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Infants in Control

Prospective Motor Control and Executive Functions in Action Development

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Abstract
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This thesis assesses the link between action and cognition early in development. Thus the notion of an embodied cognition is investigated by tying together two levels of action control in the context of reaching in infancy: prospective motor control and executive functions.

The ability to plan our actions is the inevitable foundation of reaching our goals. Thus actions can be stratified on different levels of control. There is the relatively low level of prospective motor control and the comparatively high level of cognitive control. Prospective motor control is concerned with goal-directed actions on the level of single movements and movement combinations of our body and ensures purposeful, coordinated movements, such as reaching for a cup of coffee. Cognitive control, in the context of this thesis more precisely referred to as executive functions, deals with goal-directed actions on the level of whole actions and action combinations and facilitates directedness towards mid- and long-term goals, such as finishing a doctoral thesis. Whereas prospective motor control and executive functions are well studied in adulthood, the early development of both is not sufficiently understood.

This thesis comprises three empirical motion-tracking studies that shed light on prospective motor control and executive functions in infancy. Study I investigated the prospective motor control of current actions by having 14-month-olds lift objects of varying weights. In doing so, multi-cue integration was addressed by comparing the use of visual and non-visual information to non-visual information only. Study II examined the prospective motor control of future actions in action sequences by investigating reach-to-place actions in 14-month-olds. Thus the extent to which Fitts' law can explain movement duration in infancy was addressed. Study III lifted prospective motor control to a higher that is cognitive level, by investigating it relative to executive functions in 18-months-olds.

Main results were that 14-month-olds are able to prospectively control their manual actions based on object weight. In this action planning process, infants use different sources of information. Beyond this ability to prospectively control their current action, 14-month-olds also take future actions into account and plan their actions based on the difficulty of the subsequent action in action sequences. In 18-month-olds, prospective motor control in manual actions, such as reaching, is related to early executive functions, as demonstrated for behavioral prohibition and working memory. These findings are consistent with the idea that executive functions derive from prospective motor control. I suggest that executive functions could be grounded in the development of motor control. In other words, early executive functions should be seen as embodied.

Keywords: infant development, action development, prospective motor control, executive functions, action planning, motor development, motion tracking, embodied cognition, developmental psychology

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One day, in retrospect, the years of struggle will strike you as the most beautiful.

Sigmund Freud

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I. Gottwald, J. M., & Gredebäck, G. (2015). Infants' prospective control during object manipulation in an uncertain environment. *Experimental Brain Research*, *233*(8), 2383–2390.

II. Gottwald, J.M., de Bortoli Vizioli, A., Lindskog, M., Nyström, P., Ekberg, T.L., von Hofsten, C., & Gredebäck, G. (2016). Infants prospectively control reaching based on the difficulty of future actions – To what extent can infants' multiple step actions be explained by Fitts' law? *Under revision.*

III. Gottwald, J.M., Achermann, S., Marciszko, C., Lindskog, M., & Gredebäck, G. (2016). An embodied account of early executive functions development: Prospective motor control in infancy is related to prohibition and working memory. *Under revision.*

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Contents

Abbreviations

ADHD	Attention Deficit Hyperactive Disorder
ANOVA	Analysis of Variance
ASD	Autistic Spectrum Disorder
EEG	Electroencephalography
EMG	Electromyography
fMRI	Functional Magnetic Resonance Imaging
ICC	Inter Class Correlation
M	Mean
MD	Mean Difference
MRI	Magnetic Resonance Imaging
SD	Standard Deviation
TMS	Transcranial Magnetic Stimulation

Introduction

> It is impossible to understand the self without grounding it in action (Knoblich, Elsner, Aschersleben, & Metzinger, 2003, p. 488).

Why do we care about body movement in psychology? What does reaching behavior in particular in infants tell us about action planning? And how is the apparently simple process of planning manual movements related to more complex planning of actions? These questions will be addressed in this thesis and the related answers will be corroborated with empirical support from three experimental infant studies.

There are three key arguments for why we care about movement in psychology and why we should not leave this field entirely to biology, medicine and engineering.

First, the brain seems to be especially relevant for movement. Unlike humans and other animals, plants – which do not voluntarily move or navigate – have no brain. But humans produce meaningful, goal-directed movements during most of their time awake. One purpose of the brain is to control actions, and again, actions consist of movements. A striking illustration of the importance of the brain for movement is given by the sea squirt, a small marine invertebrate animal. As an infant, the sea squirt still possesses a brain for navigating the sea, but as soon as it finds a surface to attach to permanently, it transforms into a "stationary filter feeder" and digests its own brain. Without the need to move, the brain loses its purpose beyond serving as nutrients for the animal (Kalat, 2013).

Nevertheless, there are other human activities that are not, at first glance, directly related to movement, such as seeing or hearing. These perceptual activities may take place without conscious movement (yet still with movement at the muscular level, such as eye muscle or ear muscle movements), but are still necessary for action. This leads to the second argument for why action should be studied within the realm of psychology. Perception, which is a core aspect of psychology, guides action and may have primarily developed to enable interaction with the world. Perception itself can be regarded as embodied, since humans perceive with their bodies. This idea is central in accounts of direct perception and embodied cognition (Gibson, 1979; Merleau-Ponty, 1962; Wilson, 2002).

Third, motor development is deeply intertwined with perceptual and cognitive development, and is thus extremely important for understanding human psychological development as a whole (Diamond, 2000; Thelen, 1992, 1995; von Hofsten, 2004).

One key aspect of action development is action planning, which can be stratified on different levels of control that are parts of a hierarchical organization of action (Grafton & Hamilton, 2008). For instance, the same action can be understood on the level of kinematics (e.g. reaching for a laptop) or on a cognitive level of goals and intentions (e.g. writing a thesis). The current thesis describes three empirical infant studies on early action planning that address the different levels of control.

Study I investigated the prospective motor control of current actions via the example of lifting different weighted objects in 14-month-olds. Study II examined the prospective motor control of future actions in action sequences via the example of reach-to-place actions in 14-month-olds. Study III took prospective motor control to a higher (cognitive) level by investigating it in combination with executive functions in 18-month-olds.

Before discussing these studies, a theoretical background is provided. I begin with a chapter on embodied cognition and its different claims and approaches. Next is a chapter on motor development addressing the links between motor behavior, perception and cognition, in which the development of reaching and the contributions of vision, proprioception and the integration of information are outlined. The third chapter describes the hierarchy of action planning. The fourth chapter defines the concept of prospective motor control as an important feed-forward control process and also provides a description of a fine-grained measure of prospective motor control. The last chapter approaches action planning from a cognitive-control perspective and discusses executive functions and the two components of behavioral inhibition and working memory.

I Embodied cognition

> To say that cognition is embodied means that it arises from bodily interactions with the world. From this point of view, cognition depends on the kinds of experiences that come from having a body with particular perceptual and motor capabilities that are inseparably linked and that together form the matrix within which reasoning, memory, emotion, language, and all other aspects of mental life are meshed (Thelen, Schöner, Scheier, & Smith, 2001, p. 1).

Embodied cognition, as one perspective of cognitive science, is an umbrella term for the basic assumption that the mind is shaped by the body – that is, the body beyond the brain (Wilson, 2002). In understanding cognition as derived from the body and its interactions with the world, this assumption opposes the Cartesian tradition of conceptualizing body and mind as two separate substances (Descartes, 1644/1983). Hence, the embodied cognition approach does not distinguish between a material body and an immaterial mind and thus does not consider the body as a kind of action and perception device of the mind (Wilson, 2002), as the body is sometimes viewed in traditional cognitive psychology (cf. Neisser, 1967/2014).

In the course of the cognitive revolution, Newell and Simon (1961) created a computer program named the *General Problem Solver* (for a historical review, see Miller, 2003). This program was designed to simulate human cognition. In doing so, they compared human problem-solving to computer calculations. They also emphasized the importance of symbol manipulation and claimed that there are symbols and operations on these symbols in the brain. In other words: Newell and Simon regarded mental processes as computational (cf. Shapiro, 2011):

> We can postulate that the processes going on inside the subject's skin – involving sensory organs, neural tissue, and muscular movements controlled by the neural signals – are also symbol-manipulating processes; that is patterns in various encodings can be detected, recorded, transmitted, stored, copied, and so on, by the mechanisms of this system (Newell & Simon, 1961, p. 2012).

Embodied cognition theories are sometimes defined by distinguishing embodied cognition from what is assumed to be "standard cognitive science" (see e.g. Barsalou, 2008). One popular line of argument often starts with rejecting the computer metaphor of the human brain illustrated above. Proponents of *embodied cognition* could counter by stating, for example, "while we might one day have machines that work like brains, our brains do not work much like current computers, and certainly not much like computers of the late 1950s and early 1960s" (Charles, Golonka, & Wilson, 2014, pp. 182–183). Instead, according to the embodied cognition perspective, brain functioning is regarded as highly dependent on the body and vice versa (Shapiro, 2011; Wilson, 2002). Mental representations – which are central in cognitive psychology – are thus sometimes regarded as unnecessary in embodied cognition approaches: "My body has its world, or understands its world, without having to make use of my 'symbolic' or 'objectifying function'" (Merleau-Ponty, 1962, p. 140f). However, other theories of embodied cognition explicitly include mental representations (see Burr & Jones, 2016).

Embodied cognition subsumes at least six different approaches or basic claims that are not necessarily exclusive, but are partly contradictory: Cognition is situated; cognition is time-pressured; cognitive work is off-loaded onto the environment; the environment is part of the cognitive system; cognition is for action, and off-line cognition is body-based (see Wilson, 2002, for a theoretical review).

Embodied cognition approaches vary in their view on mental representation (for classification see Burr & Jones, 2016). Radical embodied cognition approaches assume that cognition can be explained without mental representations (Chemero, 2011). More moderate embodied perspectives describe cognition with embodied representational states (Barsalou, 1999), and others explicitly implement representations in their theoretical framework by explaining abstract concepts as embodied (Casasanto, 2009).

Additionally, embodied cognition approaches differ in the field of origin respectively in their main area of interest, such as language (Lakoff & Johnson, 1980a), metaphors (Gottwald, Elsner, & Pollatos, 2015), perception and action (Gentsch, Weber, Synofzik, Vosgerau, & Schütz-Bosbach, 2016), memory (Glenberg, 1997), artificial intelligence (Brooks, 1999), psychotherapy (Leitan & Murray, 2014), psychoanalysis (Buchholz, 2007; Sletvold, 2013), and philosophy (Merleau-Ponty, 1962).

For the purpose of this thesis, three basic claims of embodied cognition, as discussed by Wilson (2002), are of special interest. First, the claim "cognition is situated"; second, the claim "cognition is for action"; and third, the claim "off-line cognition is body-based."

Cognition is situated

The claim of situated cognition assumes that cognition is embedded in an environment and that it does therefore coercively include perception and action. In other words, cognition is seen as situated activity (Beer, 1995; Chiel & Beer, 1997; Clark, 2011; Thelen & Smith, 1994). Consequently, the particular context in which cognition takes place is taken into consideration: "Perception is the interface where the world affects the mind, and that action is the interface where the mind affects the world," as Chalmers vividly phrases it in his foreword to "Supersizing the mind" by Clark (2011, p. xi). The context is defined by task-relevant inputs and outputs. Perceptual information is continuously affecting cognitive processing and, at the same time, performed motor activity is affecting the environment in task-relevant ways. According to this claim, every "on-line" cognitive activity is situated. *On-line* means being coupled to the mentioned task-relevant context. Wilson (2002) mentions driving or holding a conversation as examples of situated cognition. Off-line cognitive activity, such as daydreaming or remembering, is not covered by the situated approach and will be discussed in the section of the third claim, *Off-line cognition is body-based* (p. 19; Wilson, 2002).

According to Wilson (2002), the *dynamic systems theory* (Corbetta & Snapp-Childs, 2009; Corbetta, Thelen, & Johnson, 2000; Thelen, 1992; Thelen et al., 1993; Williams, Corbetta, & Cobb, 2015) can be understood against the background of this claim and may help provide an understanding of human development in general. The theory emphasizes the importance of a tight perception-action coupling. Exploration in the form of cycles of action and perception are regarded as crucial for the emergence of new skills, such as reaching (Williams et al., 2015). An example of this exploration could be reaching with different velocities. According to the dynamic systems approach, the skill emergence and development can be explained by taking the continuous interactions between the brain, the biomechanical and energetic properties of the body, the environmental support and the changing task-relevant context into account (Thelen, Corbetta, & Spencer, 1996).

Empirical support for this approach is given by Thelen et al. (1993, 1996). These researchers followed four infants from reach onset to the end of the first year of life and measured reaching kinematics. They found individual differences, but also common changes in the process of learning to reach successfully.[1] All infants demonstrated active periods with reaches of higher velocity and less straight trajectories, and they demonstrated stable periods with reaches of lower velocity and more straight trajectories. The infants differed in their timing and the order of these active and stable periods, as well as in the time of reach onset. Thelen et al. (1996) interpreted the results

[1] Successful reaches consist of direct and smooth movements toward the goal (Thelen et al., 1996, p. 1067).

as demonstrations of explorations of the individual infant's own abilities in order to learn to reach successfully. The infants scaled their reaching speed through sensorimotor experiences that are cycles of action and perception (see also *The development of reaching,* p. 22).

Cognition is for action

This claim states that the mind functionally guides action and that, in turn, cognitive mechanisms such as perception and memory have developed to serve the body in action. This idea of a close action-perception[2] link can be found in the philosophy of Merleau-Ponty (1962):

> In perception we do not think the object and we do not think ourselves thinking it, we are given over to the object and we merge into this body which is better informed than we are about the world, and about the motives we have and the means at our disposal for synthesizing it" (Merleau-Ponty, 1962, p. 238).

Visual perception, as one example of perception, can be considered to have its "evolutionary rationale rooted in improved motor control" (Churchland, Ramachandran, & Sejnowski, 1994, p. 25). In other words, humans are primarily able to see in order to move and interact with the world, and not primarily in order to create internal representations of the world (Churchland et al., 1994; Milner & Goodale, 2006).

Empirical support for the close link between action and visual perception was provided by experimental work using response time measures. I will mention two studies in this context.

First, Tucker and Ellis (1998) asked adults to judge the orientation of everyday life objects with handles, such as teapots or frying pans. The participants saw pictures of graspable objects and had to state as quickly as possible whether the pictured objects were in an upright or reversed orientation. The participants responded fastest when the object was oriented toward the participant's hand that would grasp for it. In other words, the participants responded faster when grasping for these objects would have been easier. The authors regarded these results as consistent with the assumption that visually perceiving objects supports actions they afford.

Second, Craighero, Fadiga, Rizzolatti, and Umiltà (1999) demonstrated that visually perceiving a form in a certain (congruent) orientation facilitates grasping performance. In their experiments, adults had to prepare a grasping

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[2] Some of the mentioned theories either treat perception and cognition as two domains, or perception as a subdomain of cognition. The heading of this section could have also been "Cognition and perception are for action." I continue to use *perception* and *cognition* separately, but sometimes use only one of these terms to not confuse the reader too much.

movement before they got to see a bar in one of two possible orientations. Subsequently, they had to grasp the presented bar as fast as possible. The participants grasped quicker when their prepared grasps matched the orientation of the presented bars, as opposed to when they did not match. The authors suggested that preparations to act on objects lead to faster processing of object properties when these preparations are congruent with the object.

Furthermore, the work by Goodale, Milner, Jakobson, and Carey (1991) can be partially regarded as supporting the assumption that visual perception is for action. These researchers had a patient with *visual form agnosia* (an impairment in visual recognition of objects due to damage in certain brain regions)[3], verbally judge the orientation of lines and place cards into a slot with different orientations. While the patient's performance in the placement task was the same as in healthy controls, the performance in the visual judgment task was clearly impaired. To put it differently, the patient was not able to visually recognize certain orientations of lines, but was able to use these orientations for action when placing a card into slots. Building on these observations, Goodale et al. (1991) and Goodale and Milner (1992) argued that there are two visual pathways (*streams*) in the brain. Besides the *ventral stream*, which is for object perception and which was impaired in the mentioned patient, there is the *dorsal stream,* which is for visual guidance of action and which was fully functioning in the patient.

I mention this research here not to describe the function of the two visual pathways, which was the point made by Goodale and Milner (1992), but to underline that visual perception and the processing of action are closely linked via pathways in the brain. The dorsal stream could be especially important for the idea that cognition and perception have an important function for action. The striking observation of the possibility of sensitivity to an appropriate motor action without the need to consciously process the orientation of the goal area, as demonstrated by the patient, could be seen as a possible link to accounts of *direct perception* and the term of *affordance*s, which has been touched upon in the work described above by Tucker and Ellis (1998).

Gibson (1979) formulated the idea of *direct perception,* a perception that does not rely on cognitive construction. His ecological psychology could be seen as an embodied account, as it emphasizes that both the body and the environment are important for perception. Proponents of *direct perception* acknowledge that passive perception (i.e., perception without action) is theoretically possible, but also state that active perception (i.e., perception coupled with action) provides us with more information by making use of the

[3] The patient, in the literature known as D.F., had damage in the lateral occipital and the parasagittal occipitoparietal region.

bodily relationships between motion and sensory input (Burr & Jones, 2016; Gibson, 1979; Golonka & Wilson, 2012; Noë, 2004).

A classical animal experiment by Held and Hein (1963) can serve as empirical support for this notion. These researchers studied two groups of newborn cats. They had one group of kittens drag a carriage, while the other group was placed in carriages in a carousel. The rationale behind this was that the first group explores the environment actively by moving around, whereas the other group perceives the same world passively by being moved by the carousel. After a while, both groups of kittens were examined. While the actively moving kittens demonstrated typical perceptual abilities, the abilities of the carousel-riding kittens were impaired. For instance, these cats did not develop depth perception, which suggests that these kittens did not form bodily relationships between their own movements and sensory input, resulting in perceptual impairments (see Gentsch et al., 2016).

Further empirical support for the notion of active perception was provided by a study by Dahl et al. (2013) with 7-month-old pre-crawling infants. One group of infants was trained to drive a powered-mobility device, while the other group did not receive such training. In other words, the trained group had experiences with active locomotion and the control group did not. Afterwards, their wariness of heights was tested by measuring their heart rate as they were held over a visual cliff. The results showed that the training group was more wary of heights than the control group. The author interpreted the discrepancy in wariness of heights as the result of the differences in the visual experiences of both groups. Usually, non-crawling infants around 7 months do not actively move through their environment and they do not avoid heights. However, the opportunity to drive a device allowed the infants to navigate through the room. Height consequently became an important factor.

A central term of Gibson's (1979) approach is *affordances.* In brief, affordances are possibilities for action. Or, as formulated differently by Golonka and Wilson (2012): Affordances are "organism-scaled action relevant properties of the environment" (Golonka & Wilson, 2012, p. 42). The idea behind this is, that vision functionally serves action. If this claim is taken seriously, vision must provide us with information for how to act on the objects in our environment. In this process, it is not important exactly how far away a cup is placed from us; rather, it matters whether we can reach it. The aspect of the reachability of the cup is an example of an affordance (Golonka & Wilson, 2012). According to Gibson (1979), affordances are perceived directly, for example as a chair would be perceived as an opportunity to sit. This is possible because of a close perceptual attunement between the human (or another animal) and his environment, which allows for direct sensitivity to environmental properties (cf. Noë, 2004).

Approaches that relate perception and cognition more basically to motor control are discussed by Gentsch and colleagues (2016). The authors propose a meta-theoretical framework to explain the nature of this link and argue for an understanding of perception and cognition as grounded in motor control. Motor control thus partially constitutes perception and cognition. In this context, the term partial constitution refers to a certain relationship between these two (three) areas: While cognition is enabled by sensorimotor experiences, this does not mean that all cognition can be explained by sensorimotor experiences. However, according to Gentsch et al. (2016), there would be no cognition without sensorimotor experience.[4] One family of theories that fits into the framework of Gentsch et al. is the one of *internal models*, which will be further discussed in the section *Feed-forward control, feedback processes and internal models* in chapter IV (p. 31).

Off-line cognition is body-based

The two above-mentioned claims *Cognition is situated* (p. 15) and *Cognition is for action* (p. 16) involve explicitly the environment. However, the claim "offline-cognition is body-based" involves the environment rather implicitly via body-based (*sensorimotor*) simulations. Sensorimotor simulations are "neural correlates between the content of what is […] represented (e.g. action words) and the areas in the brain being activated (e.g. actions)" (Dijkstra & Post, 2015, p. 2).

The claim "off-line cognition is body-based" states that first, these sensorimotor simulations are central for cognitive activities, such as problem-solving, and second, that they are central for interacting with the environment even when being decoupled (*off-line*) from this environment.

Examples of off-line cognitive activities could include daydreaming or remembering. When off-line, sensorimotor processes simulate certain features of the environment (Wilson, 2002). Different areas of research propose various approaches for conceptualizing these simulations, such as the *perceptual symbol systems* theory, which explains the embodiment of mental concepts (Barsalou, 1999), or the metaphor-based approach of Lakoff and Johnson (Lakoff & Johnson, 1980a, 1980b).

