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Manual Motor Development in Infancy

Execution and Observation of Actions

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Abstract

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Of all motor skills, manual reaching might be the one ability that matters most for infants' perceptual, cognitive and social development. Reaching allows infants to learn about object properties, but also gives opportunities for socializing with others. The general aim of the present thesis was to study the importance of manual motor development in infancy from different perspectives; first, through examining stereopsis as a prerequisite for efficient reaching development, second, with regard to understanding others goal-directed reach actions by means of the mirror neuron system (MNS), and third, in relation to possible atypical development, with a specific focus on autism spectrum disorder (ASD).

Study I shows that under monocular viewing conditions, infants at six, eight and 10 months of age perform slower and less accurate reaches. Longer times to object contact during monocular trials specifically imply that motor prediction is less effective when depth and distance information is compromised.

Study II demonstrates that, by eight months of age, infants seem to have a MNS that functions in a similar manner to the adult MNS, thus activity can be registered over the motor cortex when infants simply observe an action they can master themselves. This activation is predictive, indicating anticipation of the goal of the observed reach.

Study III indicates that infants at elevated familial risk for ASD present with reduced prospective motor control at 10 months of age. Compared to a low-risk control sample, high-risk infants perform reactive rather than predictive reach actions. Follow-up assessment at 36 months will show whether this measure can be used as a predictive diagnostic marker for ASD.

The main contribution given by this work is the insight that it is important to take manual motor aspects into account when considering typical as well as atypical cognitive and social development, and in addition, that motor prediction is a key factor behind being able to timely execute and understand reaching actions.

Keywords: Infancy, Motor development, Reaching, Actions, Motor prediction, Prospective motor control, Social cognition, Stereopsis, Mirror neuron system, Mu rhythm, Motor impairment, Autism Spectrum Disorder, High-risk siblings

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For my family

List of Papers

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

I. Ekberg, T. L., Rosander, K., von Hofsten, C., Olsson, U., Soska, K. C., & Adolph, K. E. (2013). Dynamic reaching in infants during binocular and monocular viewing. *Experimental Brain Research*, *229*(1), 1–12.

II. Nyström, P., Ljunghammar, T., Rosander, K., & von Hofsten, C. (2011). Using mu rhythm desynchronization to measure mirror neuron activity in infants. *Developmental Science*, *14*(2), 327–335.

III. Ekberg, T. L., Falck-Ytter, T., Bölte, S., Gredebäck, G., & The EASE Team (2015). Reduced prospective motor control in 10-month-olds at risk for autism spectrum disorder. *Clinical Psychological Science,* in press.

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Contents

Abbreviations

ADHD	Attention Deficit/Hyperactivity Disorder
ASD	Autism Spectrum Disorder
BAP	Broader Autism Phenotype
DSM	Diagnostic and Statistic Manual
DST	Dynamic Systems Theory
EASE	Early Autism Sweden
EEG	Electroencephalography
EMG	Electromyography
ERP	Event Related Potential
fMRI	Functional Magnetic Resonance Imaging
GLIM	Generalized Linear Model
HR	High-Risk
ICA	Independent Component Analysis
LR	Low-Risk
MEG	Magnetoencephalography
MEP	Motor Evoked Potential
MNS	Mirror Neuron System
MSEL	Mullen Scales of Early Learning
NIRS	Near-Infrared Spectroscopy
PET	Positron Emission Tomography
TD	Typically Developing
TMS	Transcranial Magnetic Stimulation

Introduction

Of all motor skills, manual reaching might be the one ability that matters most for infants' perceptual, cognitive and social development. Through reaching, infants get in contact with objects, both stationary and moving. By grasping and touching novel objects, turning them around, and seeing what happens when they hit the floor, infants learn a great deal about different textures, affordances and physical laws. But reaching also allows infants to get in contact with other people. Reaching actions give opportunities for socializing with others. Through observing the reaching actions of others, and practicing these actions themselves, infants can learn to predict the outcome of others' behavior. By interacting with parents, siblings or peers, for example through showing and sharing new toys, it is possible for infants to develop a common understanding of objects, scenes and people around them. Movement is in fact the only way we have of interacting with the world.

This thesis will provide information on the importance of manual motor development from three different perspectives. A common theme present in all these perspectives, besides the notion that motor development is a central component for several diverse psychological processes, is the concept of motor prediction. In this text, when using the term motor prediction, I refer to both the kind of prediction that is needed for efficient execution of one's own actions, as well as the ability to predict others individuals' motor acts through observation.

This thesis focuses on manual motor development during infancy (here defined as the period before two years of age). Motor development in infancy is truly remarkable. Infants will go from barely being able to lift their heads at birth, to adult-like walking and picking peas from a plate using a pincer-grasp only twelve months later. Even though motor skills will continue to develop and be refined over the course of several years, at no other time of life will changes in motor capacity be as drastic as during the first year of life. Another restriction for this thesis is that I will not be focusing on gross motor behavior, such as crawling or walking. This thesis is centered on the development of manual motor behavior.

Data from three empirical studies will be presented here, but prior to that, the following introductory sections will aim to provide an overview of previous research as well as theoretical frameworks for the different perspectives of manual motor development that will be dealt with. Specifically, the starting point of the Introduction will be a description of what motor prediction entails. As has already been noted, this concept acts as a common denominator for the three studies. A theoretical framework around this concept will be presented. I will return to the concept of motor prediction in the sections following, where background information for the three empirical studies will be presented. A general overview of the development of manual motor behavior will be put forward, and important prerequisites for efficient reaching behavior will be described (where the concept of stereoptic vision is of special importance for Study I). The next large section of the Introduction will deal with how motor development can relate to social cognition. Here, the theory of embodied social cognition will be presented, with a specific focus on the mirror neuron system hypothesis. The infant mirror neuron system is assessed in Study II. In the last section of the Introduction I will discuss how impairments in motor development can relate to atypical social and cognitive development. This section will start with an overview of neurodevelopmental disorders that present with motor issues. After that the text will focus specifically on autism spectrum disorder, serving as motivation for Study III. After the presentation of the three empirical studies, including a Methods section, a General discussion section will follow.

Motor prediction

From birth, infants are prepared for and equipped with abilities to make sense of and to take an active part in the dynamic world around them. This entails predicting events and timing actions accordingly. Without the ability to make predictions about upcoming events, our actions would constantly be lagging behind (von Hofsten, 1983, 2014). To plan and execute an action takes time, and due to the internal processing lag of the sensorimotor system, prediction is essential. Several studies have assessed predictive ability in infants concerning motor tasks. von Hofsten, Vishton, Spelke, Feng and Rosander (1998) found that six-month-olds require at least 300 ms to adjust their reaching trajectory for an object that suddenly changed direction. Berthier and Robin (1998) found that reaching adjustments to shifts in object position required 250-400 ms of reprogramming in seven-month-old infants. If one is unable to compensate for this lag, then timing will be reactive, resulting in unsuccessful reaches, deteriorated motor ability and problems interacting with both physical objects and socially with others (Cattaneo et al., 2007; Schmitz, Martineau, Barthélémy, & Assaiante, 2003; von Hofsten & Rosander, 2012).

