridge: MIT Press.

Hawkins, J. & Blakeslee, S. (2004) *On intelligence.* Owl Books/Times Books.

Hard, B.M., Recchia, G., & Tversky, B. (2011). The shape of action. *Journal of Experimental Psychology: General, 140 (4),* 586–604.

Harris, P. L., German, T., & Mills, P. (1996). Children's use of counterfactual thinking in causal reasoning. *Cognition, 61,* 233–259.

Hauf, P. & Prinz, W. (2005). The understanding of own and others' actions during infancy: "You-like-me" or "Me-like-you"? *Interaction Studies, 6 (3),* 429-445.

Hazy, T.E., Frank, M.J., & O'Reilly, R.C. (2006) Banishing the Homunculus: Making Working Memory Work. *Neuroscience, 139*, 105-118.

Heider, F. (1958). *The psychology of interpersonal relations.* John Wiley & Sons.

Helbig, H.B., Graf, M. & Kiefer, M. (2006). The role of action representations in visual object recognition. *Experimental Brain Research, 174,* 221–228.

Helbig, H.B., Steinwender, J., Graf, M. & Kiefer, M. (2010). Action observation can prime visual object recognition. *Experimental Brain Research, 200*, 251–258.

Holcomb, P.J., & McPherson, W.B. (1994). Event-related brain potentials reflect semantic priming in an object decision task. *Brain Cognition, 24,* 259–276.

Holroyd, C.B., & Coles, M. G. H. (2002). The neural basis of human error processing: Reinforcement learning, dopamine, and the error-related negativity. *Psychological Review, 109,* 679–709.

Holt, A.E., & Deák, G. (2014). Children's task switching efficiency: missing or cue? *Journal of Cognition and Development*, doi: 10.1080/15248372.2013.833921.

Hommel, B., Müsseler, J., Aschersleben, G., and Prinz, W. (2001). The theory of event coding (TEC): a framework for perception and action planning. *Behavior and Brain Science, 24,* 849–937.

Horner, V.K., & Whiten, A. (2005). Causal knowledge and imitation/emulation switching in chimpanzees (Pan troglodytes) and children. *Animal Cognition, 8,* 164-181.

Humphreys, G. W. & Forde, E. M. E. (2001). Hierarchies, similarity, and interactivity in object recognition: "Category-specific" neuropsychological deficits. *Behavioural Brain Sciences, 24,* 453–509.

Humphreys, G.W., Riddoch, M.J., Forti, S. & Ackroyd, K. (2004). Action influences spatial perception. *Visual Cognition, 11*, 401-427.

Ibáñez, A., Cardona, J.F., Dos Santos, Y.V., Blenkmann, A., Aravena, P., Roca, M., Hurtado, E., Nerguizian, M., Amoruso, L., Gómez-Arévalo, G., Chade, A., Dubrovsky, A., Gershanik, O., Kochen, S., Glenberg, A., Manes, F., & Bekinschtein, T. (2013). Motor-language coupling: direct evidence from early Parkinson's disease and intracranial cortical recordings. *Cortex, 49 (4)*, 968-984.

Ibáñez, A., Melloni, M., Huepe, D., Helgiu, E., Rivera-Rei, A., Canales- Johnson, A., Baker, P., & Moya, A. (2012). What event related potentials (ERP) bring to social neuroscience. *Society for Neuroscience, 7,* 632–649.

Ibáñez, A., & Manes, F. (2012). Contextual social cognition and the behavioral variant of frontotemporal dementia. *Neurology 78*, 1354–1362.

Inhelder, B., Sinclair, H., & Bovet, M. (1974). *Learning and the development of cognition.* Cambridge, MA; Harvard University Press.

Izard, V., Sann, C., Spelke, E.S., Streri, A. (2009). Newborn infants perceive abstract numbers. *Proceedings of the National Academy of Sciences, 106 (25),* 10382–10385.

Izard, V., Streri, A., & Spelke, E.S. (2014) Toward exact number: Young children use one-to-one correspondence to measure set identity but not numerical equality. *Cognitive Psychology, 72,* 27-53.

Jackson, S.R., Jackson, G.M., Rosicky, J. (1995). Are non-relevant objects represented in working memory? The effects of non-target objects on reach to grasp kinematics, *Experimental Brain Research, 102,* 519-530.

Jacques, S., & Zelazo, P.D. (2001). The Flexible Item Selection Task (FIST): a measure of executive function in pre-schoolers. *Developmental Neuropsychology, 20*, 573-591.

James, W. (1890). *The principle of Psychology.* New York: Dover Publications.

Jaspers, E., Feys, H., Bruyninckx, H., Harlarr, J., Molenaers, G., & Desloovere, K. (2011). Upper limb kinematics: development and reliability of a clinical protocol for children. *Gait & Posture, 33*, 279-285.