Wilson (2002) mentioned five different cognitive activities involving sensorimotor simulations: mental imagery; episodic memory; implicit memory; problem-solving, and working memory[5]. The latter is a component of executive functions and especially interesting in the context of this thesis (see also

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[4] Gentsch et al. (2016) use the term "action cognition" instead of referring to perception and cognition separately (see footnote 2, p. 16).

[5] Working memory is a core executive function (i.e., cognitive function) and involves working with off-line information. In other words, it is the ability to hold information in mind to manipulate it (Diamond, 2013). See chapter V.

chapter V). Here, it will be examplary described as off-line cognitive activity.

Working memory is short-term memory that involves the simulation of physical events by making use of sensorimotor ressources (Wilson, 2001). As the amount of information that must be kept in mind and manipulated in working memory tasks is rather large, Wilson (2001) suggested that part of the information is off-loaded into perceptual and motor control systems in the brain, so that we can think of working memory as body-based or – in other words – as embodied.

The embodied cognition approaches mentioned above, except for the dynamic systems theory of development by Thelen and colleagues (Thelen, 1992; Thelen et al., 1993), do not explicitly involve statements of early development, even though the idea that embodied cognition is especially important in the early (preverbal) period of life, is striking.

Piaget (1952) formulated this idea in his theories on the development of intelligence throughout childhood and Freud (1923) assumed this when he wrote about early development: “The ego is first and foremost a bodily ego” (Freud, 1923, p. 26, cf. Sletvold, 2013). What is new, however, is the perspective that motor and cognitive development interact dynamically (Thelen, 1995; Wilson, 2002) and are not as distinctly as classically believed.

The following section will describe motor (and exemplary reaching) development against the background of embodied cognition, as one perspective of cognitive science.

II Motor development

The ego is first and foremost a bodily ego (Freud, 1923, p. 26).

Motor behavior is adaptive from the beginning of life (Piaget, 1952). Newborns' movements are already meaningful, goal-directed and structured as actions (van der Meer, van der Weel, & Lee, 1995; von Hofsten & Rönnqvist, 1993; von Hofsten, 1991, 2014) and infants coordinate their movements based on continuous action-perception interactions (Lockman, 1990; Thelen, 1995; see also *Cognition is situated,* p. 16). The emergence of new motor skills, such as reaching or walking, is important, as these skills offer new possibilities for action and perception. Reaching for an object presents opportunities to explore and manipulate different shapes and materials, for example, and walking allows infants to explore space and socially interact with others in a qualitatively different way (Adolph & Tamis-LeMonda, 2014; Kretch, Franchak, & Adolph, 2014; Thelen, 1995).

According to the dynamical systems approach, these transitions in development (e.g. to reaching or to walking) are of special interest, because they mark periods of instability. In other words, the emergence of new abilities causes the system to be more variable and unstable. This instability potentially enables the developmental researcher to discover underlying processes (Thelen, 1992).

Thus, studying motor development is more than listing motor milestones and investigating when these abilities emerge throughout the course of development (Thelen, 1995). Instead, studying motor development implies investigating the processes and mechanisms that lead to adaptive and complex motor behavior (Thelen, 1992). It has thus been suggested that motor development is deeply intertwined with perceptual and cognitive development (Diamond, 2000), and as such is highly important for understanding human psychological development as a whole (Karmiloff-Smith, 1994; von Hofsten, 2004).

The importance of motor development will be stressed by discussing, first, the example of reaching as a transition-marking motor skill, and second, the role of vision and proprioception for reaching.

The development of reaching

Reaching is a goal-directed extension of the arm that ends with contact between the hand and object (Thelen et al., 1996). The onset of goal-directed reaching around the age of four months indicates an important transition in infancy, as reaching offers many new opportunities for action and perception, such as object exploration and social interaction (Corbetta & Snapp-Childs, 2009; Williams et al., 2015). The acquisition of reaching requires the ability to visually locate a target, the intention to reach for this target, and sufficient control of the head, trunk, posture and the reaching arm (Thelen et al., 1993). Taking the relatively quickly changing abilities and growing body of an infant into account, this seems to be a rather keen challenge that each individual masters in her own way: “Reaching development is thus a process of individual problem solving” (Thelen et al., 1993, p. 1059).

This development can be thought of as having its initiation already before birth, when it still takes around seven more months to reaching onset. First signs of goal-directed hand movements were demonstrated in fetuses at the twenty-second week of gestation (Zoia et al., 2007).

After birth, newborns intentionally move their arms in a controlled and goal-directed way. Van der Meer et al. (1995) demonstrated this in 10 to 24-day-old infants by measuring the newborns’ spontaneous arm waving behavior. The newborns were lying on their back with their heads turned to one side and had a weight attached to their wrists. They could thus either see or not see their arms.[6] The results showed that only the infants who could see their moving arm, moved their arms up and down, which was true despite having weights attached to them. According to van der Meer et al., (1995), these newborns were sensitive to the new context (of the weights) and demonstrated controlled, intentional movements. They were thus capable of taking the new forces, as induced by the weights, into account and controlled their movements accordingly. The researchers further argued that vision plays an important role for the exploration of the body and its movements, which lead the way to successful reaching.

Three and a half months later, neonates display arm movements toward a visual target, which can be classified as pre-reaching behavior (von Hofsten, 1982, 1984). These arm movements already appear to be structured and occasionally visually controlled (von Hofsten & Rönnqvist, 1993).

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[6] The experimental design is simplified in this description.

While early hand and arm movements are primarily oriented toward an infant's own body and are self-exploratory in nature, they become oriented toward objects two months after birth (Rochat, 1993). Thus, object manipulation in form of object swatting appears between the first and the third month of life (Piaget, 1952; von Hofsten, 1984).

From a dynamic systems perspective (see also *Cognition is situated*, p. 15), reaching then emerges around four months through repeated cycles of action and perception and against the background of complex interactions between many developmental factors. These factors include neural maturation, genetics, developmental history, anatomical structure, movement preferences, and sensorimotor experiences (Williams et al., 2015).

At onset, reaches consist of jerky movements and then become straighter and smoother in the course of development (von Hofsten, 1979, 1991).

Gender differences in the first reaching behavior can be observed: Girls' reaches are straighter, shorter and contain fewer sub-movements (see chapter IV) than the reaches of boys. These differences are probably linked to maturation. Around reach onset, boys are heavier and longer and have longer forearms than girls. Longer forearms are less easy to control; consequently, girls are better at prospectively controlling their arms when reaching (Cunha et al., 2015).

The properties of the body, such as forearm length, can also function as biomechanical constraints on reaching. Reaching with a longer forearm requires more force than reaching with a shorter forearm. Consequently, it is harder to perform reaches with a straight trajectory (Thelen et al., 1996).

Additionally, every infant has her individual motor tendencies that can interfere with optimal reaching strategies and can therefore function as a constraint. Infants' reaches are not free from the influences of systematic motor tendencies, such as two-hand reaches, before the age of eight months (Corbetta et al., 2000).

Corbetta and Snapp-Childs (2009) investigated how 6- to 9-month-old infants use experiences with objects to optimize their reaches and what role systematic motor tendencies do play in this process. These researchers had the infants repeatedly reach for a small ball, a large ball or a large pompon (a cluster of streamers made of yarn). While both large objects were the same size, they required different reaches and grasps: while the ball had to be held with both hands, the pompon could easily be held with just one hand by the infants. Results showed that only the older infants (aged 8 and 9 months) seemed to learn from the repeated experience with the different objects and adapted their reaching behavior accordingly. These infants increased their unimanual (as opposed to bimanual) reaches and grasps for the pompoms, which is interpreted as adaptive, whereas the younger infants (aged 6 and 7 months) did not.

Individual motor tendencies are part of the individual reaching development in the first year of life. This development consists of active and stable periods and movement speed is individually applied (Thelen et al., 1993, 1996). Skilled reaching emerges from the exploration of different movement speeds and this variability facilitates successful prospective control of reaching trajectory (Thelen et al., 1996).

To summarize, infants demonstrate goal-directed arm movements from early on. Their movements can be seen as intentional and purposeful, and can therefore be described in terms of actions. Reaching develops from these early hand and arm movements. Even though infants are capable of controlling these movements, there are some systematic constraints that might complicate the process of learning to reach successfully.

The following section will focus on Fitts' law, a well-studied law that describes human manual movements, in order to introduce potential ways to use the law for developmental research.

Fitts' law in reaching development

Movement speed is important for many aspects of motor control and also critical for reaching development in infancy (Thelen et al., 1996). Besides the individual motor tendencies mentioned above, there are also general laws that describe human movement. One prominent example is a law of speed-accuracy trade-off in goal-directed movements – Fitts' law (Fitts, 1954). This law characterizes the relationship between action difficulty and movement time and states that the movement time (MT) required to rapidly move to a goal area is a function of the distance (D) to the goal and the size (S) of the goal given by $MT = a + b * \log_2 (2 D/S)$, where $\log_2 (2 D/S)$ is the spatial relative error or the index of difficulty and a and b are empirical constants (Plamondon & Alimi, 1997). To put it differently: the easier an action becomes, the less time is required to successfully perform it.

The relationship between task difficulty and movement speed has been studied for more than 100 years and can be observed in many goal-directed hand movements. Nowadays, it can be practically applied when designing webpages (where cursor movements to areas follow Fitts' law), for example, or other human-machine interfaces (where buttons have certain sizes and locations). Several modifications to the original formulation have been developed (for a review see Plamondon & Alimi, 1997), such as the version by Welford, Norris, and Shock (1969), which allows for the evaluation of the separate contributions of goal size and goal distance: In this model, movement time (MT) is given by $MT = a + b_D * \log_2 (D) + b_S * \log_2 (1/S)$. This version will be applied in Study II.

While the speed-accuracy trade-off has been extensively studied in adults (Beggs & Howarth, 1970; Bootsma, Marteniuk, MacKenzie, & Zaal, 1994; Carlton & Newell, 1979; Crossman & Goodeve, 1983; Gillan, Holden, Adam, Rudisill, & Magee, 1990; Knight & Dagnall, 1967; Megaw, 1979), there are fewer studies in children (Salmoni, Pascoe, Roberts, & Newell, 1978; Salmoni, 1983; Sugden, 1980; Wallace, Newell, & Wade, 1978). The participants in the aforementioned studies were four to twelve years old. To my knowledge, only one study has investigated Fitts' law in infancy regarding infants' own actions (Zaal & Thelen, 2005).[7]

Zaal and Thelen (2005) demonstrated that seven-, nine-, and eleven-month-old infants reach more slowly for smaller objects (buttons) than for larger objects (puppets). In the youngest age group, Fitts' law could explain 29% of the variation in reaching movement duration. For the nine and eleven-month-olds, the figures were 49% and 45%, respectively.

Vision and proprioception

Visual perception is a process of seeking information by eye-sight from pictures and visual scenes to guide action (Mallot, 2006).

Proprioception is the sense of the relative position of neighboring parts of the body and of the strength of effort being employed in movement. In other words, proprioception is the perception of our body in the world (Kalat, 2013). We need proprioception to keep our balance, to adjust our posture and to avoid falling down. Responsible for this ability are receptors – the so-called proprioceptors – that detect the position and the movements of body parts. Proprioceptors control reflexes and provide the brain with information. They allow us for instance to walk on a bumpy road or to ride a bicycle without falling down and without having to plan every movement intentionally (see chapter III for differently levels of action control). To sense the position of our body parts by proprioception, vision is not needed (Kalat, 2013).

Generally, proprioception and vision play a key role in the control of voluntary movements. Most everyday actions, such as preparing breakfast or riding a bicycle, require both visual and proprioceptive information. In infancy, important examples include sitting, standing or walking.

Object-directed reaching is another example, where the interplay of proprioception and vision is crucial. Regarding reaching in infancy, there are different opinions on the main source of information and whether infants rely primarily on proprioceptive information (as demonstrated by Clifton, Muir, Ashmead, & Clarkson, 1993) or on visual information (as demonstrated by Pogetti, de Souza, Tudella, & Teixeira, 2013).

One way of conceptualizing the interplay between vision and proprioception in the context of reaching was discussed by Jeannerod (1988, pp. 171–206) for adults and by von Hofsten (1993b) for infants: Reaching is suggest-

[7] Fitts' law also holds for expectations and simulations of observed actions performed by others. This was shown for 15-month-old infants (Stapel, Hunnius, & Bekkering, 2015) and for adults (Grosjean, Shiffrar, & Knoblich, 2007; Stapel, Hunnius, & Bekkering, 2012).

ed to consist of different phases: Initially, before movement onset, the object needs to be visually fixated (*foveation*). Foveation allows for the visual calibration of the position of the hand relative to the object. Secondly, proprioception guides the reaching movement of the arm to the object, while third, vision is used for potentially necessary corrections toward the object. In adults, it takes at least 100 ms before visual feedback can be used for movement corrections (Jeannerod, 1988, p. 101; see *Feed-forward control, feedback processes and internal models,* p. 31).

The interplay between different sources of information, such as vision and proprioception, necessitates a discussion of how information from different sources is integrated. This is the purpose of the following section.

Multi-cue integration

As described above, successful reaching probably requires both, visual and proprioceptive information. By using these sources of information, we do not only learn to produce skillful movements; we also learn about the objects involved. Object properties, such as weight or size, can be inferred using different cues from the same and from different sources of information. The weight of an object, for instance, can be visually inferred from its size or color and tactilely[8] inferred from its material or shape. By lifting the object, proprioception also informs us about its weight. Information acquired from multiple senses has to be combined or integrated. Multisensory integration – the ability to combine information from different sensory sources (Barutchu et al., 2011) – is specifically important for reducing uncertainty in the case of ambiguous or contradicting sensory information (Nardini, Bedford, & Mareschal, 2010; Rock & Victor, 1964).

Adults combine different kinds of information, such as visual and haptic information, in a statistically optimal manner and in this process of integrating multiple cues, vision is often given more weight (Ernst & Banks, 2002).

While the perception of multiple cues is well understood in adults, the picture is less clear for the developing child (Barutchu, Crewther, & Crewther, 2009; Nardini, Bales, & Mareschal, 2015). Infants do not fully integrate visual and haptic[9] information until the end of the first year of life (Corbetta & Snapp-Childs, 2009). If infants do not integrate different sources of information, they should favor one of the senses involved in order to prospectively control their action. While four-month-old infants predomi-

[8] The terms *haptic* and *tactile* are both related to perception by using the hands. Tactile information is information acquired through skin sense. Haptic information includes tactile and kinesthetic information. It is acquired through active exploration (cf. Lederman & Klatzky, 1987). While the terms have slightly different meanings, they are sometimes used interchangeably. In Study I (p. 58, in line with the related publication) the term *tactile* is consistently used; even though *haptic* would be the more appropriate term.

[9] See previous footnote.

nantly rely on touch for grasping objects, eight-month-olds primarily rely on vision (Newell, Scully, & McDonald, 1989). For the case of reaching, it is debated whether infants mainly rely on proprioceptive information (as demonstrated by Clifton, Muir, Ashmead, & Clarkson, 1993) or visual information (as demonstrated by Pogetti, de Souza, Tudella, & Teixeira, 2013).

In general, children often demonstrate a poorer performance than adults in tasks requiring the use of different sources of information (Nardini et al., 2015), but sometimes children also outperform adults (cf. Gopnik, Griffiths, & Lucas, 2015). Performance depends on how many object property cues are offered, whether they are from different sources and whether or not integrating them is advantageous for the task.

One way to frame the differences in cue use in adults and children is to discuss perceptual narrowing, a developmental specialization process in which experience shapes perception. At birth, humans demonstrate a broad multisensory perceptual tuning that narrows throughout the course of life (Scott & Monesson, 2010; Scott, Pascalis, & Nelson, 2007). After birth, humans are able to distinguish between many phonemes and faces, but at the end of the first year, only cues that are relevant for their own language and community can be distinguished (Lewkowicz & Ghazanfar, 2009). This developmental process offers an evolutionary advantage and often allows us to act more efficiently, but at the same time, we might lose information and behave less creatively: "Younger minds and brains are intrinsically more flexible and exploratory, although they are also less efficient as a result" (Gopnik et al., 2015, p. 87).

The size-weight illusion

In cases of contradictory sensory information, actions can be guided either by combining information across cues or by discounting the discrepant source (Ernst & Banks, 2002; Hillis, Ernst, Banks, & Landy, 2002). One classical way of studying contradictory sensory information – and thereby the use of proprioception versus vision – is the size-weight illusion: If you have two objects of the same weight, the small object feels heavier than the large object (Charpentier, 1891; Nicolas, Ross, & Murray, 2012).

The size-weight illusion was described by Charpentier at the end of the nineteenth century and since then, it has been investigated exhaustively in adults (Buckingham, Goodale, White, & Westwood, 2016; Buckingham & Goodale, 2010b; Buckingham, Michelakakis, & Rajendran, 2016; Davis & Roberts, 1976; Flanagan & Beltzner, 2000; Flanagan, King, Wolpert, & Johansson, 2001; Forssberg, Eliasson, Kinoshita, Westling, & Johansson, 1995), children (Pick & Pick, 1967; Robinson, 1964), and infants (Kloos & Amazeen, 2002; Plaisier & Smeets, 2012). More generally, weight perception was studied in weightlifting paradigms measuring verbal judgments

(Davis & Roberts, 1976), electromyography (EMG; Schmitz, Martin, & Assaiante, 1999), force (Buckingham, Goodale, et al., 2016; Li, Randerath, Goldenberg, & Hermsdörfer, 2011) or reaching and lifting kinematics (Mash, 2007), and in action observation paradigms measuring electroencephalography (EEG; Upshaw, Bernier, & Sommerville, 2015), functional magnetic resonance imaging (fMRI; Grezes, Frith, & Passingham, 2004), transcranial magnetic stimulation (TMS; Alaerts, Swinnen, & Wenderoth, 2010), force (Reichelt, Ash, Baugh, Johansson, & Flanagan, 2013), or own action performance (Hamilton, Wolpert, Frith, & Grafton, 2006).

However, the mechanisms underlying the so-called illusion[10] are still debated. One prominent explanation stresses the role of expectation: First, we expect a large object to be heavy, but while lifting, the proprioceptive feedback differs from the prior expectation – it feels lighter than it previously appeared. The consequence of this mismatch is a perception of a lightweight object (Granit, 1972).

Another possibility would be that weight is confused with density. If two objects differ in size, but not in weight, the smaller one has a higher density. The object with the higher density would be perceived as heavier (Grandy & Westwood, 2006; Kawai, 2002).

Flanagan and Beltzner (2000), however, demonstrated that fingertip forces adapt rapidly and are independent of weight judgments. While participants learned to scale their forces adaptively, the size-weight illusion persisted. Consequently, these authors argue for the independence of weight perceptions and sensorimotor predictions (cf. footnote 18, p. 35 and chapter IV).

In both explanations, vision is assigned a crucial role, either for expectations or for feedback-based corrections (cf. Buckingham & Goodale, 2010a). Chapter IV will further discuss the processes assumed to be involved in controlling and correcting in object manipulation tasks such as weightlifting and in human actions in general.

[10] The term *illusion* implicates some issues when dealing with perception. The senses themselves cannot be at fault; rather, the *failure* would apply to cognitive judgment. Von Helmholtz (1868) already described this issue, but it is still common in psychology. In general, terms such as *error* or *illusion* are problematic in the psychology of perception, as they cannot contribute to explaining the perceptual system itself (Mausfeld, 2005, 2015).

III Action planning

> Planning and control processes are influenced by the intent of what we wish to do with an object after we grasped it (Armbrüster & Spijkers, 2006, p. 313).

According to Scholnick and Friedman, “planning is the use of knowledge for a purpose, the construction of an effective way to meet some future goal” (Scholnick & Friedman, 1993, p. 145). While these authors have a cognitive, top-down approach to action planning – their model involves explicit strategies, decisions, knowledge and representations – action planning can also be addressed from a motor control perspective (Cohen & Rosenbaum, 2004; Fabbri-Destro, Cattaneo, Boria, & Rizzolatti, 2009; Keen, Lee, & Adolph, 2014). In the latter context, action planning is reflected in goal-directed movements without the need for representations or explicit processes. Thus, the brain and the rest of the body interact and produce coordinated movements oriented toward a goal, as stated in motor control accounts (Latash, 2012).

This demonstrates that action planning can be viewed from different angles involving different levels of specificity. Higher order (cognitive) action planning considers entire actions and action combinations directed at more complex[11] goals, such as maintaining a diet or finishing a doctoral thesis. Low-level (motor) action planning investigates single movements within actions directed at more simple goals, such as reaching for a salad bowl or a laptop. As the same nomenclature is partially used for different levels of complexity, in order to prevent conceptual confusion, the following paragraphs will first define these different levels hierarchically, and second, link the action hierarchy to prospective motor control and executive functions. The next two chapters will then describe prospective motor control and executive functions in more detail.

[11] In this context, “complex” means temporally and spatially complex.