Prospective/predictive motor control (commonly used as synonyms in the literature, but see Ledouit, Casanova, Zaal, & Bootsma, 2013) can be seen as a necessary integrated part of predictive ability, allowing us to compensate for the internal processing lag. In this thesis I will use the term prospective (motor) control. This concept can be defined as the ability to adjust one's actions with respect to task demands and action goals in a predicate manner (von Hofsten, 1993a). This entails 'on-line' monitoring of ongoing actions, where actual sensory input is compared to predicted input to allow for rapid detection and correction of eventual errors (see the section on computational models below). Prospective control of action is reliant on constantly incoming perceptual information to anticipate the consequences of future actions and to predict what will happen next (von Hofsten, 1993a). Perception and action are linked together in a continuously evolving loop (often called perception-action coupling), since every movement is accompanied by perceptual feedback. Many types of visual, vestibular and proprioceptive information would not exist without movement (Adolph & Berger, 2006). Reciprocally, the motor system uses this feedback in planning of the next action step. Perceptual feedback from ongoing movements thus creates the possibility of prospective control. Acquisition of prospective control is a key aspect of motor development (von Hofsten, 1993a, 1997, 2004), and through this ability we are able to interact in a seamless and predictive way with our environment.

A computational model of motor prediction

In recent years, studies of motor systems in typically developed adults have resulted in sophisticated computational models of the different control and feedback processes in the brain required to make simple, everyday movements. Here, the computational model of motor prediction put forward by Daniel Wolpert and colleagues will be presented as a theoretical framework that can be used to formalize the function of motor prediction (Davidson & Wolpert, 2005; Wolpert & Flanagan, 2001; Wolpert, Ghahramani, & Jordan, 1995; Miall & Wolpert, 1996; Wolpert, 1997; Wolpert & Ghahramani, 2000).

The idea that we predict the consequences of our motor commands has emerged as an important theoretical aspect of motor prediction (Wolpert & Flanagan, 2001). Based on theoretical and computational studies, it has been suggested that the central nervous system internally simulates the behavior of the motor system in planning, control and learning. Such "internal forward models" are causal representations (or mimics) of the motor system that uses the current state (e.g. the location of joints and velocities) of the motor system in combination with information on motor commands to predict a future state (Miall & Wolpert, 1996; Wolpert, 1997). Wolpert and colleagues (1995) developed a forward model for internal feedback that specifically fits the concept of motor prediction through sensorimotor integration, called the *Kalman filter model for sensorimotor integration* (see Figure 1). This model combines information from sensory signals with that of already executed motor commands in order to make reliable predictions concerning the body's state (which is fundamental for motor control). A model like this can handle the feedback delay present in most sensorimotor loops (see discussion above), thus preventing instability and lagging in the system (Wolpert & Flanagan, 2001; Wolpert et al., 1995).

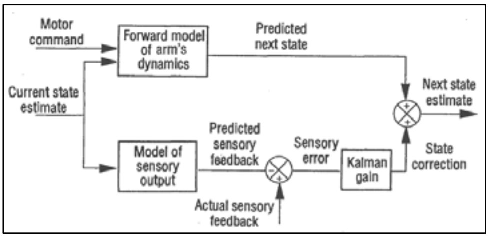

Figure 1. A schematic presentation of the Kalman filter model (Wolpert et al., 1995). The model consists of two processes. The upper half (internal simulation) uses the current state estimate and the motor command to create a state estimate using the forward model (in this case of arm dynamics). The lower part (sensory correction process) uses the difference between expected and actual sensory feedback to correct the forward model state estimate. [From Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science*, *269(5232),* 1880–1882. Reprinted with permission from AAAS.]

In Figure 1 the specific input of arm dynamics was used. The incoming motor command is from arm movements, and there is also input from sensory feedback, coming from vision and proprioception. The output is an estimate of where the next state of the arm should be. A so-called Kalman filter is used, which is a system or a model that produces an estimate for the location of a limb using both the motor outflow and sensory feedback together with an internal model of the motor system (Wolpert et al., 1995). The sensory error, i.e. the difference between actual and predicted sensory feedback, is used to correct the state estimate resulting from the forward model. So in this way, using available information from both motor commands and feedback from sensory systems, reliable motor predictions can be accomplished. The model also allows for rapid detection and correction of eventual errors.

There is evidence of widespread access to forward models in the motor system. For example, systems responsible for oculomotor control and mental imagery have been shown to have access to forward models of arm dynamics (Davidson & Wolpert, 2005). Moreover, prediction is not only essential for control of one's own actions, it is also fundamental for higher-level cognitive functions including action understanding and social interaction (Gredebäck & Falck-Ytter, 2015). Wolpert and colleagues (Wolpert & Flanagan, 2001; Wolpert, Doya, & Kawato, 2003) suggest that the concept of internal forward models can provide a general framework for prediction in all of these domains, even though it would mean predicting the sensory outcome of an action without actually performing it (cf. the mirror neuron system).

To summarize, motor prediction entails anticipating or foreseeing the next action step, either your own or another individual's. Prospective motor control is a necessary and integral part of motor prediction. Motor planning is a concept related to motor prediction, which involves considering whole action sequences, mostly before the reach is initiated. Internal forward models are computational representations of prospective motor control that can be used as a theoretical framework to explain the functionality of motor prediction. Models like these are based on studies performed on adults. However, given the importance of motor prediction for typical action development, it is interesting to consider how these mechanisms or models might support the development of early prospective motor control.

The development of manual motor behavior

Already from very early in their development, infants' own movements can be seen as actions (von Hofsten, 1993a). Actions are purposeful and contextualized movements performed by a motivated individual. Infants' actions are structured around goals and oriented into the future (von Hofsten, 1997, 2004). Even before birth, fetuses engage in clear actions (Myowa-Yamakoshi & Takeshita, 2006). At birth, the neonate's behavior is already quite rich and varied. Newborns will actively work to keep their hand in the field of view, even counteracting external forces (van der Meer, van der Weel, & Lee, 1995). van der Meer (1997) also showed that in a dimly lit room, infants who are only ten days old would work to keep their hand positioned in a narrow beam of light. The infants monitored the position of the light beam and moved their hand to keep it visible.