Jastorff, J., Clavagnier, S., Gergely, G., & Orban, G.A. (2010). Neural mechanism of understanding rational actions: middle temporal gyrus activation by contextual violation. *Cerebral Cortex, 21,* 318-329.

Jeannerod, M. (1986). The formation of finger grip during prehension: a cortically mediated visuomotor pattern. *Behavioural Brain Research 19,* 99-116.

Jeannerod, M. (1997). *The Cognitive Neuroscience of Action.* Blackwell, Oxford.

Jeannerod, M., Arbib, M. A., Rizzolatti, G. & Sakata, H. (1995). Grasping objects: the cortical mechanism of visuomotor transformation. *Trends in cognitive Neuroscience, 18,* 314-320.

Jennings, K.D. (2004) Development of goal-directed behaviour and related self-processes in toddlers. *International Journal of Behavioral Development, 28 (4),* 319–327.

Jervis, C., Bennett, K., Thomas, J., Lim, S., & Castiello, U. (1999). Semantic category interference effects upon the reach-to-grasp movement. *Neuropsychologia 37 (7),* 857–868.

Johnson-Frey S.H., Maloof F.R., Newman-Norlund R., Farrer C., Inati S., & Grafton S.T. (2003). Actions or hand-object interactions? Human inferior frontal cortex and action observation. *Neuron 39,* 1053-1058.

Johnson-Frey S.H., Newman-Norlund, R. & Grafton, S.T. (2005). A distributed left hemisphere network active during planning of everyday tool use skills. *Cerebral Cortex, 15 (6),* 681-695.

Jones, L., Rothbart, M.K., & Posner, M.I. (2003). Development of executive attention in preschool children. *Developmental Science, 6 (5),* 498-504.

Kaller, C.P., Rahm, B., Spreer, J. Mader, I., & Unterrainer, J.M. (2008). Thinking around the corner: The development of planning abilities. *Brain and Cognition, 67 (3),* 360–370.

Kane, M.J., Conway, A.R.A., Hambrick, D.Z., & Engle, R.W. (2007). Variation in working-memory capacity as variation in executive attention and control. In A.R.A. Conway, C. Jarrold, M.J. Kane, A. Miyake, J. Towse (Eds.), *Variation in Working Memory*. Oxford University Press.

Kane, M.J., & Engle, R.W. (2002) The role of prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence: an individual-differences perspective. *Psychonomic Bulletin & Review, 9,* 637-671.

Kane, M.J., & Engle, R.W. (2003). Working-memory capacity and the control of attention: The contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology: General, 132 (1),* 47-70.

Karmiloff-Smith, A. & Inhelder, B. (1978). If you want to get ahead, get a theory. *Cognition, 3 (3),* 192-212.

Keen, R. (2011). The Development of Problem Solving in Young Children: a critical cognitive skill. In S. T. Fiske, D. L. Schachter, & A. E. Kazdin (Eds.), *Annual Review of Psychology, 62*, 1-21.

Kemmerer, D. Rudrauf, D., Manzel. K. & Tranel, D. (2012). Behavioural patterns and lesion sites associated with impaired processing of lexical and conceptual knowledge of actions. *Cortex, 48 (7),* 826-848.

Kenward, B. (2012). Over-imitating preschoolers believe unnecessary actions are normative and enforce their performance a third party. *Journal of Experimental Child Psychology, 112,* 195-207.

Kenward, B., Karlsson, M., & Persson, J. (2011). Over-imitation is better explained by norm learning than by distorted causal reasoning. *Philosophical Transactions of the Royal Society: Biology, 278,* 1239-1246.

Kerns, J.G., Cohen, J.D., MacDonald, A.W., Cho, R.Y., Stenger, V.A., & Carter, C.S. (2004). Anterior Cingulate Conflict Monitoring and Adjustments in Control. *Science, 303,* 1023-1026.

Keulen, R.F., Adam, J.J., Fischer, M.H., Kuipers, H., & Jolles, J. (2004). Selective reaching: distracter effects on movement kinematics as a function of target-distracter separation. *Journal of General Psychology, 131 (4*), 345–363.

Kiefer, M. & Pulvermuller, F. (2012). Conceptual representations in mind and brain: theoretical developments, current evidence and future directions. *Cortex, 48*, 805–825.

Kiefer, M., Sim, E.J., Helbig, H. & Graf, M.(2011). Tracking the time course of action priming on object recognition: evidence for fast and slow in fluencies of action on perception. *Journal of Cognitive Neuroscience, 23*, 1864–1874.

Kilner, J.M. (2011). More than one pathway to action understanding. *Trends in Cognitive Science, 15,* 352-357.

Kilner, J.M., Neal A., Weiskopf N., Friston K.J. & Frith C.D. (2009). Evidence of mirror neurons in human inferior frontal gyrus. *Journal of Neuroscience, 29 (32),* 10153-10159.