The action hierarchy

Actions can be considered to be organized on different hierarchical levels and are represented in the brain as such (Grafton & Hamilton, 2008; Hamilton & Grafton, 2007). For example, the same action can be understood on the relatively low level of kinematics (e.g. reaching for a cup) or on the higher level of goals and intentions (e.g. drinking coffee). Hamilton and Grafton (2007) distinguish between three different levels, including both levels mentioned in addition to the muscular level. The latter is the lowest in the hierarchy and is concerned with the activity patterns of muscles (e.g. of the hand and arm when reaching for a cup); the next level, the kinematic level, describes movements (e.g. of the reaching arm), and finally, the highest level, the level of goals and intentions, deals with the goals and outcomes of an action. According to the authors, these three levels are independent of each other, so that one goal, such as drinking coffee, can be realized via different movements and with different muscular activation patterns. Vice versa, one specific pattern of muscular activity can be involved in accomplishing different goals (Hamilton & Grafton, 2007).

Prospective motor control in action planning

Prospective motor control, the ability to adapt one's actions according to action goals and future tasks, is needed for goal-directed movements (von Hofsten, 1993) and is thus involved in action planning (Claxton, Keen, & McCarty, 2003). Prospective motor control deals with the characteristics of movements and is best addressed on the second, or kinematic, level of the action hierarchy (Hamilton & Grafton, 2007).[12] Prospective motor control is addressed in chapter IV.

Executive functions in action planning

Executive functions as "self-directed actions needed to choose goals and to create, enact, and sustain actions towards those goals" (Barkley, 2012, p. 60) are crucial for higher-order action planning (Scholnick & Friedman, 1993). By investigating executive functions in action planning, we address the goals and intentions of actions and action sequences. From this it follows that executive functions are best described on the level of intentions and goals, the third level of the action hierarchy (Hamilton & Grafton, 2007). Executive functions are addressed in chapter V.

[12] Strictly speaking, prospective motor control is also addressed on the level of intentions and goals (third level of the action hierarchy), as intentions are believed to be reflected in prospective motor control (cf. Claxton et al., 2003).

IV Prospective motor control

> The development of action is basically a matter of acquiring prospective control (von Hofsten, 1993, p. 254).

Imagine you want to catch a ball. To be successful, you have to anticipate the future position of the moving ball while moving yourself. Considering the ball's current position and moving your hands toward this location instead will probably result in missing the ball, because the ball has already moved further. Another issue here is that feedback from your own body movements (proprioceptive and visual feedback) and feedback from the constant changes in the environment (such as visual, auditory and tactile feedback) need time to be processed. As time passes, the environment changes even more before feedback can be used to make any necessary corrections to our own movements. This sensorimotor delay is at least 100 ms in adults (Jeannerod, 1988) and with 200 – 400 ms suggested to be even longer in infants (Berthier, Robin, & Robin, 1998). To bridge this processing delay in the sensorimotor system, actions must be oriented to the future. In other words, actions must be prospective (von Hofsten, 2014).

The following sections will first describe control processes of action. Feed-forward control is a key component of action planning. Feedback is used to correct any errors made in the prior planning and to control movements as they unfold. Prospective motor control as a form of feed-forward control will then be described.

Feed-forward control, feedback processes and internal models

Motor control is the interaction between the brain and the (rest of the) body with the environment to create coordinated, goal-directed movements. Control theories discuss how the nervous system uses sensory information and information about the environment to control movements that result in meaningful actions. In other words, control theories are concerned with the tight coupling of perception and action, as discussed in chapter I (Latash, 2012).[13]

How and when is sensory information, such as visual or haptic information, used to control movements? Basically, there are two processes that must be considered and have been implicitly glanced at in the section *Vision and proprioception* (p. 25): feed-forward and feedback control processes (Latash, 2012, pp. 114–115).

In feed-forward control (also called *open-loop control*)[14], motor plans are created before movement onset (Latash, 2012). An example of a *pure* feed-forward controlled movement (or *ballistic movement*)[15] is hitting a flying ball with a racket. The movement is planned before performing it, and no corrections can be applied in the course of the movement. One important feed-forward process is prospective motor control, which will be described in *Definition and development of prospective motor control* (p. 35).

In contrast, feedback control (also called *closed-loop control*) is used to correct movements while they unfold. In this adaptation process, sensory information is used to correct movements on-line to avoid mistakes in the movement outcome (Latash, 2012). One example would be to use proprioceptive information on object weight while lifting an unknown object. If the object is lighter than expected and in the event that we merely rely on feed-forward control, the object could be damaged by an excessively high lifting movement (*overshoot*). Usually, however, adults are able to adapt their lifting movements to the actual weight of an object while lifting it, so that overshoots and possible damage to the object can be avoided (Forssberg et al., 1992).

The lifting example illustrates the fact that feedback loops seldom occur without feed-forward control loops (and vice versa). This is mostly the case because of the time delays involved in feedback control. There is a consider-

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[13] In certain points, computational theories about motor programs and internal models occasionally oppose embodied cognition accounts, such as the dynamical systems theory or the idea of direct perception. For example, both theory groups have different perspectives on the role of mental representations (Latash, 2012, p. 167; Shapiro, 2011), the functional role of reflexes, the brain as either reactive or active system (cf. Latash, 2012, p. 174), and the brain as either a kind of prediction-generating machine or a kind of embodied laboratory to perceive and act on the world. However, computational theories and embodied cognition accounts are not necessarily exclusive (for discussion see Burr & Jones, 2016). Both groups deal with the perception-action coupling and deepen the understanding of action development and are thus included in this thesis.

[14] The term *loop* emphasizes that all outputs are available as inputs in a system. Open-loop and feed-forward control as well as closed-loop and feedback control are not synonymous, but match up in the discussed context (cf. Latash, 2012, p. 115).

[15] Pure feed-forward controlled movements rarely occur. Most human movements are controlled by both feed-forward and feedback processes (Latash, 2012).

able time delay between the occurrence of an error and the correction of it, since human sensory information processing is relatively slow given the short duration of some actions. Voluntary corrections of an action can be applied around 150 ms[16] of action onset, whereas, for example, reflexes can be activated much faster: Around 30 ms after action onset (Latash, 2012, p. 220). Because of this substantial processing lag in the sensorimotor system, feed-forward control is required to allow for successful goal-directed movements.

How does the combination of both control loops work? The question of the interplay between feed-forward and feedback processes is of high interest for motor control theories (Latash, 2012) and approaches of *internal models* aim to explain how movements are controlled by the brain (Kawato, 1999; Wolpert & Flanagan, 2001, 2016; Wolpert, Ghahramani, & Jordan, 1995).

Internal models are computational processes that predict effects of body-environment interactions (Latash, 2012). An underlying assumption of internal model approaches is that the brain uses knowledge of the mechanical properties of limbs and the environment to control movements. This knowledge subsequently forms internal models that pre-compute (*predict*) forces grounded in sensorimotor information.

Wolpert and Flanagan (2001) call this process *motor prediction*[17] and describe skilled actions, such as lifting a teapot, as relying on accurate predictive models of both the body and the environment. Thus, different contexts, such as full or empty teapots, can be taken into account and the likelihood of each context can be estimated *(Figure 1)*. When performing an action, first a motor plan is generated and sensory consequences of a planned action are simulated (*feed-forward control*). Different sensorimotor feedback is predicted based on different contexts (*context estimation*). In the course of the movement, these predictions are compared to the actual sensorimotor feedback (*feedback*). If the actual feedback matches the predictions of a certain context, we assign a high likelihood to this context and a lower likelihood to other contexts. If there is a mismatch (*prediction error*), we consequently give less weight to a certain context and more weight to alternative contexts.

According to Wolpert and Flanagan (2001), existing models are updated and new models are acquired through experience. These model-training processes are made possible by using occurring errors – in other words, by the comparison of the predicted and the actual outcome of a motor command.

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[16] In some cases, visual feedback toward moving objects can be used after 100 ms (Jeannerod, 1988, p. 101).

[17] In the context of internal models of motor control, sometimes the term *sensorimotor prediction* is used (Buckingham, Michelakakis, et al., 2016; Flanagan et al., 2001) and sometimes *motor prediction* (Haggard & Clark, 2003; Wolpert & Flanagan, 2001). However, except in this section, I talk about feed-forward processes using the slightly different terminology of *prospective motor control* (see footnotes 13 and 18).

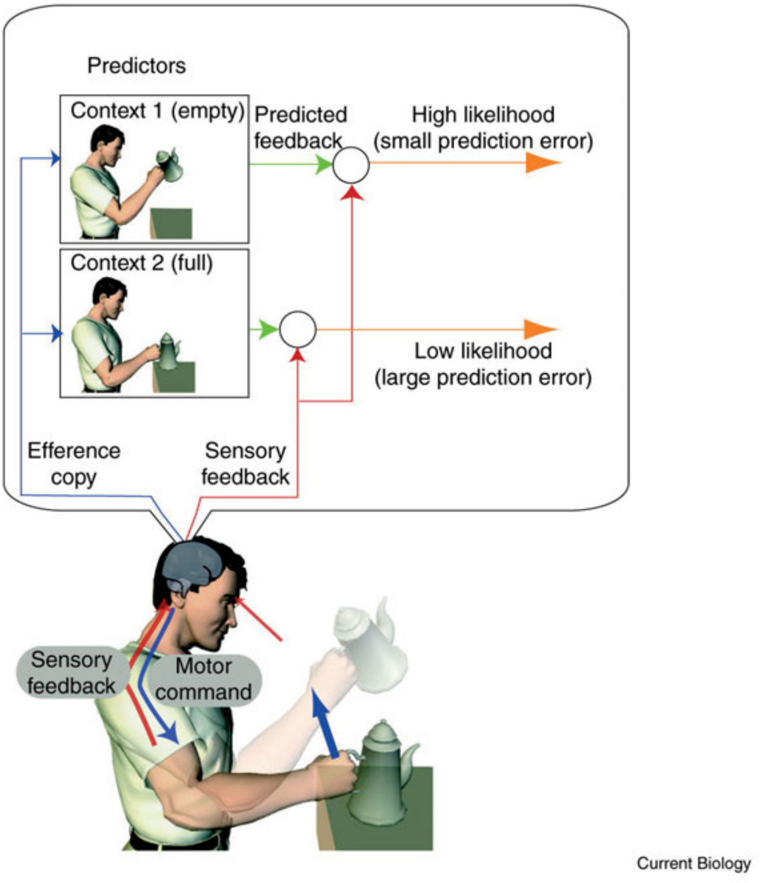

Figure 1. A schematic of context estimation, feed-forward and feedback processes when lifting a teapot. Two contexts are considered, that are either an empty teapot or a full teapot. First a motor command is generated and sensory consequences of the planned lifting action are simulated for the two possible contexts. The predictions based on the empty teapot propose that lift-off will be earlier and higher as compared to the full teapot context. In course of the movement, these predictions are compared to the actual sensorimotor feedback. The teapot is de facto empty and the feedback matches the predictions of the empty teapot context. This results in a high likelihood for the empty teapot and in a low likelihood for the full teapot. [From Wolpert, D. M., & Flanagan, J. R. (2001). Motor prediction. *Current Biology : CB*, *11*(18), R729–R732. Reprinted with permission from Elsevier.]

Definition and development of prospective motor control

The next two sections will describe prospective motor control as a feed-forward control process and one way to measure it.

As mentioned above, the term *motor control* generally describes the interaction between the brain and the rest of the body with the environment to create coordinated, goal-directed movements (Latash, 2012). *Prospective* motor control[18] is the ability to adapt one's actions according to action goals and future tasks in an *anticipatory* manner (von Hofsten, 1993). Thus, information about the environment and the specific task is functionally coupled with the currently unfolding movement (Ledouit, Casanova, Zaal, & Bootsma, 2013). In other words, prospective motor control is a basic component of action facilitating successful interactions with an ever-changing environment.

Prospective motor control is crucial for the developing infant (von Hofsten, 1993) and motor control is partly prospective from early on (see chapter II). An infant's reaching is prospective from the age of five months (von Hofsten & Rönnqvist, 1988). By the age of eight months, infants are able to catch objects moving with a velocity of 120 cm/s (von Hofsten, 1983).

Prospective motor control in reaching is well studied (Cunha et al., 2015; Grönqvist, Strand Brodd, & von Hofsten, 2011; von Hofsten & Rönnqvist, 1993; von Hofsten, 1979, 1991, 1993) and large parts of this thesis deal with this aspect of motor development. How does prospective motor control influence reaching and how can a well-controlled reach be described? Thelen and colleagues (1996) frame it as follows: "Good control means (…) learning to maintain a smooth, straight reach under various speed and load conditions and from many locations in the reaching space" (Thelen et al., 1996, p. 1074). As outlined above in chapter II, reaching movements develop from first being less continuous, less organized and less straight to increasingly straight and more controlled and direct (von Hofsten, 1993). While adult reaching movements are usually smooth and straight and consequently contain fewer sub-movements (Jeannerod, 1988; Marteniuk, MacKenzie,

[18] A distinction is sometimes drawn between *prospective* control and *predictive* control. According to Ledouit and colleagues (2013), predictive control is based on explicit knowledge of physical rules and expressed by accurate, calculated estimates of events, while prospective control relies on a functional coupling between movement and information. The latter is conceptualized as a more robust process (Ledouit et al., 2013). Von Hofsten and others, however, do not distinguish between these terms and use them interchangeably (von Hofsten, personal communication). Consequently, in this thesis, the term *prospective (motor) control* will be used according to both Ledouit's et al. (2013) and von Hofsten's (1993) definition. For further discussion see Fink, Foo and Warren (2009), and two posts on the blog "Notes from Two Scientific Psychologists" by Wilson and Golonka (http://psychsciencenotes.blogspot.se/2011/10/prospective-control-i-outfielder.html; http://psychsciencenotes.blogspot.se/2016/04/brains-learn-to-perceive-not-predict.html; retrieved 21.04.2016).

Jeannerod, Athenes, & Dugas, 1987), infant reaching movements are typically less smooth and straight and consequently contain more sub-movements (von Hofsten, 1993). These sub-movements are called *movement units* (von Hofsten, 1979, 1991) and will be discussed in the following paragraph.

Movement units as a measurement of prospective motor control

Movement units structure human movements in a meaningful way. A movement unit is a small sub-movement and is defined based on the movement's velocity profile (von Hofsten, 1979, 1991). Velocity is crucial for human goal-directed movements (Plamondon & Alimi, 1997) and typically has a bell-shaped pattern (Jeannerod, 1988). This pattern is produced by several increases and decreases in velocity. To put it differently, human movements have phases of acceleration and deceleration: They speed up and slow down. Together, these two phases form a movement unit, whereas each movement unit contains one acceleration and one deceleration phase and lasts a few hundred milliseconds (von Hofsten, 1979, 1991).

Movement units are considered to be meaningful entities and each one is planned in advance, that is prospectively controlled (von Hofsten, 1979). Furthermore, the movement trajectory within one movement unit is relatively straight and can be adjusted in the following movement unit (von Hofsten & Rönnqvist, 1993). The first movement unit is especially important for prospective motor control as it reveals the initial motor plan before the initiation of the action and before a feedback-based correction can be applied (Jeannerod, 1988). Additionally, the first movement unit in reaching becomes more important in the course of development. At reach onset around four months, all movement units of one reach usually have the same duration, but as the infant gains more reaching experience (around seven months), the duration of the first movement unit increases relative to the other units. The largest movement unit is, accordingly, often named the transport unit and in most reaches after seven months of age, the transport unit is the first movement unit (von Hofsten, 1993).

Prospective motor control can in turn be measured by making use of the previously mentioned fact that movement units are planned consecutively. If the first movement unit reveals the initial motor plan (Jeannerod, 1988; von Hofsten, 1993), different characteristics of the movement in this period could index prospective motor control. If, for example, lifting height in a weightlifting task is of interest, amplitude at the end of the first movement unit would be a measure for prospective motor control (see Study I). If movement speed in a reach-to-place is of question, peak (or average) velocity of the first movement unit could indicate prospective motor control (see Studies II and III).

V Executive functions

> An essential component in EF [executive functions] is that of time. It plays an important role in the contemplation of the future and especially in the appraisal or valuation assigned to means […] and ends […] and more generally to the total time between the decision to act and the attainment of the goal toward which it aims (Barkley, 2012, p. 94).

Executive functions are “self-directed actions needed to choose goals and to create, enact, and sustain actions towards those goals.” They can be defined as cognitive functions of “self-regulation to achieve goals” (Barkley, 2012, p. 60).

Executive functions comprise the three components inhibition, working memory, and cognitive flexibility (Diamond, 2013). Inhibition is defined as the “ability to ignore distraction and stay focused, and to resist making one response and instead make another”; working memory is the “ability to hold information in mind and manipulate it”; and cognitive flexibility is the “ability to flexibly switch perspectives [and the] focus of attention” (Diamond, 2006, p. 70). These components are distinct functions in adulthood and in childhood (Friedman, Miyake, Robinson, & Hewitt, 2011; Miyake et al., 2000), with inhibition being a core aspect (Barkley, 1997a; Miyake & Friedman, 2012).

Executive functions as functions of cognitive control underlie the self-regulation of behavior (Barkley, 1997a) and are therefore crucial in many areas of adaptive functioning. Good executive functioning has been found to contribute to academic achievement in preschoolers (Cameron et al., 2012), school-aged children and adolescents (Best, Miller, & Naglieri, 2011; Bull & Scerif, 2001). Impaired executive functioning in turn has been found to be related to neurodevelopmental disorders such as attention deficit hyperactivity disorder (ADHD; Barkley, 1997b) and autism spectrum disorders (ASD; Hill, 2004).

The importance of executive functions to adaptive functioning and the positive effects of intervention programs (Diamond, 2013), necessitate the need to find early markers of possibly impaired executive functioning. However, the early development of executive functions is still not sufficiently understood (cf. Johansson, Marciszko, Brocki, & Bohlin, 2015).

The following sections will first describe findings about the development of executive functions on a behavioral level. Second, they will introduce the relationship between executive functions and motor development.

Early development

While executive functions in the preschool years and middle childhood are well studied (Best et al., 2011; Carlson, 2005; Diamond, 2013; Garon, Bryson, & Smith, 2008), there are fewer studies on the early development of executive functions in infancy and toddlerhood.

When exactly do executive functions emerge in development and when can they be reliably measured? The youngest age groups in studies of executive functions vary from around 18 months (Bernier, Carlson, Deschênes, & Matte-Gagné, 2012; Bernier, Carlson, & Whipple, 2010; Hughes & Ensor, 2007), 15 months (Wiebe, Lukowski, & Bauer, 2010), 14 months (Miller & Marcovitch, 2015), and 12 months of age (Johansson et al., 2015).

Taking into account some of the studies mentioned and the repeated observation that early executive function performance in infancy is related to later executive function performance, Garon, Smith, & Bryson (2008, 2014) distinguished between simple and complex forms of executive functions and suggested that simple forms lead the way to complex forms via enhanced coordination of the simpler forms. Direct support for this hierarchical model by Garon and colleagues (2008, 2014) was provided by two longitudinal studies.

First, Friedman et al. (2011) studied inhibition, working memory, and cognitive flexibility (here called *shifting*) longitudinally in 14, 20, 24, and 36-month-olds as well as in 17-year-olds. They demonstrated that simple inhibition (as measured by a prohibition task; see *Inhibition*, p. 39) was stable from 14 to 36 months of age (r = .30). Additionally, simple inhibition at 14 to 36 months of age predicted complex inhibition and complex working memory at 17 years of age.

Second, Johansson et al. (2015) tested infants in different inhibition and working memory tasks longitudinally at 12, 24 and 36 months of age. They found that simple inhibition (as measured by a prohibition task) at 12 months predicted complex forms of working memory at 36 months.

The following section describes simple and complex forms of inhibition and working memory, as well as ways to measure them. Cognitive flexibility, the third component of executive functions, is not considered, as it is not relevant in the context of this thesis.

Inhibition

Inhibition is often divided in two subcomponents, whereas classifications differ between authors (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Diamond, 2013; Gandolfi, Viterbori, Traverso, & Usai, 2014; Garon et al., 2008). A common distinction is drawn between a more simple form of inhibition, where a behavioral response has to be inhibited, and a more complex form of inhibition, where there is a conflict between two ore more behavioral responses. This conflict has to be reduced by favoring one (subdominant) response over another (dominant) response in order to reach a certain goal (cf. Diamond, 1990; Garon et al., 2008).

Diamond (2013) for example differentiates between the two components of *behavioral control* and *interference control*. Behavioral control requires restraining from impulsive behavior, such as reaching for an attractive toy. Interference control requires ignoring some stimuli in favor to another, such as ignoring one toy and instead attending to another or to favor one action over another.

Gandolfi, Viterbori, Traverso and Usai (2014) similarly distinguish between two dimensions of inhibition: *response inhibition* with relatively low additional working memory demand and *interference suppression* with higher additional working memory demand.

Garon et al. (2008) also draw the distinction according to differences in additional working memory requirements. Simple forms of inhibition include withholding or delaying a predominant response. Complex forms of inhibition require not only inhibiting an automatic response, but also holding a certain rule in mind.