Historically, the way that human motor development is conceptualized has changed over time. During the first half of the twentieth century, 'maturationists' believed that the relatively uniform pattern of acquiring motor milestones in children was due to a gradually increasing maturation of the brain (Forssberg, 1999). This view implies that experience and training have little effect on motor development. In 1967, Bernstein introduced a systems approach to the study of motor control, arguing that coordinating an action involves the whole organism and has to be understood as a dynamic interaction between the organism and the external world. Bernstein's work was followed by Ester Thelen and colleagues, who introduced the dynamic systems theory (DST) of motor development (e.g. Thelen & Spencer, 1998; Thelen & Smith, 1996; Thelen, 1989). This theory proposes that movement is produced from the interaction of multiple sub-systems between person, task and environment. These sub-systems (e.g. muscle strength, environmental constraints, motivation) spontaneously self-organize with increasing experience to produce the most efficient movement solution for a specific task (Thelen, 1989). The DST approach ascribes an important role to experience.

In line with this, von Hofsten (1993a) argues that actions develop through actions. Spontaneous exploratory activity provides the infant with information about herself and her surroundings, and this knowledge is used in increasingly advanced action patterns.

So what does the development of reach-to-grasp actions look like in human infants? To start with, newborn infants do not grasp objects that are reached for. The movement of arms and hand are synergistically coupled at this age, such that the hand will open when the arm is extended (von Hofsten, 1993b). At around two months of age, this synergy begins to break up, and the hand is typically fisted while approaching an object (von Hofsten, 1984). Successful reaching and grasping for stationary objects appear around 12-18 weeks of age (Berthier & Keen, 2006). The hand is open during the reach and will start closing as the object is approached. The reach onset is associated with a more efficient organization of shoulder, neck and trunk muscles, which provide necessary postural stability (Forssberg, 1999). The onset for use of stereoptic vision is also important (see below). Infants' first goal-directed reaches are accomplished using whole-hand (ulnar) grasps, with all fingers closing in on the palm. The first reaches and grasps are typically jerky and crooked. Initial reach-to-grasp actions have been shown to contain several 'movement units' (von Hofsten, 1979, 1991), where reaching speed first accelerates and then decelerates within one unit. These movement units can also change direction slightly before the hand finally makes contact with the object. The number of movement units and direction changes decrease during the first months of active reaching, until the reaching movement is made up of only two movement units, the first one to approach the target and the second one to grasp it (von Hofsten, 1979, 1991). Number of movement units can be considered a measure of prospective motor control, with fewer movement units meaning better control (Cunha et al., 2015). During the second half of the first year, grasping becomes increasingly precise. Infants start using the fingers more, and toward the end of this period they master the pincer grasp and can then manipulate small objects (von Hofsten, 1993b). The onset of purposeful reaching significantly improves exploration and manipulation opportunities of the environment for infants (Lobo & Galloway, 2013).

Prerequisites for competent reaching

What factors are crucial for competent performance of reaching actions? A selection of the more necessary prerequisites for manual development will be presented here.

Postural control

As has already been noted above, in order to be able to perform spontaneous reaches, the muscles in the upper body need to be strong and wellcoordinated enough (Forssberg, 1999). Postural control is definitely an influencing factor in manual development (de Graaf-Peters, Bakker, van Eykern, Otten, & Hadders-Algra, 2007). Maintaining balance is not optional, and actions require a stable postural base. All actions provide challenges for body equilibrium by displacing the location of the entire body's center of gravity. In order to maintain balance, the inertial forces produced by movements need to be prospectively controlled (e.g. von Hofsten, 1993a, 2004; Witherington et al., 2002), or one will fall over. Postural stability improves reaching performance as it facilitates more efficient strategies for reaching for and grasping objects (Bakker, de Graaf-Peters, van Eykern, Otten, & Hadders-Algra, 2010; Cunha et al., 2015; de Graaf-Peters et al., 2007). If an infant is given postural support, inklings of goal-directed reaching can be observed much earlier than otherwise possible, even in newborns (von Hofsten, 1982). Hopkins and Rönnqvist (2002) studied reaching behavior in six-month-olds who could not yet sit independently. When provided with support around the pelvic girdle and the upper legs, infants performed much smoother reaching movements (i.e. fewer and straighter movement units) and the head was also more stable. Moreover, Spencer, Vereijken, Diedrich and Thelen (2000) concluded from longitudinal data that postural control of the head and upper torso was an important precursor to the onset of reaching.

Vision and proprioception

In order to grasp an object successfully, you not only need information about the target itself (e.g. its size and position), you also need information about where your own hand and arm are in relation to your body and in relation to the object to be reached for. Vision can give detailed information about the position and orientation in space of a manual target (before the time of touch), whereas proprioception (the sense of the relative position of neighboring parts of the body) provides means for defining the position and movements of the hands and arms relative to the body, without the influence of vision. It has been argued that a reach-to-grasp action can be divided into two phases (Jeannerod, 1981). During the first phase (reach), the hand is transported to the vicinity of the target. Vision is used during this first part of the reach to define the position of the object in reaching space, while proprioceptive feedback guides the movement of the arm. During the second phase (grasp), vision is used for defining both the position of the object and guiding the hand once it enters the visual field (von Hofsten, 1993b). Proprioception is used for reaching in the dark, something that infants are capable of at the same time as they reach successfully under light conditions (Clifton, Muir, Ashmead, & Clarkson, 1993). Thus, the 'feel' of the hand and the arm as they move in relation to the body and reaching targets is an important factor for efficient reaching.

Eye-hand coordination

Another important factor is the concept of eye-hand coordination. Following from the fact that vision is used for guiding a reach once it has entered the visual field, eye-hand coordination is essential for visually guided reaching. In a seminal study, von Hofsten (1982) was able to show that even newborns exhibited a rudimentary form of eye-hand coordination as they more frequently performed forward extended arm movements while fixating a target compared to when they were looking elsewhere or had their eyes closed. The movements were also aimed much closer at the target during visual fixation. Several studies have shown that infants prefer to look at their own hands (e.g. van der Meer et al., 1995; van der Meer, 1997), and this allows for necessary practice for effective eye-hand coordination.

Stereopsis

In order to plan and execute a reach effectively, access to depth and distance information is critical. Stereopsis or binocularity is a very important factor for judging depth, mainly due to binocular disparity (i.e. the difference in image location of an object seen by the left and right eyes, resulting from the eyes' horizontal separation). The brain uses binocular disparity to extract depth information from the two-dimensional retinal images in stereopsis (Birch, 1993). Visually guided reaching utilizes relative depth information, where the position of the hand relative to the object must be seen for the correction of the reach (von Hofsten, 1977). Monocularity in adults leads to greater perceptual uncertainty, resulting in longer reach durations and larger end-point variance (Loftus, Servos, Goodale, Mendarozqueta, & Mon-Williams, 2004).