Kim, C., Chung, C., & Kim, J. (2013). Task-dependent response conflict monitoring and cognitive control in anterior cingulate and dorsolateral prefrontal cortices. *Brain Research, 1537,* 216-223.

Kirkham, N.Z., Cruess, L.M., & Diamond, A. (2003). Helping children apply their knowledge to their behavior on a dimension-switching task. *Developmental Science, 6(5),* 449-467.

Kirkham, N. Z., Slemmer, J. A., & Johnson, S. P. (2002). Visual statistical learning in infancy: Evidence of a domain general learning mechanism. *Cognition, 83*, B35–B42.

Koslowski, B., & Bruner, J.S. (1972). Learning to use a lever. *Child Development, 43*, 790-799.

Koechlin, E. (2008). The cognitive architecture of the human lateral prefrontal cortex. In P. Haggard, Y. Rosetti, M. Kawato (Eds.), *Attention and Performance,* Vol. XXII. Oxford University Press.

Koechlin, E., & Jubault, T. (2006). Broca's area and the hierarchical organization of behavior, *Neuron, 50*, 963–974.

Koechlin, E., Ody, C., & Kouneiher, F. (2003). The architecture of cognitive control in the human prefrontal cortex. *Science, 302,* 1181–1185.

Koechlin, E. & Summerfield, C. (2007). An information theoretical approach to prefrontal executive function. *Trends Cognitive Science, 11,* 229–235.

Kuhtz-Buschbeck, J.P., Stolze, H., Jöhnk, K., Boczek-Funcke, A., and Illert, M. (1998). Development of prehension movements in children: a kinematic study. *Experimental*

Brain Research 122, 424-432.

Kuperberg, G., Caplan, D., Sitnikova, T., Eddy, M., & Holcomb, P. (2006). Neural correlates of processing syntactic, semantic and thematic relationships in sentences. *Language and Cognitive Processes 21*, 489–530.

Kuperberg, G., Kreher, D.A., Sitnikova, T., Caplan, D., Holcomb, &, P.J., (2007). The role of animacy and thematic relationships in processing active English sentences: evidence from event- related potentials. *Brain and Language, 100,* 223–238.

Kushnerenko E, Ceponiene R, Balan P, Fellman V, Naatanen R. (2002). Maturation of the auditory change detection response in infants: a longitudinal ERP study. *Neuroreport, 13*, 1843–1848.

Kutas, M., & Federmeier, K. D. (2011). Thirty years and counting: finding meaning in the N400 component of the event-related brain potential (ERP). *Annual Review in Psychology, 62*, 621–647.

Kutas, M. & Hillyard, S. A. (1980a). Reading between the lines: event-related brain potentials during natural speech processing. *Brain and Language, 11*, 272-293.

Kutas, M. & Hillyard, S. A. (1980b). Reading senseless sentences: brain potentials reflect semantic incongruity. *Science, 207*, 203-205.

Lashley, K. (1951). The problem of serial order in behavior. In L. Jeffress (Ed.), *Cerebral Mechanisms in Behavior* (pp. 112–136).New York: Wiley.

Leber, A.B., Turk-Browne, N.B., & Chun, M.M. (2008). Neural predictors of moment-to-moment fluctuations in cognitive flexibility. *Proceedings of the National Academy of Science USA, 105*, 13592-13597.

Lehto, J.E., Juujärvi, P., Kooistra, L. & Pulkkinen, L. (2003). Dimensions of executive functioning: Evidence from children. *British Journal of Developmental Psychology, 21*, 59-80.

Levin, H.S., Culhane, K.A., Hartmann, J., Evankovich, K., Mattson, A.J., Harward, H., Ringholz, G., Ewing-Cobbs, L., & Fletcher, J.M. (1991). Developmental changes in performance on tests of purported frontal lobe functioning. *Developmental Neuropsychology, 7*, 337-395.

Levy, F. (1980). The development of sustained attention (vigilance) and inhibition in children: some normative data. *Journal of Child Psychiatry, 21*, 77–84.

Livesey, D.J., & Morgan, G.A. (1991). The development of response inhibition in 4- and 5-year-old children. *Australian Journal of Psychology, 43*, 133–137.

Lotze, R.H. (1952) *Medizinische Psychologie, oder Physiologie der Seele*. Leipzig: Weidemann.

Lucks, S.J. (2005). *Event-related potential technique.* (Ed.). Cambridge: MIT Press.

Luria, A.R.(1959). Development of speech and formation of psychological processes. *Psychological Science in the USSR, 1,* 516-577.

Luria, A.R. (1973). The frontal lobes and the regulation of behavior. In: K. H. Pribram (Ed.). *Psychophysiology of the frontal lobes. (pp. 219-224)* Oxford: Academic Press.

Luria, A.R (1974). A child's speech responses and the social environment. *Soviet Psychology, 13 (1*), 7-39.