According to Garon et al. (2008), simple inhibition can be measured either in a prohibition task from the age of 8 months, where the infant is not allowed to touch an attractive toy, for instance, or from the age of two years, in the form of delayed gratification, where the child must wait for a reward. One form of this task is known beyond the world of psychological science as the *marshmallow task*, but there are several other forms. One often-used form is a prohibition task (Friedman et al., 2011): An attractive toy is placed in front of the infant and the infant is told not to touch it. The waiting time before touching the toy indicates the ability to inhibit an action.

Complex inhibition can be measured from 18 months onwards, whereas most of the possible tasks are recommended for use only from the age of 24 months and onwards, or even only starting from 36 months (Garon et al., 2008, 2014). An example is Garon's and colleagues (2014) task of object retrieval from a tricky box, where the child opens a box to retrieve an attractive toy. The toy is behind a window and clearly visible to the child. In order to get the toy, the child has to pull a knob to open the box first. So instead of directly reaching toward the toy, the child has to remember this opening mechanism of the box, perform it and then reach for the toy.

Garon et al. (2014) further distinguish between a simple conflict and a complex conflict. Consequently, these researchers have two different ways of measuring inhibition with their tricky box. In the simple version, the child has to open the window by pulling a knob directly above this window. In the complex version, the child has to pull a knob that is above another window. Garon et al. (2014) themselves classify the described simple version of the tricky box task as measure of simple inhibition and the complex version as a measure of complex inhibition.

In contrast to a prohibition task however, where the only requirement is to withhold a response (and not to perform a sequence of actions), the simple tricky box task is complex. Therefore I name this form of inhibition complex inhibition in the context of this thesis.

Working memory

There are different kinds of working memory. Baddeley (1995) distinguishes between auditory working memory and visual-spatial working memory. For the purpose of this thesis, only visual-spatial memory is of relevance and will be addressed.

Simple working memory means to hold information in mind over a certain period and can be measured from the age of 5 months onwards. The task could be a hide-and-seek game: A toy is hidden at one of two or more locations and the child searches for it after a certain delay (Garon et al., 2008).

Besides holding information in mind, complex working memory tasks also require updating or manipulating this information. Consequently, these tasks usually include more than one object and/or a change of scene by, for example, spinning the locations. Children must be at least 15 months to participate in these kinds of tasks (Garon et al., 2008).

Executive functions and motor development

One promising route to understanding the development of executive functions is to investigate executive functions in the context of motor development. As described in chapter II, motor and cognitive development are generally thought to be intertwined (Diamond, 2000). From an embodied perspective, there should be a link between motor control and cognitive control (Thelen et al., 2001; Wilson, 2001), as cognition is suggested to emerge from action (Gentsch et al., 2016; see chapter I). The action hierarchy (as described in chapter III) further justifies the link between motor control and executive functions.

In this regard, two studies should be mentioned. First, Berger (2010) demonstrated interdependencies between motor abilities such as crawling and walking and cognitive capacities in infancy and provided a reasoning for a common attentional resource in action and cognition. Second, Diamond (2000) discussed the role of reduced activity in the cerebellum and prefrontal cortex. Both brain areas are relevant for executive functions and motor control, and are interconnected, which means the dysfunction of one system can affect the other and vice versa.

This possibility of a relationship between executive functions and motor control is supported by clinical findings: First, in disorders that include impairments of executive functions, such as ADHD, ASD and conduct disorder, motor impairments are also often found (Barkley, 1997b; Gustafsson et al., 2014). Second, Mariani and Barkley (1997) demonstrated that both motor control (as measured by manual speed and dexterity) and executive functions (here: working memory) are impaired in preschool children with ADHD compared to typically developing children.

Further support for this idea is given by a study with 10-month-old infants at risk of ASD: Siblings of children with ASD demonstrate reduced prospective motor control as compared to siblings of typically developing children (Ekberg, Falck-Ytter, Bölte, Gredebäck, & EASE Team, 2016).

Additionally, one longitudinal study showed relationships between motor abilities and executive functions explicitly: Ridler et al. (2006) found infant gross motor skills to predict executive functions in adulthood. Infant gross motor skills were described by the age at onset of standing without support, and walking with and without support. Executive functions were measured at 33 to 35 years of age with a task requiring working memory and categorization. Structural MRI data was measured the same day. Earlier onset of standing and walking was correlated with better executive function performance in adulthood. Both were accompanied by increased gray matter density (frontal and parietal lobes in infancy; premotor cortex striatum and cerebellum in adulthood). The authors argue that motor abilities predict later executive function abilities.

Together, the studies mentioned either directly or indirectly suggest a link between executive functions and motor control. One of the aims of this thesis is to study this link. All of the aims will be outlined on the next page.

Aims of the thesis

The ability to plan our actions is the inevitable foundation of reaching our goals. Action planning can be stratified on different levels of control that are part of a hierarchical organization of action. There is the relatively basic or low level of prospective motor control, and the comparatively high level of cognitive or executive control. Prospective motor control is concerned with goal-directed actions on the level of single movements and movement combinations in our bodies and ensures purposeful, coordinated movements, such as reaching for a cup of coffee. Cognitive control – in the context of this thesis, more precisely referred to as executive function – deals with goal-directed actions on the level of entire actions and action combinations and facilitates mid and long-term goals, such as maintaining a diet or finishing a doctoral thesis. While prospective motor control and executive functions are well studied in adulthood, early development of both is not sufficiently understood. Furthermore, these two control aspects of action planning have commonly been investigated separately.

The overarching aim of this thesis is to assess the link between action and cognition early in development. Thus the notion of embodied cognition shall be investigated by linking two levels of action control in the context of reaching: Prospective motor control and executive functions. Several studies are needed to shed light on action control and action planning early in development. The three studies conducted follow the time line of action planning and connect the now with the future.

How do infants use different sources of information to prospectively control their actions? Study I investigated the prospective motor control of current actions by having 14-month-olds lift objects of varying weights. In doing so, multi-cue integration was addressed by comparing the use of visual and non-visual information to non-visual information only.

Do infants take the difficulty of future actions into account to prospectively control their actions in sequences? Study II examined the prospective motor control of future actions in action sequences by investigating reach-to-place actions in 14-month-olds. Thus the extent to which Fitts' law can explain movement duration in infancy was addressed.

Is motor action control related to cognitive action control? Study III lifted prospective motor control to a higher that is cognitive level, by investigating it relative to executive functions in 18-months-olds. Thus an embodied account of executive functions will be proposed.

Methods

Participants

Participants were recruited from the Uppsala Child and Baby Lab's database of parents who expressed interest in participating in research studies with their child. For participation parents received a gift voucher of 100 Swedish Crowns (≈ 10 Euro). All procedures were in accordance with the ethical standards of the regional ethics committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from the parents of all individual participants.

In Study I – Prospective motor control of current actions (p. 58), the final sample included 30 14-month-old infants (age *M* = 431 days, *SD* = 5 days, 12 female). The infants participated either in the *same color condition* (age *M* = 432 days, *SD* = 5 days, *n* = 15) or in the *different color condition* (age *M* = 429 days, *SD* = 5 days, *n* = 15). In addition, 19 infants were tested but excluded due to poor-quality motion-tracking data (*n* = 11), due to incomplete task performance (*n* = 7, see *Data analysis Study I,* p. 51 for details) or because of technical issues (*n* = 1).

In Study II – Prospective motor control of future actions (p. 65), the final sample consisted of 37 14-month-old infants (age *M* = 427 days old, *SD* = 9 days, 16 female). They participated either in the *short distance condition* (age *M* = 413 days old, *SD* = 12 days, *n* = 20) or the *long distance condition* (age *M* = 416 days old, *SD* = 4 days, *n* = 17). Additional 19 infants were tested but excluded because of no participation in the task (*n* = 5) or incomplete task performance (*n* = 14). For the movement velocity analysis, 95% (*n* = 35) of the sample was included (age *M* = 415 days, *SD* = 9 days, *n* = 35; see *Data analysis Study II*, p. 53 for details).

In Study III – Prospective motor control and executive functions (p. 71), 53 18-months-olds were included in the final sample (age *M* = 542 days, *SD* = 9 days, 22 female). An additional 17 infants were tested but excluded from analysis due to incomplete task performance (*n* = 11), technical error (*n* = 4) or low-quality motion-tracking data (*n* = 2). To be included in the sample, infants had to complete all experimental tasks. Task completion ranged from 96% to 84% of all participants (see *Data analysis Study III*, p. 55 for details).

A note on dropout rates

All three studies have relatively high dropout rates ranging from 24% in Study III to 39% in Study I. Generally, high dropout rates are common in infancy research and – dependent on the utilized method and experimental paradigm – it can be as high as 50% of the sample. As compared to adults, infants have a shorter attention span and they tolerate experimental procedures less. Whereas adults can attend exhausting experimental procedures for some hours and usually follow the experimenter's instructions, infants might be tired or fussy after 10 minutes and they do not follow verbal instructions. Therefor we need to design our experimental tasks as enjoyable and short as possible to make them suitable for infants.

In the case of these three studies, the highest amount of dropout (14% to 25%) is due to trial inclusion criteria. We opted for a high number of included trials per participant as inclusion criterion to gain high-quality data, therefor participants with fewer valid trials had to be excluded from the analyses. The reasons for an insufficient number of valid trials are manifold.

First of all, the three studies involved active participation in object manipulation. In the prospective motor tasks, infants were asked to lift objects or to place them into cylinders, but there are of course many other actions possible. Toys can be thrown away, shown to the caregiver, put into the mouth or banged on the table for example, instead of utilized in the way the experimenter wishes for.

Second, all three studies aimed for the specific measure of prospective motor control of the first movement unit, which is a relatively short period around 500 milliseconds. It needs to be precisely defined in order to get meaningful data. Consequently, the infants had to fulfill certain criteria for valid trials. In most of the tasks, infants had to start their reaches from a defined area for example. Therefor we let the caregivers assist by gently holding the younger infant's hand in the area, which sometimes lead to protests on the side of the infants and sometimes to invalid data because of parental interference. (The slightly older infants were able to place their hand on the starting area themselves, but they did not always do this.)

Third, even though performance might have been fine with regard to task criteria, motion data can be insufficient. When investigating the 500 ms of an action, data loss in this exact period leads to exclusion of the whole trial.

These were some possible reasons for trial exclusion (leading sometimes to exclusion of full data sets of participant from analyses), but there are more reasons for dropout such as general fussiness, tiredness, shyness, interfering caregivers, technical issues, experimenter error, just to mention a few.

Procedure

All performed studies involved manual motor behavior and movements were recorded using an eight-camera passive motion-tracking device at a sampling rate of 240 Hz (Qualisys, Gothenburg, Sweden). In Study I, lifting amplitude was measured by tracking the vertical position of the involved objects. In Study II and III, reaching velocity in a reach-to-place action sequence was measured by tracking the hands of the participants. Study III additionally involved behavioral measures of executive functions that were analyzed using video coding. In all studies, the infants sat on their caregiver's lap at a table facing the experimenter. Breaks were possible, whenever the infant needed it.

Procedure Study I

In Study I, prospective motor control in a lifting task with differently weighted cylindrical objects (10.1 cm in height, 3.5 cm in diameter) was investigated (*Figure 2*). Thereby we were interested in the influence of visual and non-visual information (*different color condition*) and of non-visual information only (*same color condition*). Prospective motor control was assessed by measuring the lifting amplitude at the end of the first movement unit of the lifting action.

Infants were randomly assigned to one of the experimental conditions: In the *different color condition*, a blue and a yellow object differing in weight (color–weight combination was counterbalanced) were used. In the *same color condition*, either two blue or two yellow objects differing in weight were used (colors were counterbalanced). In both conditions, one object was light (54 g) and the other object was heavy (271 g), while they differed in their appearance or looked alike. They produced the same rattling sound by shaking and had one reflective marker each for motion tracking attached to it.

After a give-and-take game to ensure, that the infant is firstly able to perform reaching and grasping and secondly is in the adequate mood for the experiment, the infant was placed on the caregiver's (mostly the father of the infant)[19] lap. They were seated at a table facing the experimenter. The task was initially performed two times by the caregiver to show the action to the infant: The experimenter placed the heavy object (out of the certain set) in front of the right hand of the caregiver, who lifted it up and shook it expressing joy. Thereafter he gave it back to the experimenter. Subsequently the testing phase started. The experimenter presented the object to the infant and

[19] For the sake of effortless reading, only one personal pronoun out of the two offered options in the English language is used. As the caregiver was mostly the father of the infant, ”he” is used. This is true for the 14- and the 18-month-old infants. The experimenter was female in all cases and therefor “she” is used. For infants sometimes “she” and sometimes “he” is used.

placed it (approximately 5 cm) in front of the infant's dominant hand (by parent's report) by verbally encouraging the infant to lift and shake the object. After the infant finished the action or after 10 s had passed, the experimenter held her open hand toward the infant and asked for the object. If the infant was not returning the object, the experimenter delicately took it. This was done for 24 trials subdivided into three blocks (each containing eight trials). Every block contained 4 (±1) trials with the heavy object in the beginning and further 4 (±1) trials with the light object.

Figure 2. Picture of the four objects differing in color and weight (left picture) and two snapshots of a 14-month-old lifting one of the objects (middle and right picture)

Procedure Study II

In Study II, prospective motor control was assessed in a multiple step reach-to-place action with different difficulty levels. We were investigating, if infants not only prospectively control their current action (reaching), but also their subsequent action (placing) in the beginning of an action sequence. Difficulty of the second action (placing) was manipulated by goal size and goal distance to investigate its influence already on the beginning of the first action (reaching). Therefore, prospective motor control was measured via peak velocity of the first movement unit of the reaching action.

The task was to reach from a defined starting area (a colored circle, 5 cm in diameter) for an object (4.5 cm in diameter) and subsequently place it into one cylinder (*Figure 3*). This cylinder could be either big (12.3 cm in diameter, 16 cm in height) or small (5.3 cm in diameter, 16 cm in height) and it was placed in an either short distance (17 cm) or long distance (34 cm) from the pick-up area. The infants were randomly assigned to one of the following two groups: In the *short distance condition*, the particular cylinder (big or small) was only placed close to the object, whereas in the *long distance condition* the same cylinders were only placed far from the object. Position and size of the cylinders were counterbalanced. All positions of the cylinders and the object were in a semicircle around the infant representing the reaching space. The distance between the starting area and the pick-up area of the object remained constant (20.5 cm).

After a give-and-take game ensuring the ability of the infant to perform these actions and for warm-up purposes, the caregiver and the infant were seated at a table facing the experimenter. On the infant's side, this table had a semi-circle-shaped edge facilitating reaching and placing actions. The task was initially performed twice by the caregiver to demonstrate the action to the infant. The caregiver was asked to express joy while performing the task. Subsequently the experiment started. The experimenter presented the object and one cylinder to the infant and placed them on the specific locations on the table. The caregiver was instructed to hold the right arm of the child from behind to so that the right hand was on the starting area. When the experimenter indicated a new trial by saying "again", the caregiver released the arm. The infant was verbally encouraged to perform the task and praised afterwards. In the first block, 24 trials in a counterbalanced ABBA order were performed. A second block of 24 trials was performed, if the infant was still interested.

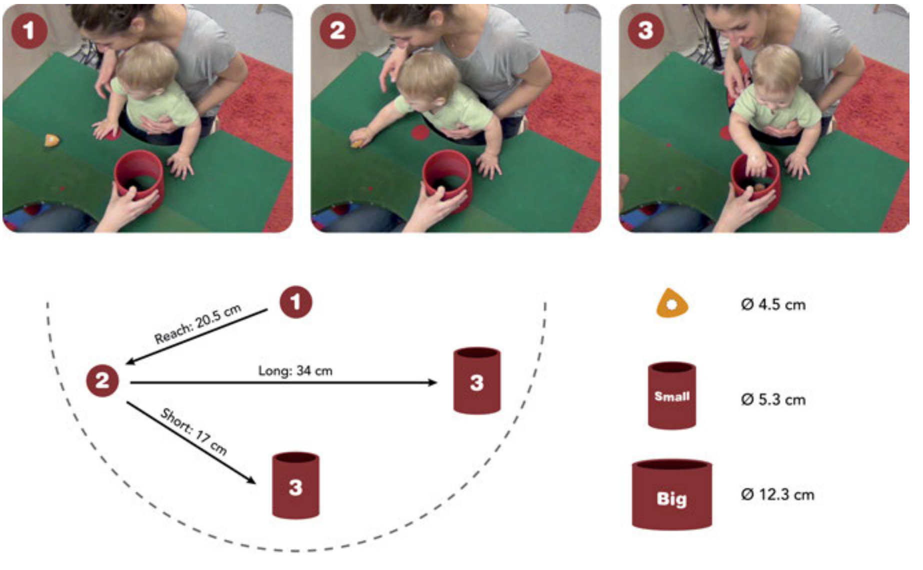

Figure 3. The experimental task consists of placing the hand in a marked area (1), reaching for the object (2) and placing it in a cylinder (3). All participants placed an object (4.5 cm in diameter) in a small (5.3 cm in diameter) and a big cylinder (12.3 cm in diameter; within-subject variable goal size), whereas the cylinders were positioned either in a short (17 cm) or long distance (34 cm) from the pick-up area (between-subject variable goal distance). The positions of the object (2) and the cylinders (3) were on a half-circle around the infant defined by the reaching space of the right hand (1).

Procedure Study III

In Study III, prospective motor control was measured in a similar manner as described in Study II. Additionally, executive functions (prohibition, working memory and complex inhibition) were assessed by three behavioral tasks. The material of all tasks can be seen in *Figure 4*. Additionally, gross and fine motor developmental state were acquired by the second edition of the Vineland Adaptive Behavior Scales, a questionnaire that one of the caregivers filled out at home before coming to the lab (Vineland-II, Sparrow, Cicchetti, & Balla, 2012).

Prospective motor control task

The procedure was similar to the one described in *Procedure Study II* (p. 46) with the following age-group relevant adaptations: Three boxes (16 cm in height) were used as goals: a large box (9 cm in diameter), a medium box (6 cm in diameter) and a small box (3.5 cm in diameter). The boxes were placed in the following two distances from the object: The long distance was 37 cm and the short distance was 12 cm. The object was 2 cm in diameter. Every child performed all possible size-distance combinations, as we were interested in individual differences. Eighteen trials were performed in counterbalanced order in blocks of three identical trials and the task was continued until the child lost interest. The caregiver was not instructed to hold the arm of the infant, as the 18-month-olds were capable to place their hand themselves with being verbally reminded by the experimenter.

Prohibition task

This task described by Friedman et al. (2011) was used to measure simple inhibition in seconds, that is the ability to inhibit reaching for an attractive toy for 30 s. This toy was a colorful, glittering wand (31 cm in length, 2 cm in diameter).

The experimenter established eye contact with the child, presented the toy and placed it on the table within the infant's reach (approximately 20 cm from the infant). In doing so, she shook her head and said "now, [child's name], are you not allowed to touch this". Then she looked away with a neutral facial expression. The experimenter verbally encouraged the child to play with the toy, after 30 s had passed, or earlier in case the child had already touched it.