Binocular perception is not present at birth. The onset of binocular interaction in the human visual cortex occurs between 10 and 16 weeks of age in most infants (Birch, 1993; Braddick, 1996). As noted above, this is about the same time as the occurrence of reach onset. Soon after the onset of sensitivity to binocular information, infants begin to use binocular information to guide reaching (von Hofsten, 1977). Only a few studies have systematically examined the effects of monocularity in infants. When reaching for stationary objects, infants judge distance and object size more accurately in binocular than monocular viewing conditions (Braddick, Atkinson, & Hood, 1996; Granrud, Yonas, & Pettersen, 1984). For example, when presented with a small reachable object and a large out-of-reach object, five- and seven-month-olds reached for the closer, smaller object in binocular but not monocular viewing conditions (Granrud et al., 1984). From the infant's point of view, the visual angles to the objects were identical, and thus in the monocular condition, the objects appear to be equally reachable because of lack of additional distance information.

What is the role of binocular information for catching moving objects? Motion information improves peripheral vision (Finlay, 1982), and therefore it is also conceivable that motion improves monocular vision as a larger part of the visual field is in the periphery under this condition. Between three and eight months of age, infants increasingly rely on binocular information to control the timing of interceptive arm movements (van Hof, van der Kamp, & Savelsbergh, 2006). Infants produced more reaching attempts for objects viewed binocularly than those viewed monocularly. Latency to initiate reaching and movement time increased in monocular conditions, and infants produced fewer reaching attempts. Thus, binocular viewing enhanced the spatial accuracy of the interceptive arm movements at all ages studied. Van Hof and colleagues (2006) conclude that attunement to binocular information is a key process in infants' prospective control of goal-directed arm movements.

Motor prediction

As was outlined above, one very important prerequisite for efficient and correct reaching is motor prediction. The results of the study by van der Meer (1997), where neonates actively kept their hand positioned in a beam of light, can be seen as evidence for early prospective motor control since the infants slowed down their hand movement before the hand arrived in the light beam, rather than when they could first see it. von Hofsten and Rönnqvist (1988) studied reach-to-grasp actions for stationary objects, both in adults and in infants at various ages. They found that both adults and infants start to close their hand around a target well before they make contact with the target, and also that the timing of starting to close the hand is task dependent. The hand started to close earlier around a smaller object. Lockman, Ashmead and Bushnell (1984) studied whether infants at five and nine months of age will prospectively rotate their hand into an appropriate orientation in order to grasp a horizontally or vertically oriented dowel. It was found that nine-month-olds make this reorientation of their hand before tactual contact with the object, whereas the younger infants did so reactively, i.e. after tactual contact (but see von Hofsten & Fazel-Zandy, 1984). Six-month-old infants have also been shown to be able to adjust their reaching speed in anticipation of object contact (Clifton, Rochat, Robin, & Berthier, 1994). These predictive abilities are evident also in the early stages of an action sequence. Claxton, Keen and McCarty (2003) showed that 10-month-old infants reach faster for a ball if they plan to throw it into a tub (less demanding task) as compared to fitting it into a narrow tube (more demanding task).

The importance of motor prediction becomes particularly obvious concerning actions performed on moving objects. In order to catch a moving object, it is necessary to predict the upcoming course and speed of the object to intercept its path (Ledouit et al., 2013; von Hofsten, 1980). Studies on infants' ability to catch moving objects have shown that infants begin reaching for moving objects at about the same age as when they reach for stationary ones, and this reaching is of comparable effectiveness and accuracy as for stationary objects. von Hofsten and Lindhagen (1979) were the first to show that already at 18 weeks, infants can catch an object moving at 30 cm/s. By eight months of age, this skill has developed so that infants can catch an object moving at 120 cm/s (von Hofsten, 1983). These reaches are aimed ahead of the object's current position, in order to intercept and contact the object further down its movement trajectory (von Hofsten, 1980). von Hofsten, Vishton, Spelke, Feng and Rosander (1998) studied the ability for predictive reaches in six-month-old infants, and found that they were able to extrapolate the movement of objects on linear paths, and reach prospectively for them. Of importance with regard to action understanding, prediction of others' actions will be dealt with in more detail in the section on embodied cognition below.

Of course, none of the above-described factors or prerequisites for efficient reaching can be viewed in isolation from one another. Rather, they work together, and are dependent on one another in order to produce smooth, well-timed and precise reaching actions.

The relation between motor development and (social) cognition

Infants gather information about their environment, both regarding objects and other individuals, through active exploration. These basic explorative behaviors have far-reaching consequences for infants' future development. On several occasions the importance of motor actions for cognitive, social and communicative proficiency have been stressed (Campos et al., 2009; Diamond, 2000; Gredebäck & Falck-Ytter, 2015; Iverson, 2010; von Hofsten, 2004, 2007). It is argued that cognition and actions are mutually dependent and that cognitive development, both mental and social, has to be understood in the functional perspective provided by actions (von Hofsten, 2007). Concerning the acquisition of language, Iverson (2010) argues that the emergence of new motor skills (e.g. reaching, self-produced locomotion) changes infants' experience with objects and people, and that the increasing amount of opportunities to interact with the environment sets the stage for language development. Empirical evidence is starting to accumulate that shows how early motor skills affect subsequent cognitive and social development. Concerning cognitive development higher motor activity at two to five months of age has been associated with a larger attention span at 13 months (Tamis-Lemonda & Bornstein, 1993), and the amount of self-sitting and manual exploration experience has been shown to facilitate 3D object completion (Soska, Adolph, & Johnson, 2010). With regard to social development, the onset of independent walking has been found to increase active social engagement by the child (Clearfield, Osborne, & Mullen, 2008), and also alter how mothers respond to object sharing bids from the child, with more encouragements to act on objects presented by walking infants (Karasik, Tamis-Lemonda, & Adolph, 2014). Action experience has also been shown to influence our perception of other people. Following active reach training using 'sticky mittens', three-month-old infants changed their patterns of visual exploration by looking more at the face of a presented actor as compared to infants who only received passive training (Libertus & Needham, 2010, 2011). Research like this demonstrates that there is undoubtedly a close link between action and perception of the physical as well as the social world, a coupling that was also proposed already by Gibson (1979) in his theory of ecological psychology.