Lyons, D.E., Damrosch, D.H., Lin, J.K., Macris, D.M., & Keil, F.C. (2011). The scope and limits of overimitation in the transmission of artefact culture. *Philosophical Transactions of the Royal Society: Biology, 366,* 1158-1167.

Lyons, D. E., Young, A.G., & Keil, F.C. (2007). The hidden structure of overimitation. *Proceedings of the National Academy of Science USA, 104,* 19751-19756.

MacDonald, A.W., Cohen, J.D., Strenger, V.A. & Carter, C.S. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulated cortex in cognitive control. *Science, 288*, 1835-1838.

Manoel, E. J., & Moreira, C. R. P. (2005). Planning manipulative hand movements: Do young children show the end-state comfort effect? *Journal of Human Movement Studies, 49*, 93–114.

Marcovitch, S., Boseovski, J.J., & Knapp, R.J. (2007). Use it or lose it: Examining preschoolers' difficulty in maintaining and executing goals. *Developmental Science, 10*, 559-564.

Marcovitch, S., Boseovski, J.J., Knapp, R.J., & Kane, M., J. (2010). Goal neglect and working memory capacity in 4- to 6-year-old children. *Child Development, 81*, 1687-1695.

Marsh, L.E., Ropar, D., & Hamilton, A.F. de C. (2014). The Social Modulation of Imitation Fidelity in School-Age Children. *PLOS One, 9,* e86127.

Marteniuk, R.G., MacKenzie, C.L., Jeannerod, M., Athenes, S., & Dugas, C. (1987). Constraints on human arm movement trajectories. *Canadian Journal of Experimental Psychology, 41*, 365-378.

Martin, A., Wiggs, C. L., Ungerleider, L. G. & Haxby, J. V. (1996). Neural correlates of category-specific knowledge. *Nature, 379*, 649–652.

McCarty, M.E., Clifton, R.K. & Collard, R.R. (1999). Problem solving in infancy: the emergence of an action plan. *Developmental Psychology, 35*, 1091-1101.

McCarty, M.E., Clifton, R.K. & Collard, R.R. (2001). The beginnings of tool use by infants and toddlers. *Infancy, 1*, 233-256.

McCrink, K., & Wynn, K. (2004). Large-number addition and subtraction by 9-month-old infants. *Psychological Science, 15 (11),* 776-781.

McGuigan, N. (2012). The role of transmission biases in the cultural diffusion of irrelevant actions. *Journal of Comparative Psychology, 125*, 555-565.

McGuigan, N., Gladstone D., & Cook L. (2012). Is the cultural transmission of irrelevant tool actions in adult humans (homo sapiens) best explained as the result of an evolved conformist bias? *PLoS One, 7,* e50863.

McGuigan, N., Makinson, J., & Whiten, A. (2011). From over-imitation to super-copying: adults imitate causally irrelevant aspects of tool use with higher fidelity than young children. *British Journal of Psychology, 102*, 1-18.

McGuigan, N., Whiten, A., Flynn, E., & Horner, V. (2007). Imitation of causally opaque versus causally transparent tool use by 3- and 5-year-old children. *Cognitive Development, 22,* 353-364.

McGuigan, N. & Whiten, A. (2009). Emulation and "overemulation" in the social learning of causally opaque versus causally transparent tool use by 23- and 30-month-olds. *Journal of Experimental Child Psychology, 104* (4), 367-381.

McPherson, W.B., & Holcomb, P.J. (1999). An electrophysiological investigation of semantic priming with pictures of real objects. *Psychophysiology 36,* 53–65.

McRae, K., Hare, M., Ferretti, T. R., & Elman, J. L. (2001). Activating verbs from typical agents, patients, instruments, and locations via event schemas. In J. D. Moore and K. Stenning (Eds.), *Proceedings of the Twenty-Third Annual Conference of the Cognitive Science Society* (pp. 617-622). Mahwah, NJ: Erlbaum.

Mendoza, J.K., & Baldwin, D. (2014). Shining light on infants' discovery of structure. In J. Benson (Ed.), *Advances in Child Development and Behavior*. Elsevier.

Meyer, M., & Baldwin, D. (2011). Statistical learning of action: The role of conditional probability. *Learning and Behavior, 39(4),* 383-398.

Miller, E.K. & Cohen, J.D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24*, 167–202.

Mills, D.L., Coffey-Corina, S., & Neville, H. (1997). Language comprehension and cerebral specialization from 13 to 20 months. *Developmental Neuropsychology 13*, 397–445.

Mischel, W., Ayduk, O., Berman, M.G., Casey, B.J., Gotlib, I.H., Jonides, J., Kross, E., Teslovich, T., Wilson, N.L., Zayas, V., & Shoda, Y. (2011). 'Willpower' over the life span: decomposing self-regulation. *Social Cognitive and Affective Neuroscience, 6,* 252-256.