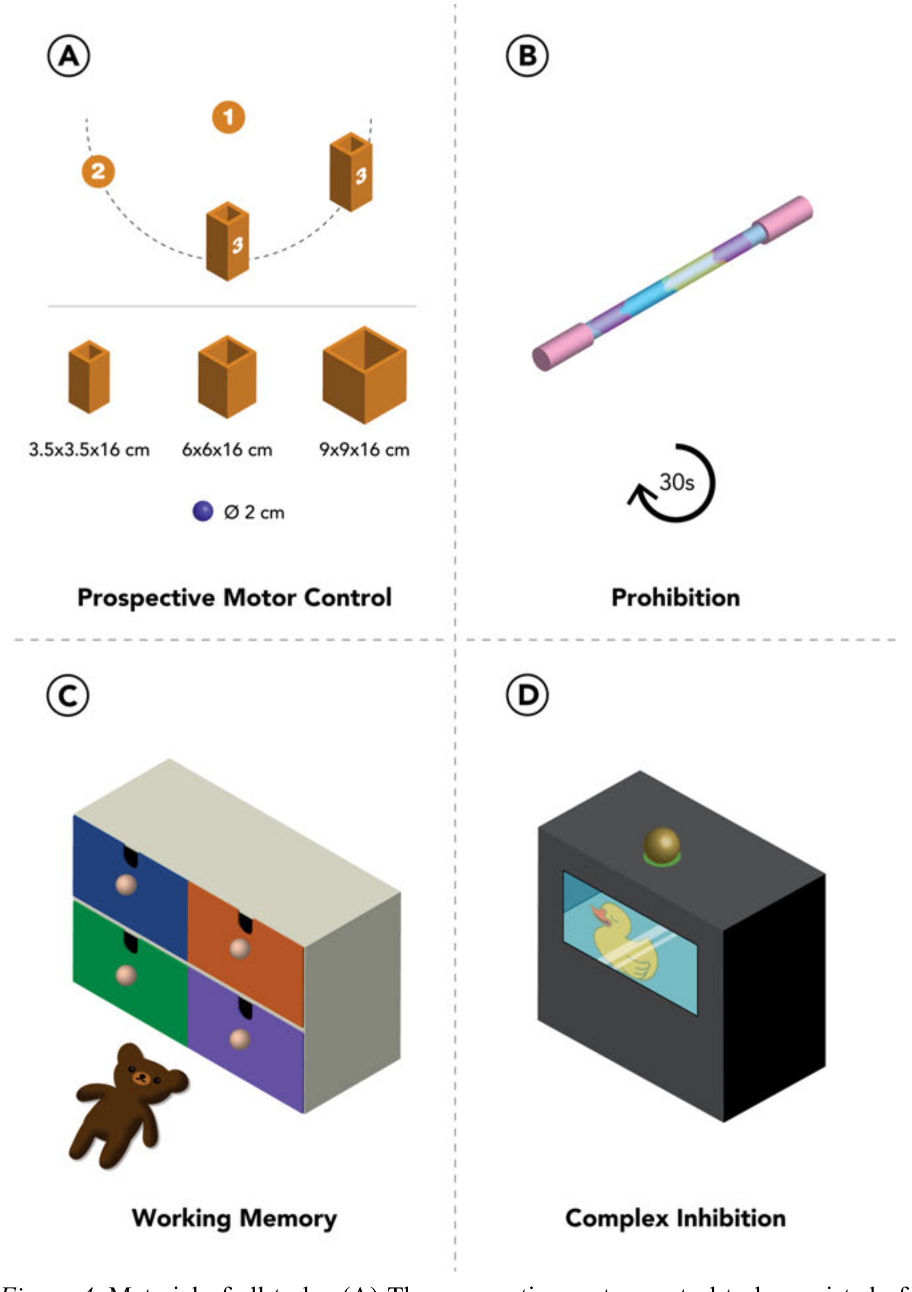

Figure 4. Material of all tasks. (A) The prospective motor control task consisted of placing the hand in a marked area (1), reaching for the object (2) and placing it in a box (3). All participants placed an object in a small, a medium, and a big box. The boxes were positioned either in a short or long distance from the pick-up area. (B) The prohibition task was to inhibit reaching for a glittering wand for 30 seconds. (C) In the working memory task, a toy was hidden and searched for in 4 different locations with a time delay of 5 seconds. (D) The complex inhibition task required opening the window of the box via the knob in order to retrieve the duck.

Working memory task

This classical hide-and-seek task with a time delay of 5 s was used to measure visual-spatial working memory (see e.g., Garon et al., 2008). A chest of four drawers was used (21 cm in height, 28.5 cm in length, 18.5 cm in width). The drawers were colored in different colors. A cloth was attached to the chest to cover it in the delay between hiding and searching.

In the warm-up phase, the infant picked one of three toys for the hide-and-seek task. Two warm-up trials were performed during which the toy was hidden in two different drawers. These trials included neither covering nor a time delay before searching.

In the test phase, four trials were performed, where the toy was hidden in all four locations in the same order for all participants. The experimenter presented the toy and held it in front of one drawer by saying "Now I am hiding it here!" She then covered the chest and looked away with a neutral facial expression for 5 s. The caregiver was instructed to hold the arms of the infant in order to prevent pointing to the drawers during the delay. After the delay the experimenter uncovered the chest and pushed it toward the infant by saying "Now you can search!" The child could search for the toy maximally four times, before the experimenter started a new trial.

Complex inhibition task

This task measuring complex inhibition was a modified version of Garon's tricky box task (Garon et al., 2014; see p. 40 for distinctions between simple and complex inhibition). A custom-built wooden box was used (22 cm in height, 22 cm in length, 12.5 cm in width). This box had one wooden knob (4.5 cm in diameter) on top above one plexi-glass window (15 cm in length, 8.5 cm in height). A color-changing plastic duck could be placed on a shelf behind the window. On the backside of the box an electric switch was attached which enabled the experimenter to control the opening mechanism of the box without the infant noticing it.

The task was to inhibit one action in favor of another action. In this case, the child had to inhibit direct reaching towards the attractive toy behind the window. Instead the infant had to pull the knob first and reach to the duck afterwards in order to successfully retrieve the toy.

In the warm-up phase, the experimenter presented the black box and the way to open its window by pulling the knob – whereas she actually opened the box by operating the switch at the backside of the box out of sight of the infant. She then pushed the box towards the infant verbally encouraging it to open the box. The experimenter reminded the infant of the opening mechanism by saying "you have to pull here" and pointing to the knob, in case the infant reached to the window. When the infant reached for the knob, the experimenter pressed the switch to open the box. This was repeated until the infant opened the box two times to ensure that the infant understands the opening mechanism. Then the experimenter presented the duck and gave it to the infant for 10 to 15 seconds.

In the test phase, four trials were performed, where first the duck was placed on the shelf inside the box, and second the infant was asked to retrieve the duck. The caregiver was instructed to hold the arms of the infant until the box was pushed toward them. If the infant only reached for the window, the experimenter waited for 10 seconds and then pointed to the knob by saying "You have to pull here!" If the infant did not pull the knob, the experimenter opened the window by pulling the knob, and took out the duck and gave it to the infant. After getting the duck the infant could play with it for 5 to 10 seconds.

Data analysis

Data analysis Study I

Videos were coded for different categories of actions, such as lifting, throwing, rolling, shifting, pushing and shaking. Only lifting movements of the infant's dominant hand followed by a shaking movement were counted as valid trials. Onset of the lifting movement was pre-defined as the first contact between hand and object (and later, in the following kinematic analysis defined based on the velocity profile). Thereby were we not interested in the shaking movement itself, but interested in ruling out possible differential effects of handedness or action planning. The rationale for the latter is the following: In multiple-step actions, such as reaching for something to either place or throw it or as lifting something to either lift or shake it, the intention for the next action already influences the movement characteristics, such as velocity, of the current actions. Reaches for a ball are faster, if the ball is subsequently thrown as compared to placed somewhere. This was shown for 10-month-old infants, interpreted as indicator for action planning (Claxton et al., 2003) and will be further discussed in Study II (p. 65). Infants, who accomplished minimum half of the procedure, that is 12 out of 24 trials, and who contributed useable kinematic data of two consecutive lifts with both different weighted objects, were included in the statistical analyses. On average, infants accounted for 7 out of 12 trials per object, resulting in 14 out of 24 trials in total.

Motion-capture data were used to extract the lifting amplitude at the end of the first movement unit. A movement unit is defined based on the (for humans typically) bell-shaped velocity profile of the movement. It contains one acceleration and one deceleration phase and always ends with a minimum in the velocity curve (von Hofsten, 1991; see *Movement units as a measurement of prospective motor control, p. 36)*. The position data were polynomially interpolated with the criterion of a maximal gap of 30 frames using Qualisys Track Manager before exporting the vertical position data to MATLAB. A custom script was used to calculate and to subsequently smooth velocity data (by 10 samples resp. 41.67 ms). Position and velocity data were plotted in order to extract lifting amplitude data of every single valid trial (i.e., vertical position at the end of the first movement unit) manually to SPSS. Lifting amplitudes at the end of the first movement unit were manually detected based on the velocity profiles (*Figure 5*).

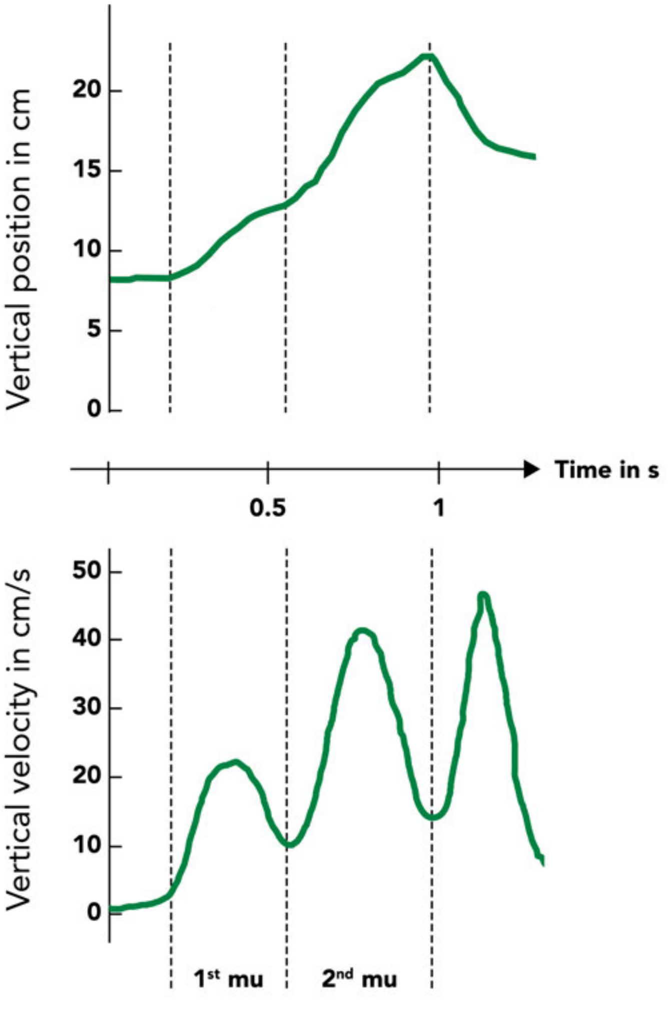

Figure 5. Position and velocity profiles for one typical lifting action of one participant. Movement units (mu) are defined based on the velocity profile.

Statistical analyses were conducted to test the three hypotheses, which will be described on page 59. Average lifting amplitudes were calculated for every participant resulting in two values per participant. A 2-by-2 mixed design analysis of variance (ANOVA) with the within-subject variable weight and the between-subject variable condition (different color or same color) for lifting amplitude at the end of the first movement unit was performed. Two *t*-tests were subsequently conducted to study the characteristics of the interaction effect between the variables weight and condition on lifting amplitude. In doing so, a multiple comparison correction according to Benjamini and Hochberg (1995) was applied.

Additionally – to rule out that infants were using a default strategy and thus were applying the same force to both objects, lifting force was cautiously inferred by using the formula $Force_{[N]} = mass_{[kg]} * acceleration_{[m/s2]}$. Thereby we assumed a parabolic lifting movement, $amplitude_{[m]} = ½ \; acceleration_{[m/s2]} * time_{[s2]}$ or generally spoken $y(t) = ½ \, at^2 + y_0$. As objects were lifted upwards against the force of gravity, the estimation of force resulted in the formula $Force = Force_{lifting} + Force_{gravity}$, assuming constant force and no force loss due to friction resistance.

Data analysis Study II

Videos were coded for beginning and end of the reaching and placing actions using Qualisys Track Manager (Qualisys, Gothenburg, Sweden). In doing so, the last frame before the start of the reaching movement of the right hand (*reaching start*), the frame of the first contact between hand and object (*reaching end / placing start*) and the last frame before letting the object go to place it into the cylinder (*placing end*). A valid reaching movement had to start from the starting area and was defined as an extension of the right arm towards the object that ended with the touch of the object. Because infants were usually not keeping their hands still before the start of trial, reaching onset was not always easy to define. Sometimes, infants were lifting their hands vertically or moved the hand backwards before moving their hands towards the object. As we were particularly interested in the beginning of the reach, only direct reaches – that are reaches without the mentioned reaching preludes – were included in the analysis (cf. Corbetta & Thelen, 1995; Thelen, Corbetta, & Spencer, 1996). Trials were further limited to direct reaching movements from the starting area to the object that were followed by direct placement movements and were free from any interference of the caregiver. *Direct* in this context addresses movement trajectory and also means the absence of interrupting movement breaks or additional actions, such as taking the object to manipulate it before placing it into the cylinder. Valid placement movement included both successful and failed placements of the object, assuming that the intention to place the object into the cylinder did not differ between these actions. On average, 10% of the valid trials included unsuccessful placements (small cylinder: 9%, big cylinder: 11%). Infants who completed at least half of the first block (12 trials) and contributed useable data of minimum 3 valid trials per goal size were included in the analysis.

Motion capture data were employed to extract peak velocity of the first movement unit. Thereby, the data were first polynomially interpolated in Qualisys Track Manager exactly as done in Study I (see p. 51) and subsequently exported to TimeStudio (http://timestudioproject.com; Nyström, Falck-Ytter, & Gredebäck, 2016), a plug-in based toolbox for MATLAB. Data filtering was consistent with Grönqvist, Strand Brodd, and von Hofsten (2011): data were filtered for x-, y- and z-coordinates applying a three-sample-median filter (i.e. 12.5 ms) in order to remove outlier. Subsequently, a Butterworth low-pass filter at 10 Hz was used on position data. Three-dimension velocity was inferred and thereafter smoothed by the 10 Hz Butterworth low-pass filter. Movement units were semi-automatically defined applying the following criteria: A minimal peak distance of 1 sample (i.e. 4.18 ms), and a merge threshold of 8 samples (i.e. 33.34 ms). After visual inspection, further trials were excluded due to the following reasons: less than 50% data, incompletion of the first movement unit or noisiness of the full trial. Peak velocity of the first movement unit was extracted *(Figure 6).*

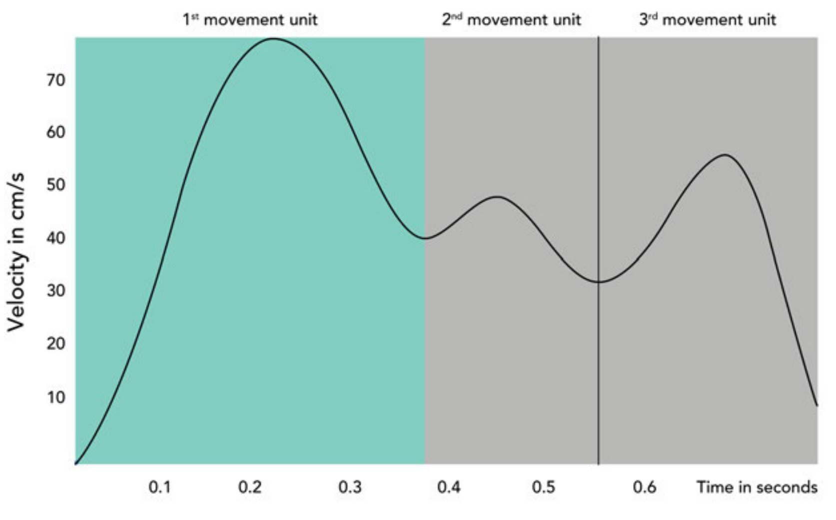

Figure 6. Velocity profile of one typical reach of a 14-month-old in this study. Movement units contain one acceleration and one deceleration phase.

Movement velocity analyses

Statistical analyses were conducted to test the first hypothesis (see p. 66). Average peak velocities were calculated for every participant on the two goal size conditions and a 2-by-2 mixed design ANOVA with the within-subject variable goal size and the between-subject variable goal distance for peak velocity of the first movement unit was performed.

Movement duration analyses

Additionally, movement durations were modeled, as Fitts' law is predicting movement time (Fitts, 1954; see *Fitts' law in reaching development,* p. 24), that means two multiple linear regression analyses were conducted. In order to investigate the distinct effects of goal size and goal distance on movement duration, a formulation of Fitts' law that allows to evaluate the separate contributions of both factors was applied (Welford et al., 1969). According to this formula, movement time (MT) is given by MT = $a + b\text{D} * \log2\ (\text{D}) + b\text{S} * \log2\ (1/\text{S})$, with a and b being empirical constants, D goal distance and S goal size. Durations of the complete reaching and placement actions were inferred from previously described video coding. Note that in the movement analyses two more participants could be included as in the velocity analyses. A further difference to the velocity analyses is that the complete movement instead of the first movement unit only was analyzed.

Data analysis Study III

The movement and video data of Study III to infer prospective motor control were coded, pre-processed and analyzed in a similar manner as the data in Study II. The videos of the three executive functions measures prohibition, working memory and complex inhibition were coded and the data were analyzed as following.

Prospective motor control

Movements and valid trials were defined as in Study II. As previously, only right-hand reaches were analyzed, whereas left- or both-handed reaches seldom occurred. Out of the sample, 19 infants contributed together 42 non-right handed reaches, which is a bit more than in Study II. To be included in the subsequent analyses, infants had to have at least 3 valid trials (independent of condition). In total, 59 infants (84% of the participants) contributed valid data. The remaining 11 infants had to be excluded due to the following reasons: No participation (n = 3), technical error (n = 4), low motion-tracking data quality (n = 2), or because of incomplete task performance (n = 2). A second rater double-coded 20 of the 70 videos to judge trial validity. The resulting inter-rater reliability was high; inter class correlation (ICC) was .97.

The kinematic data was pre-processed and analyzed using the same work-flow as applied in Study II. After visual inspection, a few trials were excluded due to the following reasons: incompletion of the first movement unit (5% of performed trials, 9% of valid trials) or noisiness of the full trial (1% of performed trials, 2% of valid trials). These percentages are similar as the ones in Study II. Peak velocity of the first movement unit was inferred and average peak velocity was calculated for every participant.

Prohibition

Videos were coded for the moment when the experimenter let go of the wand and – if applicable – for the moment when the infant touched the wand. A second rater double-coded 20 of the 70 videos and inter-rater reliability was high, ICC = .99. The latency between both defined events, that is the child's waiting time, was calculated in seconds. If the child did not touch the wand within 30 seconds, the maximal value of 30 seconds was assigned. A number of 67 participants (96% of all participants) contributed valid data. The data of three participants had to be refrained from analyses due to parental interference (n = 1) or technical failure (n = 2).

Working memory

The warm-up trials were coded for openings of the drawers – independently which ones were opened or whether the toy was found. All participants opened drawers in both warm-up trials.

The test trials were coded for the number of searches for the toy assigning the highest score to success on the first try (4 points) and the smallest amount to no success after 4 attempts (0 points). Subsequently, the mean score of all 4 trials was calculated for every participant. High working memory performance was indexed by a high value (maximal 4 points). To be included in the analyses, participants needed to have at least 1 valid trial. A second rater double-coded 20 videos and the inter-rater reliability was high with ICC = .92. A number of 63 participants (90% of the sample) contributed valid data. The data of six participants had to be excluded due to technical error (n = 3) or to mismatching the inclusion criterion (n = 3). One additional infant did not take part in this task.

Complex inhibition

The warm-up trials were coded for openings of the box revealing that 85% of the final sample opened the box without the experimenter's reminder in at least one of the two trials. Another 13% needed a reminder before opening the box and the remaining 2 % (that is one infant) did not open the box.

In the coding of test trials the following points were assigned: Two points for directly reaching towards the knob, one point for initially reaching towards the window and subsequently reaching towards the knob, and zero points for either reaching towards the window and only reaching towards the knob after being reminded by the experimenter or for no reaching to the knob at all. The mean score for all four trials was calculated for every participant, whereas high complex inhibition performance was indicated by a high value (maximal 2 points). A second coder double-coded 20 videos and the inter-rater reliability was high, ICC = .98. To be included in the subsequent analyses, participants needed to contribute valid data of at least one trial. Four data sets had to be excluded, because the participants performed no valid test trial (n = 3) or because of technical failure (n = 1). One additional infant did not participate in the task.

Statistical analyses

Outlier detection and testing of skewness and kurtosis of the data were performed before conducting statistical tests. One outlier in the motion data was removed (criterion: +/- 3 *SD* from *M*). No violation of normal distribution was detected as indicated by skewness and kurtosis (range of skewness: -.496 – 1.432; range of kurtosis: -1.017 – 1.859; cf. Kline, 2005).

To investigate the relations between variables, bivariate correlations were calculated. *T*-tests were calculated to check for gender difference in performance in prospective motor control and executive functions. Subsequently, a hierarchical regression analysis was conducted on reaching peak velocity of the first movement unit with the control variables gender, age, fine motor skills and gross motor skills (step 1), and then additionally with the variables prohibition, working memory, and complex inhibition (step 2). The first step tested only the contributions of the control variables, whereas the second step took all variables into account. All reported statistical tests were two-tailed.

Study I – Prospective motor control of current actions (lifting)

Study I investigated how infants use different sources of information to prospectively control their current actions. This was done by the example of lifting of differently weighted objects, where weight was either indicated by the object's color or not. We gave 14-month-olds toys for lifting (and shaking) and measured how high the infants lifted the objects using a motion capture system. We used the first movement unit as indicator for prospective motor control early in the movement course.

Prospective motor control is a central aspect of action development, crucial for action planning and enables us to successfully interact with an ever-changing environment in an anticipatory fashion (von Hofsten, 1993; see chapter IV).

Different sources of sensory information feed into this forward control process and whereas visual information is often found to be of particular significance in adults (e.g., Rock & Victor, 1964), tactile[20] information (Johansson & Flanagan, 2009) and sensorimotor memory (Flanagan, King, Wolpert, & Johansson, 2001) are also used. Adults combine these different – sometimes contradictory – pieces of information in a statistically optimal manner (Ernst & Banks, 2002; see *Multi-cue integration,* p. 27), but children do not integrate multiple perceptual cues in an optimal way until the age of eight years (Nardini, Jones, Bedford, & Braddick, 2008). Multisensory integration – the ability to combine information from different sensory sources (Barutchu et al., 2011) – is specifically important to reduce uncertainty in the case of ambiguous or contradicting sensory information (Nardini et al., 2010; Rock & Victor, 1964). If children and infants do not integrate different sources of information, they should favor one of the involved senses in order to prospectively control their action. To date, little is known about what kind of information infants use for prospective motor control in goal-directed actions.