Embodied cognition

The idea that actions are of great importance to psychological development fits well with the concept of embodied cognition (sometimes also referred to as grounded cognition). More classical accounts of human cognition stress the importance of abstract information processes, where computation of symbols separate from the brain's modal systems (perception, action and introspection) constitute cognition (Barsalou, 2008). As opposed to this view, proponents of embodied cognition emphasize the contribution of action and perception to cognitive processes. Thus, cognitive mechanisms are considered as shaped by bodily interactions with objects in the environment, and also with increasing experience of performing own actions. There are different types of embodied cognition, but common for most accounts is the focus on simulation processes (Decety & Grèzes, 2006; Gallese & Sinigaglia, 2011; Goldman, 2006). (For a recent comparison between different embodied cognition theories, see [Gentsch, Weber, Synofzik, Vosgerau, & Schütz-Bosbach, 2015]). Simulation can be defined as 'the re-enactment of perceptual, motor and introspective states acquired during experience with the world, body, and mind' (Barsalou, 2008, p. 618). The role of simulation mechanisms is especially pronounced in theories concerning human social cognition. Actions performed by other individuals are a category of stimuli of great importance to humans. Without an understanding of other people's actions, socialization would be impossible (Gallese, Keysers, & Rizzolatti, 2004). Briefly put, social simulation theory (also referred to as action resonance theory) assumes that observers represent other people's actions and minds using simulations of their own actions and minds (Barsalou, 2008; Gallese et al., 2004). Accordingly, visually perceived kinematics of others' actions are mapped onto corresponding motor representations in the observer. This information thus 'resonates' with the observers motor system, as if the observer was acting herself/himself (Iacoboni & Dapretto, 2006; Rizzolatti, Fogassi, & Gallese, 2001; Rizzolatti & Craighero, 2004). It is assumed that observers are able to understand[1] others' actions by activating and re-enacting own perceptual and motor states. Mirror neuron circuits typically underlie social simulation theories (Barsalou, 2008). The idea that simulation processes in the motor system (i.e. the MNS, see below) could underlie social cognition has added a neurophysiological level to the embodied account (Gallese & Sinigaglia, 2011; Rizzolatti & Craighero, 2004).

Although influential, it should be noted that embodied accounts are by no means undisputed. Alternative (non-embodied) accounts include, for example, teleological reasoning ideas, which assume that the principle of rational actions is what helps humans encode goals (e.g. Gergely & Csibra, 2003), and statistical learning accounts, which emphasize the importance of statistical regularities for action understanding (e.g. Aslin & Newport, 2012).

If we can learn to understand the goal of other people's actions, we can also learn to predict them. Several studies have shown that motor activity registered during action observation is predictive, starting before the action is completed, both in adults (Kilner, Friston, & Frith, 2007; Kilner, Vargas, Duval, Blakemore, & Sirigu, 2004), and in infants (Marshall, Saby, & Meltzoff, 2013; Nyström, 2008; Southgate, Johnson, El Karoui, & Csibra, 2010). The capability to make on-line predictions about likely outcomes of ongoing actions is paramount for a number of social cognitive abilities, for example coordinating one's actions with others, which is at the basis of human cooperative ability. The most dominant embodied account of action understanding and prediction, the mirror neuron system hypothesis, will be reviewed in more detail below.

The mirror neuron system hypothesis

There is a large body of research which indicates that others' actions are processed and predicted through activation of the observer's own motor system, and an assumed neural basis for linking production of own actions with perception of others' actions is the mirror neuron system (MNS). Here the evidence for the existence of a human MNS will be reviewed, followed by a section reporting on the connection between MNS activity and desynchronization of the mu rhythm.

Mirror neurons are a special class of visuomotor neurons, originally discovered about 20 years ago in the so-called area F5 of the macaque monkey premotor cortex (di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992;

[1] Here I refer to action understanding as recognizing what the goal of a reach is, not as encoding the purpose of the goal of the action (cf. teleological reasoning). That is, action understanding in terms of understanding the *what*, but not the *why* of the action. See also General discussion.

Gallese, Fadiga, Fogassi, & Rizzolatti, 1996; Rizzolatti, Fadiga, Gallese, & Fogassi, 1996). Using single-cell recordings, it was found that these neurons discharged both when the monkey performed an action, but also in a similar way when the monkey simply observed the same action. It was estimated that about one third of the motor neurons used for grasping also showed these mirroring properties (Rizzolatti et al., 2001). The monkey area F5 consists of two classes of visuomotor neurons, 'canonical neurons', which fire in response to self-performed actions, and are triggered by presentation of graspable objects, and 'mirror neurons', which respond when the monkey performs or observes object-related actions (Rizzolatti & Craighero, 2004). Mirror neurons do not discharge in response to simple object presentation; in order to be triggered they require an observed action (Rizzolatti & Arbib, 1998).

After the discovery of the MNS in monkeys, a vigorous search for the human homologue of the monkey area F5 started. Since single-cell recordings are not feasible in humans for ethical reasons, almost all human findings come from behavioral or neural population studies (but see Mukamel, Ekstrom, Kaplan, Iacoboni, & Fried, 2010), where larger groups of mirror neurons are assumed to increase the activation in a brain area. Activation like this can be measured using a variety of neuroimaging techniques, such as EEG, MEG, TMS, fMRI and PET. Previous studies have shown that the observation of actions made by others activates a complex brain network in humans. MNS activity has primarily been found in the ventral premotor cortex (Broadmann area 44), the inferior parietal lobule and in the superior temporal sulcus (Molenberghs, Cunnington, & Mattingley, 2012; Rizzolatti & Craighero, 2004). Together, these regions form the core of the human MNS. In addition, there are studies which suggest that the human MNS also resides beyond the more classical fronto-parietal mirror circuit, also including for example the primary somatosensory cortex and the superior parietal lobule (Molenberghs et al., 2012; Mukamel et al., 2010). Common for these areas is that they all show overlapping activation during both executed and observed actions, characteristic of the MNS.

Luciano Fadiga and colleagues provided the first demonstration of a MNS in humans in 1995. By measuring motor evoked potentials (MEPs) in arm and hand muscles, they confirmed their hypothesis of a selective increase in the MEPs when the participants observed various actions performed by an experimenter. The same hand muscles in the participants were activated while observing actions that they would normally use for performing the actions themselves (Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995). It was concluded that there is a system in humans that matches action observation and action execution, and that this system resembles the MNS described in the monkey. In a similar vein, using EEG, Cochin, Barthelemy, Roux and Martineau (1999) showed that the motor and frontal cortex are specifically activated during both observation and activation of finger movements. They drew the conclusion that observation and execution of movement share the same cortical network. Using single-cell recordings in epilepsy patients, Mukamel and colleagues (2010) showed that while observing and executing grasping and facial expression actions, there were cells in the medial frontal and temporal cortices that fired in a similar way during both the observation and execution conditions. This study provides what is the currently most direct evidence that there are 'mirroring' cells in the human brain. The studies just described and many subsequent ones have given solid support for the supposition that there is indeed a MNS present in the human brain (e.g. Avanzini et al., 2012; Cannon et al., 2014; Fadiga, Craighero, & Olivier, 2005; Grèzes & Decety, 2001; Hari et al., 1998).