Mohler, J., Anderson, B.A., & Song, J.H. (2015). Dissociable effects of salience on attention and goal-directed action. *Current Biology, 25,* 2040-2046.

Montgomery, D.E., & Koeltzow, T.E. (2010). A review of the day-night task: the stroop paradigm and interference control in young children. *Developmental Review, 30,* 308-330.

Morr, M.L., Shafer, V.L., Kreuzer, J.A., & Kurtzberg, D. (2002). Maturation of mismatch negativity in typically developing infants and preschool children. *Ear and Hearing, 23,* 118–136.

Munakata, Y., O'Reilly, R., & Morton, J. B. (2007). Developmental and computational approaches to variation in working memory. In A. R. A. Conway, C. Jarrold, M. J. Kane, A. Miyake, & J. N. Towse (Eds.), *Variation in working memory* (pp. 162–193). NewYork: Oxford University Press.

Munakata, Y., & Yerys, B.E. (2001). All together now: when dissociation between knowledge and action disappears. *Psychological Science, 12 (4),* 335-337.

Napier, J.R. (1956). The prehensile movements of the human hand. *Bone Joint Surgery, 38*, 902-913.

Newell, K.M., Scully, D.M., McDonald, P.V, & Baillargeon, R., 1989. Task constraints and infant grip configuration. *Developmental Psychobiology, 22,* 817-831.

Newtson, D. (1973). Attribution and the unit of perception of ongoing behavior. *Journal of Personality and Social Psychology, 28,* 28-38.

Newtson, D., & Engquist, G. (1976). Foundations of attribution: The perceptual organization of ongoing behavior. *Journal of Experimental Social Psychology, 12*, 436-450.

Nishitani N., & Hari R. (2000). Temporal dynamics of cortical representation for action. *Proceedings of the National Academy of Sciences USA, 97,* 913–918.

Noble, K.G., Norman, M.F., & Farah, M.J. (2005). Neurocognitive correlates of socioeconomic status in kindergarten children. *Developmental Science, 8,* 74-87.

Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behaviour. In R.J. Davidson, G. E. Schwartz, & D. Shapiro (Eds). *Consciousness and Self- regulation* (Vol. 4 pp. 1-18). New York: Plenum.

O'Connell, B.G. & Gerard, A.B. (1985). Scripts or scraps: the development of sequential understanding. *Child Development, 56,* 671-681.

O'Reilly, R.C. & Frank, M.J. (2006). Making working memory work: A computational model of learning in the prefrontal cortex and basal ganglia. *Neural Computation, 18*, 283–328.

Over, H., & Carpenter, M. (2012). Putting the social into social learning: explaining both selectivity and fidelity in children's copying behavior. *Journal of Comparative Psychology, 126 (2)*, 182-192.

Pace, A., Carver, L.J. & Friend, M. (2013). Event-related potentials to intact and disrupted actions in children and adults. *Journal of Experimental Child Psychology, 116,* 453-470.

Pang, E.W., & Taylor, M.J. (2000). Tracking the development of the N1 from age 3 to adulthood: an examination of speech and non-speech stimuli. *Clinical Neurophysiology, 111*, 388–397.

Pascalis, O., de Haan M., &, Nelson. C,A. (2002). Is face processing species-specific during the first year of life? *Science 296,* 1321–1323.

Piaget, J. (1926). *The language and thought of the child.* New York: World.

Piaget, J. (1983). Piaget's theory. In P. Mussen (ed.). *Handbook of child psychology*. 4th edition. Vol. 1. New York: Wiley.

Posner, M.I., & Rothbart, M.K. (1998). Attention, self-regulation, and consciousness. *Philosophical Transactions of the Royal Society of London, B: Biological Science, 353,* 1915–1927.

Pratt, J., & Abrams, R.A. (1994). Action-centred inhibition: effects of distractors on movement planning and execution. *Human Movement Science, 12 (2*), 245-254.

Proverbio, A. M., & Riva, F. (2009). RP and N400 ERP components reflect semantic violations in visual processing of human actions. *Neuroscience Letters 459*, 142–146.

Ragozzino, M.E. (2007). The contribution of the medial prefrontal cortex, orbitofrontal cortex, and dorsomedial striatum to behavioural flexibility. *Annals of the New York Academy of Sciences, 1121*, 355-375.

Reid, V.M., Csibra, G., Belsky, J., & Johnson, M.H. (2007). Neural correlates of the perception of goal-directed action in infants. *Acta Psychologica, 124,* 129-138.

Reid, V.M., Hoehl, S., Grigutsch, M., Groendahl, A., Parise, E., & Striano, T. (2009). The neural correlates of infant and adult goal prediction: evidence from semantic processing system. *Developmental Psychology, 45*, 620-629.

Reid, V.M. & Striano, T. (2008). N400 involvement in the processing of action sequences. *Neuroscience Letters, 433,* 93–97.