One classical way of studying the questions of ambiguous sensory information is to present participants with objects with certain weights that additionally differ in color (Mash, 2007), size (Flanagan et al., 2001), material

[20] See footnote 8, p. 26 for definitions of "tactile" and "haptic" information.

(Paulus & Hauf, 2011) or shape (Mash, Bornstein, & Banerjee, 2014).[21] A lifting task, where object weight is indicated by visual and non-visual information, such as tactile and sensorimotor memory information, can reveal prospective control processes of the involved movements (Buckingham & Goodale, 2010; Flanagan, Bowman, & Johansson, 2006).

Study I used a paradigm inspired by the work of Marshall, Saby, and Meltzoff (2013) and Mash (2007): Fourteen-month-olds participated in one of two conditions, where they were given different weighted objects (one light and one heavy object) for lifting and shaking – one object at a time of a pair. In the *different color condition* they lifted two objects that differed in color, where different colors indicated different object weight, serving as a visual cue before manual contact. In the *same color condition,* the infants lifted two objects that were visually indistinct, so no visual information on object weight was available prior to lift-off. Lifting amplitude at the end of the first movement unit served as early indicator of prospective control before possible proprioceptive feedback processes influence the current lifting action (Jeannerod, 1988). Using this methodology enabled us to choose a measurement that is directly related to the inherent structure of every single movement, instead of applying a fixed time criterion (as Mash, 2007) or having to rely on the end state of every movement. The particular age group was chosen, because infants at this age are able to use color cues for object differentiation (Mash, 2007). We had the following hypotheses (*Figure 7*):

1) Based on previous work (Mash, 2007), we expected infants in the *different color condition* to lift the light object higher than the heavy object at the end of the first movement unit.

2) Additionally, we investigated whether infants are able to prospectively control their lifting action in the *absence* of weight-relevant visual information, where three alternatives were possible. (I will further elaborate on these hypotheses below *Figure 7*.)

    a) *Visual hypothesis:* Infants in the *same color condition* lift heavy objects lower and light objects higher than infants in the *different color condition*.
    b) *Non-visual hypothesis:* Infants in the *same color condition* show the same lifting pattern as infants in *different color condition*.
    c) *Enhanced non-visual hypothesis:* Infants in the *same color condition* lift heavy objects higher and light objects lower than infants in the *different color condition*.

[21] This body of research relates to research on the size-weight illusion (Amazeen & Turvey, 1996; Buckingham & Goodale, 2010a; Kloos & Amazeen, 2002; Robinson, 1964; see *The size-weight illusion*, p. 27)

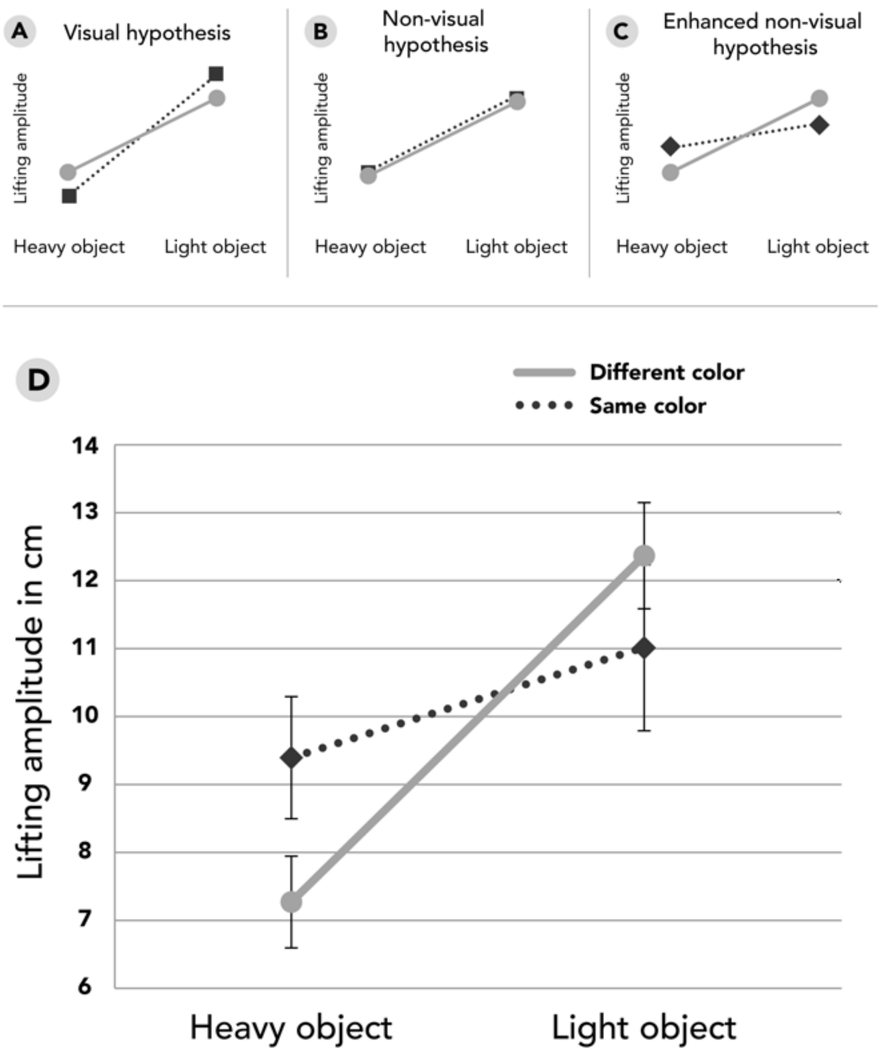

Figure 7. Hypothesized result patterns (**a–c**) and actual results (**d**) of the mean lifting amplitude of the first movement unit as a function of object weight (heavy, light) and experimental condition (dashed line same color condition, solid line different color condition). Hypotheses: **a** the visual hypothesis states that infants in the same color condition lift heavy objects lower and light objects higher than infants in the different color condition; **b** the non-visual hypothesis states that infants in the same color condition show the same lifting amplitudes as infants in the different color condition; and **c** the enhanced non-visual hypothesis states that infants in the same color condition lift heavy objects higher and light objects lower than infants in the different color condition. Results: **d** mean lifting amplitudes (in cm) of the first movement unit as a function of object weight and experimental condition. Error bars indicate the standard error of the mean.

If infants rely exclusively on vision to prospectively control their lifting actions, they should fail to do so in the absence of relevant visual cues. This would be indicated by the lifting pattern as described in the *visual hypothesis* (2a), as infants in the *same color condition* would use a default strategy. This default strategy of applying equal load force on both objects would result in overshoots in case of the light object and in too low lifting amplitudes on case of the heavy object.

If infants instead do not rely on vision, but on either tactile information[22] from the brief period between the first manual contact with the object and lift-off (as shown in adults, Johansson & Westling, 1984; Johansson & Flanagan, 2009) or on sensorimotor memories[23] from the preceding trial (as shown in adults, Buckingham & Goodale, 2010b; Mawase & Karniel, 2010), the lifting pattern as described in the *non-visual hypothesis* should occur (2b). There would be no difference between both conditions in lifting amplitude, as all infants would use the same non-visual information.

If no reliable visual information on object weight is available, infants could also demonstrate enhanced performance due to higher attention to tactile respectively sensorimotor memory information, as stated in the *enhanced non-visual hypothesis* (2c). The importance of tactile information for object exploration was stressed by Klatzky and colleagues (Klatzky, Lederman, & Reed, 1987; Lederman & Klatzky, 1987) and tactile object exploration has been shown to be more elaborated in the absence of visual information (Abravanel, 1973). Instead of using a default strategy (cf. Corbetta, Thelen, & Johnson, 2000), infants in the *same color condition* might be using this information more efficiently[24] resulting in lifting amplitudes that differ less for both objects than in *the different color condition*. In other words, infants *in the same color condition* should increase their load force towards heavy objects and decrease load force towards light objects.

Results

The ANOVA demonstrated a significant main effect of object weight, $F(1,28) = 21.56$, $p < .001$, $\eta 2 = .44$, indicating that infants lifted light objects (*MD* = 11.69 cm, *SD* = 3.96) higher than heavy objects (*MD* = 8.33 cm, *SD* = 3.21) within the first movement unit (*Figure 7*). This is in line with our

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[22] Tactile information from the period before lift-off was facilitated by using relatively high (10.1 cm) and at the same time narrow (3.5 cm) objects.

[23] Sensorimotor memory might play a role, as each weighted object was presented on several subsequent repetitions before it was interchanged. The order was not predictable, but the probability of lifting the same weight twice in a row was high with 78%.

[24] More efficiently in that sense that both objects would be lifted to the same height already during the first movement unit. However, as maximal lifting height (at the end of the lifting movement) was not predefined by the experimental design, this is a speculation about the infants' intentions.

first hypothesis. Secondly, a significant interaction effect between weight and condition was found, F (1,28) = 5.76, p = .023, $\eta 2$ = .17, indicating a different lifting pattern across conditions and thereby suggesting a rejection of the *non-visual hypothesis*. The direction of the interaction is in line with the *enhanced non-visual hypothesis*.

Multiple comparison *t*-tests showed that the infants in the *same color condition* lifted heavy objects higher than the infants in the *different color condition* (MD = 2.12 cm, SD = 1.23), t (28) = 1.89, p = .069 (two-tailed). There was no significant difference in lifting amplitude for the light objects, t (28) = 0.94, p = .357 (two-tailed).

The interference of load force indicated that infants exerted different amounts of force to light and heavy objects in both the *different color condition*, $\text{Force}_{\text{heavy}}$ = 2.85 N (SD = 0.13) and $\text{Force}_{\text{light}}$ = 0.59 N (SD = 0.04), and the *same color condition*, $\text{Force}_{\text{heavy}}$ = 2.82 N (SD = 0.11) and $\text{Force}_{\text{light}}$ = 0.57 N (SD = 0.02).

Discussion Study I

Already in the beginning of their lifting actions (i.e., during the first movement unit), infants lifted light objects higher than heavy objects when weight-related visual information was available (*different color condition*). Given that proprioceptive feedback about the actual weight should influence the action *not* before the end of the first movement unit (cf. Jeannerod, 1988; Latash, 2012), the observed differences in lifting amplitude at the end of the first movement unit are ascribed to the influence of prospective control processes. The visual information on object weight is acquired before manual contact with the object. This means – in line with our first hypothesis and with Mash (2007)[25] – that infants use visual information to prospectively control their lifting actions.

In the absence of relevant visual information, infants showed a different lifting pattern (*same color condition*). The significant interaction effect on lifting amplitude does neither correspond with the *visual hypothesis* – stating a larger amplitude difference for heavy and light objects in the *same color condition* than in the *different color condition* – nor with *the non-visual hypothesis* – stating the same lifting pattern for both conditions. The supported *enhanced non-visual hypothesis* predicts enhanced performance due to higher attention to tactile respectively sensorimotor memory information in the absence of reliable visual weight-related information. According to this hy-

[25] Study I is more precise in that respect, as Mash (2007) used 500 ms as a fixed time criterion instead of the measure of the first movement unit. In the sample of Study I, the durations of the first movement unit were ranging from 270 to 1431 ms (M = 526 ms). In case the first movement unit is shorter than 500 ms, feedback-based adaptation processes can influence the action before the 500 ms mark.

pothesis, infants are becoming more sensitive to the actual weight of an object when visual cues are absent. This is illustrated by higher lifting of heavy objects and lower lifting of light objects in the *same color condition* than in the *different color condition*. Given that there is no visual information on object weight prior to manual touch in the *same color condition*, we assume that either tactile information from the brief period between the first manual contact and lift-off or sensorimotor memory from prior trials is used to prospectively control the action. In this case, infants seem to be better at adjusting their load force to the actual weight in case they cannot rely on vision. These mentioned two sources are not mutually exclusive and future studies are needed to clarify whether infants solely rely on one or on a combination of the two.

Our interpretation of the results that infants might perform more efficiently (see footnote 24, p. 61) in the absence of visual information becomes especially interesting in light of object-lifting studies demonstrating dominance of vision over other sources of information (Buckingham & Goodale, 2010b; Cole, 2008; Forssberg et al., 1992; Gordon, Forssberg, Johansson, & Westling, 1991) and of developmental studies demonstrating that infants rely on vision to estimate object weight (Marshall et al., 2013; Mash et al., 2014; Mash, 2007). On the other hand, there is research demonstrating the importance of tactile information. First, whereas adults rely on vision during object manipulation tasks, their tactile exploration is more efficient in the absence of visual information (Abravanel, 1973). Second, Klatzky et al., (1987) found the tactile system to provide similarly rich information as the visual system. Third, in comparing blind and blind-folded children aged three to eight years, Morrongiello, Humphrey, Timney, Choi, and Rocca (1994) found no difference in object exploration performance between them, indicating that prior visual experience might not be relevant for manual object exploration. Altogether, these findings demonstrate the importance of sensorimotor information for object exploration and that this information can be used in the absence of visual information. Study I is in line with this mentioned work in demonstrating this for object-lifting in infancy.

One alternative way of interpreting the results could be to argue for a default strategy (or intrinsic motor tendencies, see Corbetta, Thelen, & Johnson, 2000). Being unable to infer weight by vision, as was the case in the *same color condition*, infants might simply apply the same load force to both objects without having expectations about their weight. Consequently this would result in higher lifting amplitudes for light objects (*overshoot*) and lower lifting amplitudes for heavy objects. However, we ruled out this possible alternative explanation by inferring the involved load force[26] and found it to be different for both weights.

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[26] This is a cautious interference, as we have to simplify the lifting movements in order to calculate load (see *Data analysis Study I,* p. 53). We assume parabolic lifting movements with

When talking about efficient lifting behavior, the question about the infants' intentions could arise (cf. footnote 24, p. 61), which leads to a second alternative explanation of the results. Since the maximal lifting height was not predefined by the experimental task, lifting both objects with different amplitudes, as it was the case in the *different color condition*, could also be interpreted as efficient lifting behavior. Maybe the infants intended to lift the light objects higher than the heavy objects. The lifting behavior during the first movement unit of the infants in the *different color condition* could then be interpreted as matching this intention and consequently being efficiently. However, problems with this interpretation arise with regards to the results of the *same color condition*. The infants in this group lifted the heavy object as high as the light object. While accidently too high lifts of unexpectedly light objects are possible (*overshoot*), too high lifts of unexpectedly heavy objects are not very likely. Heavy objects would be rather lifted low, when their weight is not adequately inferred before lift-off (cf. Mash, 2007). Therefore this line of arguments does not provide a convincing explanation of the results.

To conclude, Study I demonstrated that 14-months-olds use visual and non-visual cues to prospectively control their lifting actions. In the absence of reliable visual information, infants might control their actions even more efficiently due to heightened sensitivity to either tactile or sensorimotor memory information on object weight. By using the first movement unit as a fine-grained measurement, we were able to capture prospective motor control based on the movement's inherent structure.

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constant velocity and no force loss due to air friction. Human movements usually do not appear so ideal.

Study II – Prospective motor control of future actions (reaching)

Study II investigated how infants plan their actions as part of action sequences. Precisely we asked, if infants take the difficulty of the subsequent action step into account while prospectively controlling their current action. Fourteen-month-olds were engaged in a reach-to-place action, where the difficulty of the placement action was varied by goal size and goal distance. The infants' hand movements were measured with a motion tracking system. Beside measuring prospective motor control of the reaching action, as indicated by peak velocity in the first movement unit, we modeled movement durations of both actions, to test whether they were consistent with Fitts' law (see below for more details).

A successful interaction with an ever-changing environment requires planning ahead and adjusting our actions to current and future task demands (von Hofsten, 2004). In adults, planning of the next action steps is evident in the kinematics of the current action (Armbrüster & Spijkers, 2006; Hesse & Deubel, 2010; Johnson-Frey, McCarty, & Keen, 2004; Marteniuk et al., 1987) – for example, we reach faster for a huge cup of caffè latte than for a tiny cup of espresso. While the overall intention – drinking coffee – is the same, the required movements of the subsequent action step – lifting the cup to the mouth – vary in speed, precision, and force (cf. Hamilton & Grafton, 2007). Similarly, 7-year-old children reach faster for an object when they subsequently place it into a large rather than in a small container (Fabbri-Destro et al., 2009). Regarding early development, 10-month-old infants are also able to plan in multiple steps. When reaching to an object, they are faster when they subsequently throw the object into a tub than when they subsequently place it in a tube (Claxton et al., 2003). Chen, Keen, Rosander, and von Hofsten (2010) demonstrated similar effects for 18- to 21-month-old infants who reached for blocks to either build a tower or to throw them into a basket.

As described in chapter III, actions are organized at different hierarchical levels, such as the level of intention (e.g. drinking coffee), or the level of kinematics (e.g. reaching for cups; Hamilton & Grafton, 2007). For infants, it is unclear at which level they are able to prospectively control their future actions. It could be that infants plan differently for different types (or categories) of actions and goal intentions (e.g., reaching with the intent to throw vs. place an object; here referred to as *action type planning*). Infants might also be able to plan their actions on a more fine-grained level, based on a continuous scale of task difficulty (here referred to as *action difficulty planning*), as shown for older children (Fabbri-Destro et al., 2009). In prior infant studies (Chen et al., 2010; Claxton et al., 2003) these two levels have been confounded.

This relation between action difficulty and movement time is described by Fitts' law (Fitts, 1954; see *Fitts' law in reaching development,* p. 24), which states that the movement time (MT) required to rapidly move to a target area is a function of the distance (D) to the target and the size (S) of the target given by MT = $a + b * \log_2 (2\ D/S)$, where $\log_2 (2\ D/S)$ is the spatial relative error or the index of difficulty and a and b are empirical constants. To put it differently: the easier an action becomes, the less time is required to successfully perform it. This leaves us two alternatives how action difficulty can be considered for prospective motor control: First, infants could use a simple heuristic to infer task difficulty, such as goal size or goal distance. Another possibility would be that infants rely on a combination of both goal size and goal distance, as described by Fitts' law.

Consequently, the aim of Study II was twofold: First, we investigated whether prospective motor control at the beginning of the reach depends on the difficulty of the subsequent placing action. Prospective motor control was assessed by the peak velocity of the first movement unit (von Hofsten, 1993a). Second, we modeled the movement times of both reaching and placing actions to determine whether infants' movements in action sequences can be described by Fitts' law and whether both difficulty aspects are involved. Therefore we had the following hypotheses:

1. Infants prospectively control their multiple step actions based on action difficulty. Consequently, they will reach faster for the object when the subsequent placement action is rather easy than difficult. This will be expressed by at least one main effect of either goal size or goal distance on reaching peak velocity of the first movement unit.

2. Goal size *and* goal distance influence perceived action difficulty. This will be expressed by two significant main effects of goal size and goal distance on reaching peak velocity of the first movement unit.

3. Movement times of both reaching and placing actions are described by Fitts' law. Accordingly, the variation in duration should be explained by both difficulty factors.

Results

Infants in the sample (n = 37) performed on average 27 trials (100%) and a 15 (54%) thereof were judged as valid trials in the video coding. Trials were excluded due to the following reasons: The reaching movement started not from the marked area (27%), non-direct reaching (7%), non-direct placing (7%), parental interference (2%), left hand reaches (1%), other actions (2%). In the movement analysis, 95% (n = 35) of the sample was included, because the motion-tracking data of two participants were low in quality. After visual inspection, further trials were excluded due to the following reasons: less than 50% data (9% of all trials), incompletion of the first movement unit (6%) or noisiness of the full trial (3%).

Movement velocity (reaching)

There were both a significant main effect of goal size, F (1,33) = 4.64, p = .039, $\eta 2$ = .12, and goal distance, F (1,33) = 11.18, p = .002, $\eta 2$ = .25, on reaching peak velocity of the first movement unit (*Figure 8*). No significant interaction effect between these two variables was detected, F (1,33) = 1.73, p = .198, $\eta 2$ = .05. In line with the hypotheses 1 and 2, the smaller the size of the goal and the longer the distance to the goal, the slower the infants were in the beginning of their reach towards the object ($MD_{goal\ size}$ = 4.52 cm/s, $MD_{goal\ distance}$ = 8.82 cm/s).