One special property of mirror neurons is that they become more activated when the observer's view reaches toward an object compared to hand movements that do not have a clear goal, for example just extending the hand into thin air (Lepage & Théoret, 2006; Muthukumaraswamy, Johnson, & McNair, 2004). Thus, mirror neurons appear to be specifically related to goal-directed actions, such as precision grips, rather than simple body movements (Muthukumaraswamy & Johnson, 2004a). This aspect of mirror neurons is shared between the human and the monkey system, but there are also differences. The human MNS has been shown to be activated not only when the action is directed toward a physical object (transitive movement), but also when the observed action is an abstract gesture (intransitive movement), for example the mimicking of an action (Rizzolatti & Craighero, 2004; Warreyn et al., 2013). The macaque MNS, however, is only activated by transitive movements.

Due to its unique properties of being activated in a similar way during both production of own actions and observation of others' actions, the MNS has been suggested as lying at the core of human social cognition. The MNS can be argued as constituting the neural base for assumed embodied processes linking action with perception (Gallese & Sinigaglia, 2011). Above all, most of the performed studies on this subject have focused on the role of the MNS for understanding and prediction of others' (goal-directed) actions. In addition, the MNS seem to be specifically tuned to stimuli that have social relevance. Oberman, Pineda and Ramachandran (2007) showed that the MNS was most strongly activated when participants observed actions where social interaction was shown, compared to a condition where individuals were moving in a similar way (tossing a ball) but not interacting with each other. The quite revolutionary idea that humans have a special brain system for understanding others has led to the attribution to mirror neurons of a large variety of social skills, including more high-level functions such as imitation (Buccino et al., 2004; Iacoboni et al., 1999), empathy (Gallese et al., 2004; Schulte-Ruether, Markowitsch, Fink, & Piefke, 2007) and language development (Rizzolatti & Arbib, 1998). However, it needs to be pointed out that these suggestions of possible functionalities of the human

MNS are still a matter of controversy, and it has been argued that the more broad inferences drawn from some MNS research depend on speculations that reach too far beyond actual empirical evidence (e.g. Dinstein, Thomas, Behrmann, & Heeger, 2008; Hickok, 2009).

The developing mirror neuron system

To date, our understanding of the infant MNS and how it develops has been relatively poor. Studying this topic in infants and children is important, since it can shed light on the ontogeny of mirror neurons. Is the system innate (Lepage & Théoret, 2007) or does it develop in accordance with the mastery of an increasing number of motor skills (Hunnius & Bekkering, 2014; Kilner & Blakemore, 2007)? This question still remains unanswered and is the subject of heated debate. The motor resonance theory implies that in order to 'mirror' someone else's actions in your own motor cortex, a correspondent representation of that action needs to exist. On several occasions it has been shown that the amount of MNS activation during action observation is modulated by the observer's own motor experience, both in adults and in children (Aglioti, Cesari, Romani, & Urgesi, 2008; Calvo-Merino, Glaser, Grèzes, Passingham, & Haggard, 2005; Cannon et al., 2014; van Elk, van Schie, Hunnius, Vesper, & Bekkering, 2008; Woodward & Gerson, 2014).

Due to the inherent difficulties in using brain imaging techniques in children, most of the evidence supporting the existence of an infant MNS comes from indirect behavioral studies, such as eye-tracking recordings. The recording of predictive eye movements has been extensively used as indirect support for the usage of corresponding motor plans when performing as well as observing actions. The underlying rationale for these studies comes from the seminal results of the study by Flanagan and Johansson (2003), demonstrating that gaze patterns during action observation are very similar to gaze patterns shown during action execution. It is well established that during execution of manual reaches, both adults and children fixate the goal of the reach before the hand arrives there (e.g. Johansson, Westling, Backstrom, & Flanagan, 2001; Rosander & von Hofsten, 2011). Hence, the same predictive gaze patterns are also used when watching someone else performing the same actions, but not when the object is self-propelled (Falck-Ytter, Gredebäck, & von Hofsten, 2006; Flanagan & Johansson, 2003). Falck-Ytter and colleagues showed movie clips of an actor placing balls into a bucket to adults and six- and 12-month-old infants. Adults and the older infants looked predictively at the bucket before the hand transporting the ball arrived there, while the six-month-old infants tracked the hand reactively. Six-month-old infants do not yet have the capacity to place objects into containers. Provided that paradigms like these reflect the recruitment of the MNS in action anticipation, this result lends further support to the idea that the ability to predict other people's actions is a function of one's own motor repertoire. Similarly, subsequent studies have shown that at six months of age, infants are indeed able to anticipate more simple reaching actions that they can manage themselves (Ambrosini et al., 2013; Kanakogi & Itakura, 2011), whereas four-month-old non-reachers are not (Kanakogi & Itakura, 2011).

Concerning neurobiological evidence of a MNS in infancy and early childhood, Lepage and Théoret (2006) recorded scalp EEG in children (mean age eight years) while they were observing as well as performing a goal-directed grasping task. This condition was compared to an intransitive action. Results showed that mere observation of the grasping task elicited a stronger response in the children's motor cortex as compared to the non-goal-directed action. Moreover, a few studies have tested the functional reactivity of the infant mu rhythm (see below) as an indicator of MNS activity in both action execution and action observation tasks. Southgate and colleagues (2009, 2010) performed two studies on nine-month-old infants, where they compared the desynchronization of the mu rhythm while the infants observed and performed a goal-directed reaching task. Significant activation over central-parietal scalp regions (consistent with the origins of the MNS) was found during action execution. Similarly, during action observation a small but significant activation in the same areas was observed as well. Marshall, Young, and Meltzoff (2011) found that 14-month-old infants showed a significant desynchronization of the mu rhythm over central electrodes both during execution of a button-pressing action and during observation of the same task. Similar results have been shown in infants and toddlers up to 30 months of age (Reid, Striano, & Iacoboni, 2011; Ruysschaert, Warreyn, Wiersema, Metin, & Roeyers, 2013; Southgate et al., 2010, 2009; van Elk et al., 2008; Warreyn et al., 2013). Data like these are generally interpreted as reflecting activation in the MNS. To date, the earliest neurophysiological evidence of an infant MNS comes from a study by Shimada and Hiraki (2006). Using near-infrared spectroscopy (NIRS) they showed that six-month-old infants had a similar level of oxygenated blood in motor areas (indicating more activity) during action observation as during action performance, and concluded that this activity was due to the activation of mirror neurons.