Reverberi, C., Görgen, K., & Haynes, J.D. (2012). Distributed representations of rule identity and rule order in human frontal cortex and striatum. *Journal of Neuroscience, 28*, 17420-17430.

Richardson, D., Spivey, M., Barsalou, & McRae, K. (2003). Spatial representations activated during real-time comprehension of verbs. *Cognitive Science, 27*, 767-780.

Rizzolatti G., Fogassi L., & Gallese V. (2001). Neurophysiological mechanisms underlying the understanding and imitation of action. *Nature Reviews Neuroscience 2,* 661-670.

Rosenbaum, D.A., Cohen, R.G., & Jax, S.A (2007). The problem of serial order in behavior: Lashley's legacy. *Human movement science, 26* (4), 525-554.

Rueda, M.R., Fan, J., McCandliss, B.D., Halparin, J.D., Gruber, D.B., Lercari, L.P., &, Posner, M.I. (2004). Development of attentional networks in childhood. *Neuropsychologia, 42,* 1029-1040

Ruh, N., Cooper, R.P., & Mareschal, D. (2010). Action selection in complex routinized sequential behaviors. *Journal of Experimental Psychology: Human Perception and Performance, 106*, 99-114.

Russell, J., Mauthner, N., Sharpe, S., & Tidswell, T. (1991). The ‘‘windows task’’ as a measure of strategic deception in preschoolers and autistic subjects. *British Journal of Developmental Psychology, 9,* 331– 349.

Sachs, J. (2001). *Aristotle's On the Soul and On Memory and Recollection*. Green Lion Press.

Searle, J. (1983). *Intentionality: An essay in the philosophy of mind.* (Vol. 9). Cambridge, England: Cambridge University Press.

Schendan, H.E., & Kutas, M. (2002). Neurophysiological evidence for two processing times for visual object identification. *Neuropsychologia 40*, 931–945.

Schneider, W., & Detweiler, M. (1987). A connectionist/control architecture for working memory. *The Psychology of Learning and Motivation, 21,* 53-119.

Schwartz, M.F. (2007). The cognitive neuropsychology of everyday action and planning. *Cognitive Neuropsychology, 23,* 202-221.

Schwartz, M., Montgomery, M., Buxbaum, L., Lee, S., Carew, T., Coslett, H., Ferraro, M., Fitzpatrick-DeSalme, E., Hart, T., & Mayer, N. (1998). Naturalistic action impairment in closed head injury. *Academic Emergency Medicine, 12* (1), 13-28.

Schwier, C. van Maanen, C., Carpenter, M., & Tomasello, M. (2006). Rational imitation in 12-month-old infants. *Infancy, 10* (3), 303-311.

Shenhav, A., Botvinick, & Cohen, 2013. The expected value of cognitive control: an integrative theory of anterior cingulate cortex function. *Neuron, 79,* 217-240.

Shultz, T. R. (1982). Rules of causal attribution. *Monographs of the Society for Research in Child Development, 47*, 1-51.

Simpson, A. & Riggs, K.J. (2007). Under what conditions do young children have difficulty inhibiting manual actions? *Developmental Psychology, 43,* 417-428.

Sitnikova, T., Holcomb, P.J., Kiyonaga, K.A. & Kuperberg, G.R. (2008). Two neurocognitive mechanisms of semantic integration during the comprehension of visual real-world events. *Journal of Cognitive Neuroscience, 20*, 2037–2057.

Sitnikova, T. ,Kuperberg, G. & Holcomb, P.J.(2003). Semantic integration in videos of real-world events: an electrophysiological investigation. *Psychophysiology 40,* 160–164.

Sitnikova, T., Perrone, C., Goff, D., & Kuperberg, G.R. (2010) Neurocognitive mechanisms of conceptual processing in healthy adults and patients with schizophrenia. *International Journal of Psychophysiology, 75,* 86-99.

Smeets, J.B., & Brenner, E. (1999). A new view on grasping. *Motor control, 3,* 237-71.

Song, J.H., & Nakayama, K. (2009). Hidden cognitive states revealed in choice reaching tasks. *Trends in Cognitive Science, 13,* 360-366.

Snyder, H.R. & Munakata, Y. (2010). Becoming self-directed: Abstract representations support endogenous flexibility in children. *Cognition, 116 (2*), 155–167.

Sobel, D.M., & Kirkham, N.Z. (2006). Blickets and babies: The development of causal reasoning in toddlers and infants. *Developmental Psychology, 42*, 1103–1115.

Sobel, D.M., & Kirkham, N.Z. (2007). Bayes nets and babies: Infants' developing representations of causal knowledge. *Developmental Science, 10*, 298–306.

Somerville, S.C., Wellman, H.M., Cultice, J.C. (1983). Young children's deliberate reminding. *Journal of Genetic Psychology, 143,* 87–96.