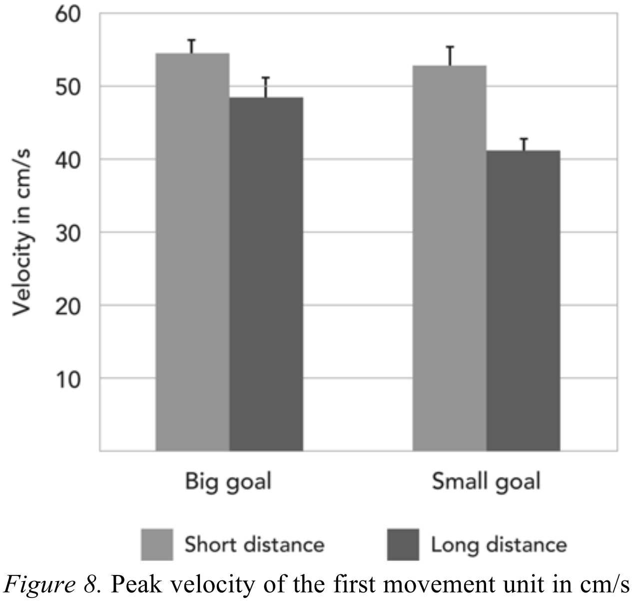

Figure 8. Peak velocity of the first movement unit in cm/s of the reach as a function of goal size (left cluster: big goal size, right cluster: small goal size) and goal distance (bright grey bars: short distance, dark grey bars: long distance). There was a significant main effect of goal size (p < .05) and goal distance (p < .01). Error bars indicate the standard error of the mean (n = 35, $n_{short\_distance}$ = 18, $n_{long\_distance}$ = 15).

Movement duration (placing and reaching)

Placing

The duration of the placing action was 1.76 seconds on average (small goal size: $M = 2.27$ s, $SD = 0.70$; big goal size: $M = 1.24$ s, $SD = 0.48$; short goal distance: $M = 1.58$ s, $SD = 0.50$; long goal distance: $M = 1.97$ s, $SD = 0.46$). The model was a good fit to the data and explained 48% of the variation in movement duration, $R^2_{adj} = .48$, $p < .001$. As stated by hypothesis 3, goal size and goal distance were significant predictors in the model, both $ps < .05$ (*Figure 9, Table 1*).

Reaching

The mean reaching time equaled 0.87 seconds (small goal size: $M = 0.87$ s, $SD = 0.15$; big goal size: $M = 0.87$ s, $SD = 0.24$; short goal distance: $M = 0.82$ s, $SD = 0.14$; long goal distance: $M = 0.93$ s, $SD = 0.18$). The model explained 6% of the variation in movement duration for the reaching action, where task difficulty is held constant, $R^2_{adj} = .06$, $p = .048$. Goal distance was a significant predictor in the model, $p = .014$, but goal size was not (*Table 1*).

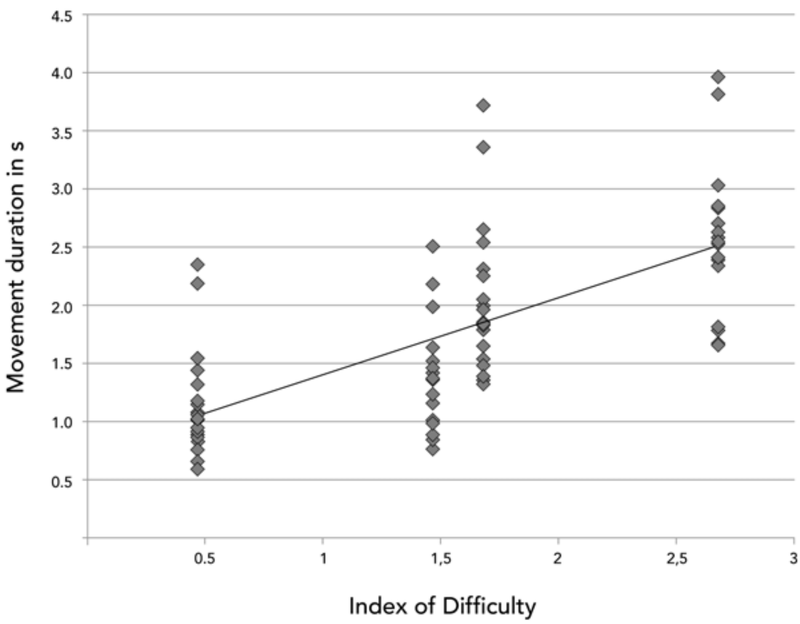

Figure 9. Placement movement duration as a function of the difficulty index, ID = log2 (D) + log2 (1/S). The line indicates the linear relation between ID and movement duration (see pp. 24, 55).

Table 1. Coefficients of the multiple linear regression analyses of the placing duration and the reaching duration with the predictors goal size and goal distance

Action		***F***	R^2_{adj}	***b (SE)***	**β**
Placing		34.19***	.48		
	Goal Size			-.654(.08)	-.654***
	Goal Distance			-.393(.13)	-.250**
Reaching		3.15*	.06		
	Goal Size			-.001(.03)	-.002
	Goal Distance			-.111(.04)	-.286*

* $p < .05$. ** $p < .01$. *** $p < .001$

Discussion Study II

Study II investigated infants' prospective motor control in action sequences. This is the first investigation of its kind to date, which examines the issue at this level of temporal precision and thus demonstrates infants' ability to plan actions based on action difficulty. Study II is also the first study investigating prospective motor control in action sequences in relation to Fitts' law. Study II demonstrated that already at the beginning of their movements, 14-month-olds reach faster for objects, when the subsequent placement action is rather easy than difficult. Moreover, the durations of the infants' whole reaching actions are partly explained by the difficulty of the subsequent placing action, more specifically by the distance of the ultimate destination of the object.

Our results indicate that infants not only plan different action types differently, as shown for throwing versus placing by Claxton et al. (2003), but also same actions with different degrees of difficulty, as shown for 7-year-olds by Fabbri-Destro et al. (2009). In line with our first hypothesis that infants prepare for different degrees of difficulty by prospectively controlling their reaching speed, infants reached faster when the upcoming action was easier (vs. more difficult). In line with our second hypotheses, both difficulty aspects, goal size and goal distance, were relevant in this context.

Additionally we modeled duration times to test, whether reaching and placing actions were in accordance with Fitts' law. As expected the model was a good fit to the placing durations, where the difficulty parameters were directly manipulated. However, the model only explained 6% of the variation in duration for the reaching action. Though difficulty parameters were held constant for the reaching action itself, the variable difficulty parameters of the subsequent placing action should have an impact. We expected Fitts' law to explain a larger amount of the variation in the reaching durations. Additionally, only the factor goal distance was a significant predictor of reaching speed. Given the general high variability in infant data and the fact that Fitts' law itself is a law for current actions, it has to be noted that Fitts' law provides a significant contribution to explain the variance of reaching velocity. However, 6% is a small amount, especially in comparison with an explained variance of 48% for the placement durations. With 45%, a similar high percentage of explanation of variance in movement times was found by Zaal and Thelen (2005) for 11-month-old infants. To my knowledge this is the only previous study that investigated Fitts' law accounting for infants' actions, but unlike the current study, Zaal and Thelen (2005) manipulated only goal size, not goal distance. With respect to older children, Fabbri-Destro et al. (2009) demonstrated significant differences in movement duration based on the goal size of the subsequent action.

However in case of 10-month-old infants, Claxton et al. (2003) found no significant effect of action type of the subsequent action on movement durations (but on movement velocity). Our results fit well with Claxton's and colleagues' results, as we primarily also found effects of the following action for movement velocity and fewer effects for movement duration. The measures of movement speed and movement time are clearly related, as the duration of a movement depends – besides the travelled distance – on the applied speed. Should not both measures consequently give similar results? An important difference in Study II though was that movement velocity was measured in the first part of the movement – the first movement unit – and movement duration was captured of the whole movement (i.e., the duration of several movement units). This is suggesting that velocity of the first movement unit might be a more sensitive measure than movement duration. We argue that this is especially the case, because the first movement is reflecting prospective motor control, whereas the full movement is additionally reflecting later occurring feedback processes.

This is further suggesting that future research should choose measures that are adjusted according to the infant's own movements, instead of fixed measures, such as time criterions. By using the fine measure of peak velocity of the first movement unit, it is possible investigate the movements' characteristics themselves, rather than only their duration.

To conclude, Study II demonstrated that infants at the age of 14 months are capable of planning a sequence of actions and of prospectively controlling the related movements. Besides prospectively controlling their current actions, as shown in Study I, they are also able to prospectively control their future actions. An open question is how individual differences relate to prospective control, which was addressed by Study III.

Study III – Prospective motor control and executive functions (reaching and beyond)

Study III investigated the link between prospective motor control and executive functions in infancy. The measure of prospective motor control – reaching peak velocity in the first movement unit – was correlated with measures of prohibition, working memory and complex inhibition. In addition, the contributions of simple and complex forms of executive functions and of motor developmental state (fine and gross motor skills) were examined.

As outlined in chapter V, executive functions are important in many areas of our daily lives and are impaired in neurodevelopmental disorders such as ADHD (Barkley, 1997a). The important role of executive functions for daily functioning and academic achievement and the positive outcomes of intervention programs (Diamond, 2013) motivate the quest for early markers. Surprisingly, little is known about the developmental origin of executive functions (see also Johansson, Marciszko, Brocki, & Bohlin, 2015).

Study III investigated the possibility of executive functions as being grounded in prospective motor control, as some of the discussed accounts of embodied cognition would suggest (Wilson, 2002; see chapter I). Both, prospective motor control and executive functions deal with the ability to plan actions in order to reach goals. Whereas action planning is addressed on a low-level in the case of prospective motor control (cf. *The action hierarchy* as discussed in chapter III, p. 30; Hamilton & Grafton, 2007), it is addressed on a higher cognitive level in the case of executive functions. The planning-related ability with the earlier onset – prospective motor control – could consequently set the ground for the development of later higher cognitive planning abilities, as executive functions (see also Diamond, 2013; Miyake et al., 2000).

Research on working memory for example, as one important component of executive functions, suggests that executive functions might be embodied (Wilson, 2001). Additionally there are lines of arguments that let the tentative link between prospective motor control and executive functions appear convincing. First, there are overlaps in neural structures related to prospective motor control and executive functions, in particular in the prefrontal cortex and the cerebellum (Barkley, 2012; Diamond, 2000). Second, longitudinal data speaks for this link. Ridler et al. (2006) demonstrated correlations between the onset of standing and walking in infancy and executive functions of adults in their thirties; an early onset of standing and walking and a better performance in working memory and categorization later in life were associated with increased gray matter density in the frontal lobes and the cerebellum. Third, the high comorbidity of deficits in motor and executive functions in several clinical diagnoses, such as ADHD (Mariani & Barkley, 1997), autism spectrum disorders (Ekberg et al., 2016) and depression (Marvel & Paradiso, 2004), further suggests a link between motor and cognitive control.

If it is the case that executive functions emerge from prospective motor control, it should be possible to find the connection between both as soon as executive functions can be reliably measured, which is at the age of 18 months (Garon et al., 2014). Study III aimed to detect this link in this age group and assessed 18-month-olds with three measures of executive functions (prohibition, working memory and complex inhibition) and with an age-appropriate version of the prospective motor control task of Study II. Thereby we expected first, prospective motor control to be associated with simple forms of executive functions (prohibition and working memory), but second, not with more complex forms (complex inhibition), given that these complex executive functions should not be sufficiently developed at this early age (Garon et al., 2008; see p. 40 for distinctions between simple and complex forms of executive functions). Third, in controlling for general motor developmental state (as measured by the fine and gross motor scales of the Vineland Adaptive Behavior Scales; Sparrow et al., 2012), we were aiming to demonstrate that the occurring individual differences in executive functions are specifically related to prospective motor control and not to general maturity.

Results

Prospective motor control

Infants in the final sample performed 25 trials on average. Approximately 50% of these trials – that is 13 trials on average – were considered as valid trials.[27]

The mean reaching peak velocity of the first movement unit was 56.21 cm/s (Range = 36.34 – 81.51, SD = 8.73 cm/s). No gender differences in task performance were observed, t (51)= - .66 p = .584.

[27] Participants of the whole sample performed 24 valid trials on average. From these trials, 48% (i.e., ≈ 12 trials) were valid.

Prohibition

On average, infants in the sample waited for 7 out of the maximal 30 seconds (Range = 0 – 30, *SD* = 11.64 s). Whereas 9 infants waited the maximal time before touching the attractive toy, 17 touched it immediately. There were no gender differences in task performance, $t\,(51) = -0.98$ $p = .331$.

Working memory

Infants in the sample contributed 3.77 valid trials out of 4.00 (*SD* = 0.81) on average and scored 2.79 out of 4.00 possible points (Range = 0.75 – 4.00, *SD* = 0.72 points). A significant gender difference in task performance was observed, $t\,(51) = -2.06$, $p = .045$, with girls ($M = 3.03$, $SD = 0.64$, $n = 22$) demonstrating a better performance than boys ($M = 2.63$, $SD = 0.74$, $n = 31$).

Complex inhibition

On average, infants of the sample contributed 3.81 valid trials out of 4.00 (*SD* = 0.81) and scored 1.28 out of 2.00 possible points. There were no significant gender differences in task performance, $t\,(51) = -0.21$, $p = .837$.

Gross and fine motor skills

The data of all participants were complete and participants of the sample scored 1.28 out of maximal 2.00 on gross motor skills (Range = 0.27 – 1.84, *SD* = 0.21 points), and 0.63 out of maximal 2.00 on fine motor skills (Range = 0.43 – 0.91, *SD* = 0.11 points) on average. There were marginal significant gender differences in fine motor skills, $t\,(51) = 1.73$, $p = .089$, with girls scoring higher than boys, and no significant gender differences in gross motor skills, $t\,(51) = 1.36$, $p = .180$.

Correlations

Prospective motor control correlated positively with both the simple forms of executive functions prohibition, $r = .31$, $p = .026$, and working memory, $r = .39$, $p = .004$ (*Figure 10*), but not with complex inhibition. A high peak velocity in the first movement unit of the reach was related to better performance in both simple executive functions tasks (prohibition and working memory), but not to differences in the complex executive functions task (complex inhibition). No significant interrelations between performances in all three executive function tasks, prohibition, working memory and complex inhibition were observed. Fine and gross motor skills as assessed with the Vineland questionnaire were significantly interrelated, $r = .42$, $p = .002$, but they were not related to any of the other variables (*Table 2*).

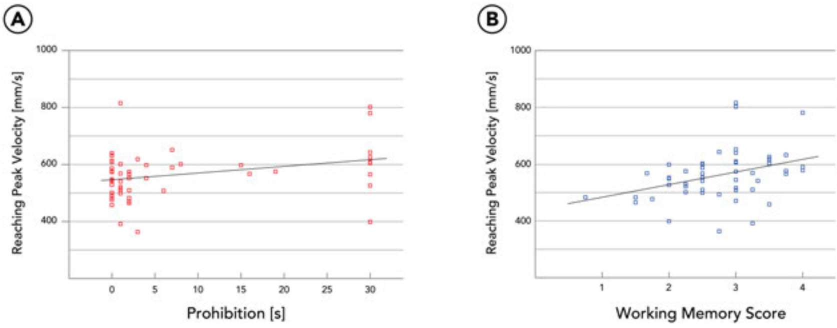

Figure 10. Correlations between (a) prohibition and (b) working memory and the peak velocity of the first movement unit during reaching.

Table 2. Correlations between prospective motor control (PMC), prohibition, working memory (WM), complex inhibition (inhibition), fine motor skills (fine motor), gross motor skills (gross motor), age, and gender (two-sided)

	Prohibition	**WM**	**Inhibition**	**Fine motor**	**Gross motor**	**Age**	**Gender**
PMC	.31*	.39**	.08	-.06	.17	-.06	-.08
Prohibition		.13	-.12	-.04	.12	.19	-.14
WM			.02	-.05	.11	.07	-.28*
Inhibition				.14	.09	.15	.03
Fine motor					.42**	.01	-.24
Gross motor						-.17	-.19
Age							-.16

* $p < .05$. ** $p < .01$.

Hierarchical regression analysis

The first step with the control variables was not significant, p = .596, suggesting that neither of the control variables accounted for the obtained relations between prospective motor control and executive functions (*Table 3*).

The second step with the additional variables prohibition, working memory, and complex inhibition was significant (F = 2.29, p = .044; ΔF = *4.21, p = .010*) and explained 26% of the variance of peak velocity in the first movement unit. Prohibition (β = .29, p = .037) and working memory (β = .35, p = .013) made significant independent contributions, but complex inhibition did not, p = .337.[28]

Table 3. Coefficients of the hierarchical regression analysis of the reaching velocity of the first movement unit with control variables (step 1 and 2) and target variables (step 2)

Step		*F*	R^2	*b (SE)*	β
1		0.70	.06		
	Fine motor (Vineland)			-138.39(126.98)	-.17
	Gross motor (Vineland)			89.56 (64.87)	.22
	Age (days)			-0.30 (1.48)	-.03
	Gender			-14.21 (25.87)	.08
2		2.29*	.26		
	Fine motor (Vineland)			-66.32 (118.99)	-.08
	Gross motor (Vineland)			41.20 (60.90)	.10
	Age (days)			-1.35 (1.42)	-.13
	Gender			6.25 (24.74)	.04
	Prohibition			2.23 (1.06)	.29*
	Working memory			42.81 (16.49)	.35*
	Complex inhibition			16.76 (17.27)	.13

R^2 = .06 for Step 1, ΔR^2 = .26 for Step 2 (p = .01). * p < .05.

Discussion Study III

Main results of this study were that executive functions performance was related to prospective motor control. In line with our first hypothesis, prohibition and working memory were positively related to prospective motor control. Complex inhibition, however, was not significantly related to pro-

[28] As reported, kurtosis and skewness values did not indicate violation of normal distribution. By inspecting the distribution of the prohibition score in *Figure 10*, questions could arise about normality. Therefore, we log-transformed the data ($\log_2$ (prohibition+1)). Correlation and regression analyses with the transformed data demonstrated similar effects with significant correlations between prospective motor control and both prohibition (r^2 = .26, p = .029) and working memory (r^2 = .39, p = .002). The second step of the regression analysis with the target variables explained 25% of the variation (F = 2.11, p = .062), with the contributions of prohibition (β = .26, p = .063) and working memory (β = .37, p = .010).

spective motor control, which is in line with our second hypothesis. Further, none of the control variables contributed significantly.

Study III proposes an embodied perspective on executive functions development. According to this perspective the ability to control actions and to plan (in an executive functions sense) emerges from the ability to prospectively control motor actions. In other words, we suggest that the development of executive functions is grounded in prospective motor control. Study III demonstrated that reaching speed in the beginning of the action is related to performance in prohibition and working memory tasks.

One caveat is that Study III does not include longitudinal data, so from these data itself we cannot conclude if prospective motor control impacts executive functions or vice versa. There are two lines of arguments however, why a pathway from motor control towards cognitive control is likely. First, prospective motor control starts to develop during the first months of life and to some extend even before birth (van der Meer et al., 1995; von Hofsten, 1983, 2004; Zoia et al., 2007), whereas executive functions emerge later in infancy (Barkley, 2012; Diamond, 2006). Second, Ridler and colleagues (2006) demonstrated long-term correlations between the onsets of standing and walking in infancy and executive function performance about 30 years later.

It is not clear from the study of Ridler and colleagues (2006), how the onsets of standing and walking specifically relate to executive functions. These motor milestones are influenced by many factors and the experiences an infant gains by interacting with the world. Consequently, these milestones could be associated with individual differences in general maturation, psychosocial context or personality. Additionally, walkers see more, go more and have their hands free for interacting with their environment (Adolph & Tamis-LeMonda, 2014). In other words, the transition from crawling to walking, as it is marked by the onsets of standing and walking, is a crucial period for the infant. Walking allows for a different perception of the world than crawling does (Kretch et al., 2014). The mentioned factors might also be related to executive functions without implying a direct link between motor development and executive functions development.

However, the process and period of learning to stand and walk requires the application of prospective motor control (von Hofsten, 1993). The study by Ridler and colleagues (2006) pinpointed this crucial period around the end of the first year of life when infants begin to stand and walk independently (Witherington et al., 2002). In that way, Ridler and colleague's (2006) measure was probably able to address motor developmental differences relevant for later executive functions development. The 18-months-olds in our study were all capable of independent standing and walking, explaining also why our acquisition of general motor developmental state presumably did not distinguish between participants relevant for executive function development.

Together, the results of Study III and of the study by Ridler et al. (2006) suggest prospective motor control to be a key component in executive function development. We propose that the prospective motor control abilities reported in Study III and the relation between executive functions and motor milestones reported by Ridler and colleagues (2006) reflect the same developmental process. Reaching, standing and walking require prospective motor control and infants being more skilled in prospective motor control are more skilled in executive functions.

It could be argued that the demonstrated relations are due to other factors such as general maturity. Infants who are further in general development should score higher in both prospective motor control and executive functions. Therefor a correlation between both variables should be found as well. This alternative explanation can be ruled out, given that general motor developmental state as assessed by the Vineland scales was not related to prospective motor control.

Taking into account that all tasks involved reaching, it is crucial to point out that the reported individual differences in executive functions are meaningful and are not just differences in different low-level reaching tasks. If the latter was true, we would have created a situation where different measures of motor control correlate with each other. This is not the case for Study III, as the executive function tasks required additional higher-order cognitive control to pass them. The working memory task involved reaching for a toy, but – on top of it – the correct location of this toy had to be remembered. In the prohibition task participants were asked *not* to touch a toy and good performance was indicated by inhibition of reaching – the direct opposite of what was needed in the prospective motor control task.