The mu rhythm as a measure of MNS activity

The first neurophysiological evidence of a system linking action production and action perception comes from studies showing that both observing and performing a certain action leads to a desynchronization or suppression of the human sensorimotor mu rhythm (Pineda, 2005). Originating from the sensorimotor cortex (Hari & Salmelin, 1997; Muthukumaraswamy & Johnson, 2004b; Nishitani & Hari, 2000), the mu rhythm consists of a special frequency band between 9-13 Hz (in adults) that shows activity in motor neurons (Hari et al., 1998; Oberman et al., 2005). At rest, the motor neurons spontaneously fire in synchrony, leading to large amplitude oscillations in the mu frequency band, which is shown as a clear signal in EEG recordings.

But if one moves or performs different actions, the activity within these neurons increases, and they start to fire asynchronously. The larger quantity of signals will cancel each other out, and thereby decrease the total power of the mu-band EEG oscillations (Hari & Salmelin, 1997; Oberman et al., 2005).

The mu rhythm interval overlaps with the alpha band (8-12 Hz in adults). However, alpha waves originates from the parieto-occipital region, and are strongest when the eyes are closed (Hari & Salmelin, 1997). Alpha waves are suppressed when the eyes are open and receive information on visual motion. Thus, the difference between the alpha and mu rhythm bands lies both in brain localization and functional response (Niedermeyer, 1997; Oberman et al., 2005; Pineda, 2005).

There are at least three reasons for associating the mu rhythm with the MNS. First, the mu rhythm originates from areas that are consistent with the locations of mirror neurons, and is suppressed both when a subject performs an action and observes someone else perform the same action. Second, similarly to mirror neurons, the mu rhythm is modulated by the goal-directedness of actions. In the studies by Muthukumaraswamy and colleagues (2004), EEG was used to measure the mu rhythm when participants viewed object-directed reaching compared to reaches into thin air. They found that the mu rhythm desynchronized during the former but not the latter condition (but see Warreyn et al., 2013) and it was argued that this desynchronization was specifically related to goal-directed actions (Muthukumaraswamy & Johnson, 2004a). Importantly, this further associates the mu rhythm with the MNS, which was earlier pointed out as being oriented towards goal-directed actions rather than just intransitive movements (Nyström, 2008). Third, no other known neural substrate can better explain the functional response and topography in the brain for the mu rhythm than the MNS (Oberman et al., 2005; Pineda, 2005). Indeed, several adult EEG studies have used suppression of the mu rhythm as an index of MNS activity (e.g. Avanzini et al., 2012; Cannon et al., 2014; Cochin, Barthelemy, Roux, & Martineau, 1999; Muthukumaraswamy & Johnson, 2004b; Oberman et al., 2007; Perry & Bentin, 2009). Notably, Braadbaart, Williams and Waiter (2013) performed sequential EEG and fMRI recordings to compare mu rhythm desynchronization with active brain areas, and found that putative mirror areas of the brain were indeed activated, but in combination with structures known to modulate motor preparation activities as well as visual input (i.e. cerebellum, left medial frontal gyrus, right temporal lobe and thalamus).

Of special importance to Study II, there are strong indications that the mu rhythm also exists in infants (Marshall et al., 2011; Reid et al., 2011; Saby, Marshall, & Meltzoff, 2012; Southgate et al., 2010, 2009; van Elk et al., 2008), but at a lower amplitude and slower frequency (~5-9 Hz) (Marshall, Bar-Haim, & Fox, 2002; Saby & Marshall, 2012; Stroganova, Orekhova, & Posikera, 1999). Very few studies have systematically assessed the infant mu rhythm, but Cuevas and collegues (2014) recently published a review paper concerning methodological considerations while measuring the infant EEG mu rhythm. Stroganova and colleagues (1999) found the mu rhythm to be 7.03 ± 0.47 Hz in eight-month-old infants. Similarly, in a longitudinal study, Marshall and colleagues (2002) argued that the 6-9 Hz band is a meaningful and useful frequency band to concentrate the infant mu rhythm to, from approximately five months of age and onwards into early childhood. The same authors suggest that the frequency of the mu rhythm increases with age until it stabilizes at around 10 Hz in early adolescence (Marshall et al., 2002). For quite some time it has been speculated that the development of the 'central rhythm' (6-9 Hz) in infants is associated with the development of new motor skills (Hagne, 1972; Smith, 1941). This speculation fits well with more recent work suggesting a functional relation between the infant central rhythm and the adult sensorimotor mu rhythm (Stroganova et al., 1999).

The relation between motor impairment and neurodevelopmental disorders

As has already been indicated in the section above, it is feasible to think that motor capacity, to some extent, could underlie both cognitive and social proficiency. If this is indeed the case, it becomes interesting to explore the possibility that motor impairments could lie at the source of different neurodevelopmental disorders (for a review on reaching actions in infants at risk, see de Campos, Rocha, & Savelsbergh, 2009), including disorders that do not have motor issues as core symptoms.

Motor disorders are defined in the fifth edition of the Diagnostic and Statistic Manual of Mental Disorders (DSM-5) (American Psychiatric Association [APA], 2013), as a new sub-category of neurodevelopmental disorders. The DSM-5 motor disorders include developmental coordination disorder, stereotypic movement disorder and tic disorders, including Tourette's disorder. These disorders include motor impairments as core symptoms, and will not be dealt with in more detail in this thesis. But there are also other disorders that include issues with motor performance, but where those impairments might not be a core symptom. These include, but are not limited to, Attention Deficit/Hyperactivity disorder (ADHD) and Autism Spectrum Disorders (ASD).

The remaining part of this section will deal specifically with the case of ASD. More precisely, the focus will be on motor impairments in individuals diagnosed with ASD, and also on infants at elevated probability for ASD due to inheritable factors. The reason for this focus is that even though motor impairment is not a diagnostic feature of ASD, it is a common problem within the diagnosis. There are also reasons to interpret motor issues as possibly underlying, at least in part, the social, communicative and cognitive difficulties that are at the heart of the disorder (Bhat et al., 2011; von Hofsten & Rosander, 2012a; Whyatt & Craig, 2013a). For example, Cook, Blakemore and Press (2013) revealed atypical movement kinematics in adult participants with ASD while they were swinging their arm in a sinusoidal movement. Interestingly, participants with the most deviant movement profiles had the most severe autistic symptoms, and these individuals were also more likely to class biological motion as 'unnatural', something that might lead to disrupted perception of others' actions. Iverson and Wozniak (2007) demonstrated clear correlations between delayed onset of early motor milestones, relative postural instability and delayed language development at 18 months in infant siblings of children with ASD. Similarly, Bhat, Galloway and Landa (2012) reported that 70% of infant siblings of children with ASD who presented with early motor delays subsequently exhibited communication delays. Of special importance to this thesis, a great deal of evidence also indicates that individuals with ASD specifically exhibit problems with motor prediction (see further discussion below).