Sommerville, J.A., & Woodward, A.L. (2005). Pulling out the intentional structure of action: The relation between action processing and action production in infancy. *Cognition, 95*, 1-30.

Spelke, E. S., Breinlinger, K., Macomber, J., & Jacobson, K. (1992). Origins of knowledge. *Psychological Review*, *99*, 605–632.

Starkey, P., Spelke, E.S., & Gelman, R. (1990). Numerical abstraction by human infants. *Cognition, 36*, 97–127.

Stefanucci, J.K., & Geuss, M. (2009). Big people, little world: The body influences size perception. *Perception, 38,* 1782–1795.

Stern, W. (1926). *Psychology of early childhood up to the sixth year of age.* New York: Henry Holt & Co.

Tipper, S.P., Lortie, C., & Baylis, G.C. (1992). Selective reaching: evidence for action-centred attention. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 891-905.

Tipper, S.P., Howard, L.A., Houghton, G. (1998). Action-based mechanisms of attention. *Philosophical Transactions of the Royal Society B: Biology, 353*, 1385-1393.

Tipper, S.P., Howard, L.A., Jackson, S.R. (1997). Selective reaching to grasp: evidence for distractor interference effects. *Visual Cognition, 4,* 1-38.

Thelen, E., & Smith, L.B. (1994). *A Dynamic Systems Approach to the Development of Cognition and Action.* Cambridge, MA: MIT Press.

Thierry, G., (2005). The use of event-related potentials in the study of early cognitive development. *Infant and Child Development, 14,* 85-94.

Thompson, P. M., Giedd, J. N., Woods, R. P., MacDonald, D., Evans, A. C. & Toga, A. W. (2000). Growth patterns in the developing brain detected by using continuum mechanical tensor maps. *Nature 404,* 190–193.

Tomasello, M. & Call, J. (1997). *Primate cognition.* Oxford: Oxford University Press.

Towse, J.N., Lewis, C., & Knowles, M. (2007). When knowledge is not enough: The phenomenon of goal neglect in preschool children. *Journal of Experimental Child Psychology, 96*, 320-332.

Tranel, D., Damasio, H. & Damasio, A. R. (1997). A neural basis for the retrieval of conceptual knowledge. *Neuropsychologia, 35,* 1319–1327.

Tranel, D., Kemmerer, D., Adolphs, R., Damasio, H. & Damasio, A.R. (2003). Neural correlates of conceptual knowledge for actions. *Cognitive Neuropsychology, 20*, 409-432.

Ullsperger, M., Danielmeier, C., & Jocham, G. (2014). Neurophysiology of performance monitoring and adaptive behaviour. *Physiological Review, 94*, 35-79.

Van der Meer, E., Beyer, R., Heinze, B., & Badel, I. (2002). Temporal order relations in language comprehension. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28*, 770–779.

Von Hofsten, C. (2007). Action in development. *Developmental Science, 10,* 54-60.

Von Hofsten, C. (1987). Catching. In H. Heuer & A.F. Sanders (Eds.). *Perspective on perception and action (pp.33-46).* Hillsdale, NJ: Erlbaum.

Waltz, J.A., Knowlton, B.J., Holyoak, K.J., Boone, K.B., Mishki, F.S., Santos, M., Thomas, C.R., & Miller, B.L. (1999). A system for relational reasoning in human prefrontal cortex. *Psychological Science, 10* (2), 119-125.

Wang, J.S., & Stelmach, G.E. (1999). Temporal and spatial relationship between reaching and grasping. Commentary on “a new view on grasping”. *Motor control, 3,* 307-1999.

Weintraub S., Dikmen, S.S., Heaton, R.K., Tulsky, D.S., Zelazo, P.D., Bauer, P.J., Carlozzi, N.E., Slotkin, J., Blitz, D., Wallner-Allen, K., Fox, N.A., Beaumont, J.L., Mungas, D., Richler, J., Deocampo, J.A., Anderson, J.E., Manly, J.J., Borosh, B., Havlik, R. & Gershon, R. (2013). NIH Toolbox for the Assessment of Behavioral and Neurological Function: Cognition domain instruments. *Neurology*, *80*, 54-64.

Welsh, M.C., Pennington, B.F., & Groisser, D.B. (1991). A normative developmental study of executive function: a window on prefrontal function in children. *Developmental Neuropsychology, 7*, 131-149.

West, W. C., & Holcomb, P. J. (2002). Event-related potentials during discourse-level semantic integration of complex pictures. *Brain Research. Cognitive Brain Research, 13*, 363–375.

Williamson, R.A. & Markman, E.M. (2006). Precision of imitation as a function of preschoolers’ understanding of the goal of the demonstration. *Developmental Psychology, 42,* 723-731.

Wislon, M. (2002). Six views of embodied cognition. *Psychological Bulletin and Review, 9*, 625-636.