In conclusion, Study III demonstrated an association between prospective motor control and executive functions at 18 months of age. The reported results are in line with an embodied approach to early executive functions development. Executive functions could be considered as grounded in motor control.

General discussion

The general aim of this thesis was to assess the link between action and cognition early in development. The notion of cognition as embodied was thus investigated by relating early executive functions to prospective motor control. The three empirical studies comprising this thesis shed light on action control on the levels of cognitive and motor control.

Study I investigated prospective motor control of the current action in the context of information from different sources. The results demonstrated that 14-month-old infants control their lifting actions differently depending on the available information. Non-visual information alone (tactile information or sensorimotor memory information) induced a different lifting pattern in the first movement unit than non-visual information in addition to visual information. Given that the infants provided with richer information (visual and non-visual information) did not demonstrate an efficient lifting behavior, we can argue that they probably did not integrate the information from both sources.

Study II examined prospective motor control of future actions in action sequences. The results demonstrated that 14-month-olds control not only their current actions prospectively (as shown in Study I), but also their future actions in action sequences. The infants reached for the object with different speeds depending on the difficulty of the subsequent action. They reached faster in the first movement unit when the subsequent action was easy compared to when it was difficult. Thus, distance to the goal (as one factor of difficulty) was more important than goal size (as the other factor of difficulty). Additionally, Study II asked the extent to which Fitts' law explains movement durations. While Fitts' law could explain 48% of the variation in placement duration, it explained only 6% of the variation in reaching duration.

While Study I and Study II examined prospective motor control on a group level in 14-month-olds, Study III investigated individual differences in 18-month-olds. Study III also combined the measure of prospective motor control from Study II with measures of early executive functions. The results demonstrated that prospective motor control (as indicated by high velocity in successful reaches) is related to prohibition and working memory. The simple executive functions prohibition and working memory were positively related to prospective motor control. Complex inhibition, however, was not significantly related to prospective motor control. Study III proposes an embodied account of early executive functions.

In the following sections, I will elaborate on the findings of the three studies and link these findings to each other and to prior theoretical and empirical work. Next, I will specify the limitations of the current work, after which future directions will be outlined. I will end with final conclusions.

Prospective motor control in action planning

Studies I, II and III investigated prospective motor control in infants' lifting and reaching actions using the measure of the first movement unit.

Study I demonstrated that 14-month-old infants prospectively control their lifting actions differently depending on the weight of the lifted object. Besides being able to prospectively control lifting actions based on object properties, 14-month-olds use different sources of information for prospective motor control, which Study I demonstrated by comparing one condition with visual and non-visual information to one with only non-visual information.

In the case of non-visual information only, infants demonstrated higher lifting amplitudes for the heavy object and lower lifting amplitudes compared to the infants with both sources of information available. We interpreted this as a more efficient lifting behavior, suggesting that in the absence of reliable visual information, infants may heighten their sensitivity to other forms of information that provide more reliable cues about object weight. This is consistent with research showing that tactile object exploration might be more extensive in the absence of visual information (Abravanel, 1973).

The infants who were provided with both sources of information on object weight demonstrated a lifting pattern that we interpreted as less efficient compared to the other group. This suggests that infants are not capable of optimally integrating multiple cues to prospectively control their actions, which is consistent with studies demonstrating that children do not optimally integrate multiple cues until the age of eight years (Nardini et al., 2008). Given that the infants did not apply the same force to both objects (which was ruled out by inferring force by calculation, see p. 53), the observed difference in lifting amplitude at the beginning of the movement most likely reflects prior planning based on object weight.

Study I measured prospective motor control after contact between hand and object, but infants' action planning can be detected earlier in the course of the action – before the object is in hand. For the example of lifting objects of differing weights, Mash (2007) demonstrated that 9 to 15-month-old infants reached faster for an object that appeared to be heavy than for an object that appeared to be light. The infants adjusted their reaching speed according to the object they were going to lift. For the example of action sequences, Claxton et al. (2003) demonstrated that 10-month-old infants' planning is based on future actions for reach-to-place versus reach-to-throw sequences. The infants reached faster for an object that they subsequently threw into a tub as opposed to an object that they subsequently placed into a tube.

This research was the starting point for Study II. While Study I investigated prospective motor control for the current action, Study II looked at prospective motor control for future actions. Study II thus compared the different degrees of difficulty of the same reach-to-place action sequence rather than comparing different actions, as Claxton et al. (2003) did. In other words, Study II asked whether 14-month-olds are able to prospectively control reaching depending on the finer criterion of *action difficulty* beyond the criterion of *action type,* as previously demonstrated.

Both difficulty aspects (goal size and goal distance) of the placing action influenced the prior reaching action: The infants reached faster for the object in the first movement unit when the cylinder was big rather than small (goal size) and when the cylinder was close rather than far away from the pick-up area (goal distance). Because the reaching distance and size of the object to be grasped did not differ, the occurring differences in reaching velocity reflect planning of the next action step (placing). Hence, Study II demonstrated that 14-month-olds are able to prospectively control their reaching actions depending on the difficulty of the subsequent action. In doing so, infants take different goal properties (size and distance) of the subsequent action into account.

These goal properties relative to movement duration are considered by Fitts' law (see chapter II, p. 24). Study II demonstrated that infants' movements follow Fitts' law. This was the case for the placing action, where the index of difficulty varied: 48% of the variation in movement duration could be explained by Fitts' law. For the case of the prior reaching action, where the index of difficulty was kept constant, it was only 6%. One prior infant study demonstrated Fitts' law for infants' reaching actions (Zaal & Thelen, 2005), but without controlling reaching distance in the experimental design.

One important reason that no other study has looked at Fitts' law in infants' movement production might be that it is difficult to spatially control the start of the infants' reach and therefore the variable goal distance (cf. Thelen et al., 1996). Zaal and Thelen (2005) did not constrain the infants and let them reach from wherever they wanted.

Together, Studies I and II demonstrate that 14-month-old infants control their actions prospectively by taking object properties (Study I) and goal properties (Study II) into account. They use visual and non-visual information to lift objects; however, they do not optimally combine the information (Study I). Infants at this age control not only their current action (Study I), but also their future actions in action sequences (Study II). Thus, they differentiate between different degrees of difficulty of the same action type for prospective motor control (Study II).

Studies I and II investigated prospective motor control as an action planning component on the kinematic level (see chapter III). Action control on the cognitive level was also addressed in Study III, which combined measures of executive functions with the measure of prospective motor control established in Study II. Thus, Study III did not examine differences in reaching velocity based on the difficulty of the subsequent action (as Study II did), but rather, interpreted faster reaches (that successfully met the goal) as more skilled than slower reaches (that successfully met the goal). To put it differently: Faster successful reaches should indicate higher prospective control than slower successful reaches. We assumed that the reach-to-place task with six possible goal size and distance combinations was sufficiently difficult to distinguish between more and less skillfully controlled reaching in infants.

The cognitive aspect of action planning will be discussed in the following paragraph and the link to prospective motor control will then be addressed.

Prohibition and working memory in action planning

Study III investigated individual differences in early executive functions relative to prospective motor control and demonstrated that higher prospective motor control was related to better performance in prohibition and working memory tasks. The better the 18-month-old infants were at controlling their reaches on the motor level, the better they were at controlling their reaches cognitively as well: The infants with faster (successful) reaching were better at restraining themselves from reaching for an attractive toy (that is, they waited longer) than infants with slower (successful) reaching. Additionally, the fast infants were also better at keeping spatial information in mind after a delay in order to search for a hidden toy.

Better performance in executive functioning tasks indicates better action planning abilities. Prohibition and working memory are “self-directed actions needed to choose goals and to create […] actions towards those goals” (Barkley, 2012, p. 94) and as such, they are important for action planning (cf. Scholnick & Friedman, 1993).

An additional important aspect of executive functions, and thus of action planning, is the aspect of time[29] (see chapter V; Barkley, 2012). Good performance in the two executive function measures of prohibition and working memory required waiting for a certain period of time before acting. Interestingly, a better ability to wait was related to the ability act faster (as demonstrated by reaching velocity in the prospective motor control task).

[29] Because planning is always directed at the future, time plays an important role in planning.

As described in chapter III, prospective motor control and executive functions are components of action planning. The results of Study III support this view by connecting them. In the following section, I will outline how I see this relationship against the background of *embodied cognition* (see chapter I).

An embodied approach to executive functions development

Study III proposes an embodied perspective of the development of executive functions and considers both prospective motor control and executive functions as evolving from the single motive to control action. What does it mean to talk about executive functions as embodied? Thelen et al. (2001) defined embodied cognition in general as a cognition emerging from the interaction of the body with the world and as a cognition depending on the body with certain perceptual and motor abilities.

Taking this definition and the approaches described in chapter I of embodied cognition seriously, executive functions could be regarded as grounded in prospective motor control. To be more specific, prospective motor control could first arise through exploration and cycles of perception-action coupling, as stated in the dynamic systems theory of development (Thelen et al., 1996; Thelen & Smith, 1994; Thelen, 1992). Second, executive functions could then emerge from prospective motor control.

In infancy, these explorative processes leading to prospective motor control could include reaching with varying speed, manual object exploration, and locomotion, and as such are interactions between the body and the world. This assumption is consistent with von Hofsten's idea of action development through actions and his empirical work on prospective motor control (von Hofsten, 1993, 2004; see chapter II and IV). Von Hofsten (2014) described prospective motor control as relying on implicit knowledge[30] about basic physical principles, and as such, prospective motor control could be understood as embodied action control.

The ability to control actions on a cognitive level (i.e. executive functions) could then derive from the ability to control actions on a motor level (i.e. prospective motor control). Cognitive action control could be strengthened during childhood into its own domain of higher order action control, in line with the idea that cognitive processes specialize in the course of development (Karmiloff-Smith, 2015).

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[30] Von Hofsten (2014) conceptualized prospective motor control as based on implicit knowledge rather than on mathematical calculations, which is consistent with the definition of prospective motor control as a robust, continuous online-coupling between movement and information by Ledouit et al. (2013). See also footnote 18, p. 35.

This embodied approach is one possible view of the results of Study III. However, as Study III does not include longitudinal data, it cannot prove the approach directly. This and other limitations will be discussed in the following section.

Limitations

Generally, the dropout rates, which ranged from 24% in Study III to 39% in Study I, could be regarded as a limitation. These rates are mostly due to applying motion-tracking. In order to gain high-quality data, we had to exclude participants with fewer trials (see *A note on dropout rates*, p. 44). Specific limitations for each study are outlined below.

Study I demonstrated different lifting patterns based on the available information for object weight. To rule out that the observed differences in lifting amplitude between the heavy and light objects were not the result of a default strategy (of applying the same force to heavy and light objects), we calculated force. These calculations (see p. 53) showed differences in force for both objects in both conditions. However, these calculations are based on assumptions of idealized lifting movements (see footnote 26, p. 63). Consequently, this interference must be interpreted cautiously and future studies should include direct measures of force.

Study I and Study II investigated prospective motor control on a group-level with between-subjects designs. Group data, however, could possibly hide individual differences. It could for instance be that individual infants use different strategies to prospectively control their actions. Some infants could dominantly use visual and some tactile information to control their lifting movements (Study I). Following this line of arguments, some infants could use information about the distance to the goal and some information about the size of the goal to prospectively control their reaching and placing actions (Study II). These eventual individual differences could not be addressed by the experimental designs and should be addressed by future research.

The design of Study II further included two distance conditions, in which the goals were placed on a half-circle representing the infant's natural reaching space (*Figure 3*, p. 47). This decision resulted in different orientations of the goals relative to the infant, which could be seen as confounding. In the *short distance condition*, the goal was placed closer to the pick-up area, but at the same time, farer away from the infant's body center as in the *long distance condition*. Given that the goal was closer to the infant's body center in the *long distance condition*, one could argue that the placement should be easier than the placement in the *short distance condition*. Consequently, this would lead to an underestimation rather than to an overestimation of our distance effect. However, we still found an effect due to distance and do not believe it is due to the difference in orientation (that is, the difference in angle between goal and infant). Future studies could compare the effect of different orientations along with different distances on infants' reaching velocity.

Study III proposes an embodied approach to the development of executive functions. We are thus assuming that prospective motor control has an effect on executive functions. However, we cannot draw conclusions from Study III alone about the direction of the effect, as it does not include longitudinal data. Given that prospective motor control develops earlier in life than executive functions (cf. Barkley, 2012; von Hofsten, 2004), our suggested direction appears likely and longitudinal data are supporting this view (Ridler et al., 2006).

Future directions

Future research should assess the link between prospective motor control and executive functions in a longitudinal design. Measuring individual differences in prospective motor control and executive functions at each particular onset could facilitate statements about the direction of the observed effects in Study III. Furthermore, by having additional testing times, the stability of motor and executive capabilities could be investigated over time.

Further exciting research opportunities could be opened up through active training studies. One possible experimental design would include one group taking part in specific training in prospective motor control, one group receiving training in general motor skills, and one group without any training. Prospective motor control and executive functions would be measured. By having at least two testing times, effects of the specific prospective motor control training on executive function abilities could be acquired in comparison to the effects of general training or no systematic training.

Demonstrating positive effect of trainings in prospective motor control on executive function development may be of interest for early interventions against deficits in executive functioning and could open up for possible future treatments.

Final conclusions

This thesis investigated the link between action and cognition early in development. Three empirical studies examined prospective motor control and executive functions in infancy. The main results were that 14-month-olds are able to prospectively control their manual actions based on the hidden object property of weight. In this action planning process, infants used different sources of information (Study I). Beyond this ability to prospectively control their current action, 14-month-olds also take future actions into account and plan their actions based on the difficulty of the subsequent action in action sequences (Study II). In 18-month-olds, prospective motor control in manual actions, such as reaching, is related to early executive functions, as demonstrated for prohibition and working memory (Study III). These findings are consistent with the idea that executive functions derive from prospective motor control. I suggest that executive functions could be grounded in the development of motor control. In other words, early executive functions should be seen as embodied.

Summary in Swedish – Svensk sammanfattning

Den här avhandlingen handlar om förhållandet mellan handlingsutveckling och kognitiv utveckling. Idén om förkroppsligad kognition (*embodied cognition*) undersöks genom att föra samman två nivåer av handlingskontroll: prospektiv motorisk kontroll och exekutiva funktioner (*executive functions*).

Förmågan att planera våra handlingar är en förutsättning för att kunna nå våra mål. Handlingar kan arrangeras i en kontrollhierarki. Till den lägre nivån hör prospektiv motorisk kontroll och till den högre nivån hör kognitiv kontroll. Med prospektiv motorisk kontroll menas hur vi rör oss för att uppnå koordinerade målinriktade handlingar, som när vi sträcker oss efter en kopp kaffe. Med kognitiv kontroll – exekutiva funktioner i denna avhandling – menas hur vi genomför målinriktade handlingar samt kombinationer av handlingar för att uppfylla medellånga samt långsiktiga mål, som till exempel att avsluta en doktorsavhandling. Prospektiv motorisk kontroll och exekutiva funktioner är välstuderade hos vuxna, men den tidiga utvecklingen av dessa förmågor är ännu inte helt klarlagd.

I denna avhandling ingår tre empiriska rörelsemätningsstudier om prospektiv motorisk kontroll och exekutiva funktioner hos spädbarn. I Studie I undersöktes prospektiv motorisk kontroll av pågående handlingar. 14 månader gamla spädbarn fick lyfta föremål som vägde olika mycket. Genom att jämföra användningen av både visuell och icke-visuell information, samt enbart icke-visuell information, undersöktes hur spädbarn integrerar information från flera informationskällor. I Studie II undersöktes prospektiv motorisk kontroll av framtida handlingar i handlingssekvenser genom att titta på grip- och placeringshandlingar. Samtidigt undersöktes hur väl Fitts lag kan förklara rörelsernas duration hos spädbarn. I Studie III studerades prospektiv motorisk kontroll i relation till exekutiva funktioner genom att studera arbetsminne och beteendehämning hos 18 månader gamla barn.

Huvudresultaten är att 14 månader gamla barn kan kontrollera sina handlingar prospektivt baserat på olika typer av information om objektens egenskaper som – i detta fall – vikt. Utöver förmågan att kontrollera sin pågående handling, så kan 14 månader gamla barn även ta hänsyn till sina framtida handlingar, och anpassa den första handlingen i handlingssekvensen efter svårighetsgraden på nästkommande handling. Vid 18 månaders ålder är prospektiv motorisk kontroll vid manuella handlingar, som att gripa, relaterat till de exekutiva funktionerna arbetsminne och beteendehämning. Dessa resultat stämmer väl överens med idén om att exekutiva funktioner bygger på prospektiv motorisk kontroll. Jag föreslår att exekutiva funktioner grundar sig i den motoriska utvecklingen. Med andra ord bör man se tidiga exekutiva funktioner som förkroppsligade (*embodied*).

Summary in German – Deutsche Zusammenfassung

Die vorliegende Arbeit beschäftigt sich mit dem Zusammenhang zwischen Handlungs- und kognitiver Entwicklung. Dabei untersucht sie die Annahme einer verkörperten Kognition (*embodied cognition*) durch die Verbindung zweier Ebenen von Handlungskontrolle im Kontext von Greifhandlungen im Säuglingsalter: Prospektiv-motorische Kontrolle (*prospective motor control*) und exekutive Funktionen (*executive functions*).

Die Fähigkeit, unsere Handlungen zu planen, ist eine notwendige Voraussetzung, unsere Ziele zu erreichen. Dabei können Handlungen als auf verschiedenen Kontrollebenen hierarchisch angeordnet betrachtet werden. Es gibt die relativ niedrige Ebene, auf der die prospektiv-motorische Handlungskontrolle angesiedelt ist, und die relativ hohe Ebene, auf der sich die kognitive Kontrolle befindet. Prospektiv-motorische Kontrolle beschäftigt sich mit zielgerichteten Handlungen auf der Ebene einzelner Bewegungen und Bewegungskombinationen unseres Körpers und ermöglicht sinnvolle, koordinierte Bewegungen, wie zum Beispiel nach einer Kaffeetasse zu greifen. Kognitive Kontrolle, im Kontext dieser Arbeit genauer mit *exekutiven Funktionen* bezeichnet, behandelt zielgerichtete Handlungen auf der Ebene ganzer Handlungen und Handlungskombinationen und fördert die Ausrichtung an mittel- und langfristigen Zielen, wie zum Beispiel das Beenden einer Doktorarbeit. Während prospektiv-motorische Handlungskontrolle und exekutive Funktionen im Erwachsenenalter genau untersucht sind, ist die frühe Entwicklung beider noch nicht ausreichend verstanden.

Die vorliegende Arbeit umfasst drei empirische Motion-Tracking-Studien, die prospektiv-motorische Handlungskontrolle und exekutive Funktionen im Säuglingsalter beleuchten. Studie I untersuchte prospektiv-motorische Kontrolle gegenwärtiger Handlungen bei 14-Monatigen am Beispiel vom Anheben verschieden schwerer Gegenstände. Mittels des Vergleiches des Gebrauchs von visueller sowie nicht-visueller Information und nicht-visueller Information allein wurde zusätzlich die Integration mehrerer Informationsquellen untersucht. Studie II betrachtete prospektiv-motorische Kontrolle zukünftiger Handlungen in Handlungssequenzen bei 14-Monatigen am Beispiel von Greif-zu-Platzier-Handlungen. Dabei wurde ergründet, wie viel der Handlungsdauer im Säuglingsalter durch Fitts Gesetz beschrieben werden kann. Studie III hob die prospektiv-motorische Hand-

lungskontrolle auf die kognitive Ebene durch die Untersuchung ihrer im Zusammenhang mit exekutiven Funktionen bei 18-Monatigen.

Die Hauptergebnisse dieser Studien waren, dass 14-Monatige in der Lage sind, ihre manuellen Handlungen bezogen auf das Gegenstandsgewicht prospektiv zu kontrollieren. Im Zuge dieses Planungsprozesses gebrauchen Säuglinge unterschiedliche Informationsquellen. Über die Fähigkeit, gegenwärtige Handlungen, prospektiv zu kontrollieren, hinaus, orientieren sich Säuglinge ebenfalls an zukünftigen Handlungen und planen ihre Handlungen bezogen auf die Schwierigkeit zukünftiger Handlungen in Handlungssequenzen. Im Alter von 18 Monaten hängt prospektiv-motorische Kontrolle von Greifhandlungen mit frühen exekutiven Funktionen zusammen, wie in dieser Arbeit für Handlungshemmung und Arbeitsgedächtnis gezeigt wurde. Diese Befunde passen zu der Idee, dass sich die exekutiven Funktionen aus prospektiv-motorischer Handlungskontrolle heraus entwickeln könnten. Ich schlage vor, dass exekutive Funktionen in der motorischen Entwicklung begründet sind. Die frühen exekutiven Funktionen sollten mit anderen Worten als verkörpert (*embodied*) betrachtet werden.

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