Wilson, A.D., & Golonka, S. (2013). Embodied cognition is not what you think it is. *Frontiers in Psychology,4*: 58. doi: 10.3389/fpsyg.2013.00058.

Whiten, A., Custance, D.M., Gomez. J.C., Teixidor, P., & Bard, K.A. (1996). Imitative learning of artificial fruit processing in children (Homo sapiens) and chimpanzees (Pan troglodytes). *Journal of Comparative Psychology, 110,* 3-14.

Whiten, A., Flynn, E., Brown, K., & Lee, T. (2006) Imitation of hierarchical action structure by young children. *Developmental Science, 9 (6),* 574 – 582.

Whiten, A., Horner, V., & Marshall-Pescini, S. (2005). Selective imitation in child and chimpanzee: a window on the construal of others' actions. In S. Hurley & N. Chater, *Perspectives on imitation: From neuroscience to Social Science* (Eds.). Cambridge, MA: MIT Press. pp. 263-283.

Whiten, A., McGuigan, N., Marshall-Pescini, S., & Hopper, L.M. (2009). Emulation, imitation, over-imitation and the scope of cultural for children and chimpanzees. *Philosophical Transactions of the Royal Society: Biology, 364*, 2417-2428.

Wood, J. N. (2007). Visual working memory for observed actions. *Journal of Experimental Psychology: General, 136* (4), 639–652.

Wood, L.A., Kendal, R.L., & Flynn, E.G. (2012). Context-dependent model-based biases in cultural transmission: Children's imitation is affected by model age over model knowledge state. *Evolution and Human Behavior, 33*, 387–394.

Wood, W., & Neal, D.T. (2007). A new look at habits and the habit-goal interface. *Psychological Review, 114,* 843-863.

Woodward, A.L. (1998). Infants selectively encode the goal of an actor' s reach. *Cognition, 69*, 1‐34.

Woodward, A.L. (2003). Infants' developing understanding of the link between looker and object. *Developmental Science, 6,* 297‐311.

Woodward, J. (2007). Interventionist theories of causation in psychological perspective. In Gopnik & Schulz (Eds.), *Causal learning*. Oxford University Press.

Woodward, J. (2011) Causal perception and causal cognition. In Roessler (Ed.), *Causation, Perception, and Objectivity: Issues in Philosophy and Psychology*, Oxford University Press.

Wurm, M.F., & Schubotz, R.I. (2012). Squeezing lemons in the bathroom: contextual information modulates action recognition. *Neuroimage, 59 (2),* 1551-1559.

Wynn, K. (1992). Children's acquisition of the number words and the counting system. *Cognitive Psychology, 24,* 220 –251.

Xu, F., & Spelke, E.S. (2000). Large number discrimination in 6-month old infants. *Cognition, 74,* B1–B11.

Yakovlev, P.I., & Lecours, A.R. (1967). The myelogenetic cycles of regional maturation of the brain. In A. Minkowski (Ed.) *Regional development of the brain in early life.* (pp. 3-70) Oxford, UK.

Yoshikawa, H., Kalil, A., Weisner, T.S., & Way, N. (2008). Mixing qualitative and quantitative research in developmental science: uses and methodological choices. *Developmental Psychology, 44,* 344-354.

Yu, Y. & Kushnir, T. (2014). Social context effects in 2- and 4-year-olds' selective versus faithful imitation. *Developmental Psychology, 50* (3), 922-933.

Zacks, J. M., & Swallow, K.M. (2007). Event segmentation. *Current Directions in Psychological Science, 16 (2)*, 80–84.

Zacks, J.M. & Tversky, B. (2001). Event structure in perception and conception. *Psychological Bulletin, 127,* 3-21.

Zacks, J.M., Tversky, B., & Iyer, G. (2001). Perceiving, remembering, and communicating structure in events. *Journal of Experimental Psychology: General. 130 (1),* 29–58.

Zelazo, P. D., Müller, U., Frye, D., & Marcovitch, S. (2003). The development of executive function in early childhood. *Monographs of the Society for Research in Child Development, 68*, 1–137.

Zelazo, P.D., & Müller, U. (2002). Executive function in typical and atypical development. In U. Goswami (Ed.), *Handbook of childhood cognitive development.* Malden, MA: Blackwell.

Zelazo, P.D. (2006). The Dimensional Card Sorting (DCCS): a method of assessing executive function in children. *Nature Protocols, 1*, 297-301.

Zmyj, N., Aschersleben, G., Prinz, W., & Daum, M.M. (2012). The peer model advantage in infants' imitation of familiar gestures performed by differently aged models. *Frontiers in Psychology, 3*, 252.

Zmyj, N., Daum, M.M., & Aschersleben, G. (2009). The development of rational imitation in 9- and 12-month-old infants. *Infancy, 14,* 131-141.

Zmyj, N. & Seehagen, S. (2013). The role of a model's age for young children's imitation: a research review. *Infant and Child Development, 22*, 622-641.