Autism Spectrum Disorders

Autism spectrum disorders are a group of heterogeneous neurodevelopmental disorders characterized by early emerging impairments in social functioning and communication, as well as the presence of restrictive and repetitive behaviors (APA, 2013). ASD is one of the most common forms of developmental disability internationally, affecting around 1% of children (Centers for Disease Control and Prevention [CDC], 2014) and prevalence has also been increasing in recent years. One of the diagnostic features of ASD is its early emergence (symptoms must begin in early childhood), and detailed work using retrospective parental interviews and home videos show that children who go on to receive an ASD diagnosis express impairments in a range of skills already during the first year of life (Barbaro & Dissanayake, 2009). Early problems include (but are not limited to): social inattention (Chawarska, Macari, & Shic, 2013; Ozonoff et al., 2010), language delays (e.g. Iverson & Wozniak, 2007; Zwaigenbaum et al., 2005), problems with executive functioning (e.g. visual attention [Elsabbagh et al., 2011], regulatory control [Clifford, Hudry, Elsabbagh, Charman, & Johnson, 2013]) and motor issues (see below). However, the majority of children are diagnosed with ASD after the age of four (CDC, 2014; Mandell et al., 2010), which is late from a developmental perspective. Early detection and enrollment in appropriate intervention programs is important to improve functionality, as well as to reduce anxiety and aggression levels in children with ASD.

There is also a condition known as the broader autism phenotype (BAP). The BAP is a constellation of autism related features (e.g. language delays, social difficulties, rigid behavior) that appear at elevated, but subclinical, levels in family members (parents and siblings) of children with ASD (Bailey, Palferman, Heavey, & Le Couteur, 1998; Bolton et al., 1994). There is no mention of the BAP in DSM-5 (APA, 2013), which seems appropriate as this condition only involves some but not all features of ASD. Also, these features do not necessarily lead to functional impairments in major life domains. It is not clear when these differences in behavior first develop, but studies have suggested that the BAP can be detected by 12 months using standardized assessment (Ozonoff et al., 2014).

Comorbidity is very common in ASD. More than 70% of diagnosed cases have concurrent conditions (Lai, Lombardo, & Baron-Cohen, 2014). Concerning developmental difficulties, around 45% of individuals with ASD have intellectual disabilities, 28-44% have ADHD, and 14-38% have tic disorders (around 6.5% have Tourette's syndrome). Other common conditions include depression, anxiety and obsessive-compulsive disorder (Lai et al., 2014). It should be noted that "pure" diagnoses (i.e. without any comorbidity with other disorders) of any kind, are rare (Kadesjö & Gillberg, 2001).

Motor issues in Autism Spectrum Disorders

Adults and older children with ASD

Motor impairments are not part of the diagnostic criteria of ASD (APA, 2013), and are typically not considered a core feature of the disorder. However, it is now well established that motor problems exist within this population (Lai et al., 2014). For example, there is research to indicate that many school-aged children with ASD experience significant difficulties with balance, postural stability and timing of movements (Jansiewicz et al., 2006; Minshew, Sung, Jones, & Furman, 2004). The importance of mapping problems within the motor domain in autism becomes evident as it has been shown that motor ability is correlated with everyday living skills in autistic children (Jasmin et al., 2009).

Studies on adults have shown that individuals with ASD often display longer reaction times before starting a reaching movement as compared to typically developing (TD) controls (see e.g. Glazebrook, Elliott, & Lyons, 2006; Glazebrook, Elliott, & Szatmari, 2008). Dowd, McGinley, Taffe and Rinehart (2012) showed that young children with ASD had more variable reaction times, as compared to controls, when completing a point-to-point movement task. Motor execution problems (for example more twitching movements) have also been reported in autistic individuals. Forti and collegues (2011) found that the movement duration of preschool children with ASD was nearly twice as long as those of controls, when transporting and dropping a ball into a hole. The ASD group also made more movement corrections during transport. In a related study, Stoit, van Schie, Slaats-Willemse and Buitelaar (2013) recently showed significantly longer movement times in an ASD group as compared to TD controls when completing a reaching task. The authors suggested that these difficulties might originate from impaired internal feed-forward models. Mari, Castiello, Marks, Marraffa and Prior (2003) reported that reaching and grasping kinematics is executed in a successive non-overlapping manner in children with ASD, whereas control subjects coordinate the whole action in a more integrative style (cf. Jeannerod, 1981; von Hofsten, 1993b).

As pointed out above, individuals with ASD seem to display specific problems with prospective motor control of actions. When autism was first introduced as a syndrome, Kanner (1943) noted deficits in prospective postural control in children with autism. Further, in a series of experiments, it has been shown that individuals with ASD display reactive rather than prospective changes in muscle activity during load-lifting tasks (David et al., 2009; Schmitz et al., 2003). Schmitz and colleagues (2003) used a load-lifting task in autistic children and TD controls, where muscle activity in the arm holding the weight was measured using EMG. As predicted, during voluntary unloading, the TD children showed changes in muscle activity prior to unloading the weight, indicating a predictive response. However, the children with ASD had longer durations of unloading, and reactive, rather than predictive, changes in muscle activity. Moreover, it has been shown that interceptive skills might be impaired in children with ASD. Examination of performance on standardized motor test batteries has found distinct difficulties in the area of ball skills (Green et al., 2009), and in particular tasks related to catching (Whyatt & Craig, 2012). Whyatt and Craig (2013b) demonstrated that children with ASD caught a significantly lower number of rolling balls when compared to groups with difficulties with receptive language and non-verbal IQ, respectively. Access to sensory information (audio and visual) specifying ball arrival time was varied between conditions. It was argued that difficulties with picking up and making use of sensory information to guide the action might be the source of the problem with impaired interceptive skills in the ASD group (Whyatt & Craig, 2013b).

A reduced ability to prospectively plan own actions with respect to future goals has also been shown in autistic individuals. Motor planning involves considering whole action sequences, and not just the next step. In a series of studies, this has been examined using a grip selection task, where participants are asked to pick up a bar and rotate it into a predetermined final position. By changing the starting angle of the bar, participants are forced to choose between an, for the wrist, awkward start position but a comfortable end state, and vice versa. Hughes (1996) tested 36 children with ASD on this task, and found that in comparison to TD controls, the autistic children were more likely to end their movement with the uncomfortable posture, suggesting that they did not take the end position into account when planning their action (but see Hamilton, Brindley, & Frith, 2007; van Swieten et al., 2010). Using another type of design, Cattaneo and colleagues (2007) also showed impaired prospective planning skills in individuals with ASD. EMG was used to record muscle activity related to mouth opening during a sequence of actions in eight autistic participants and eight controls. The task was to grasp a piece of food and either put it in the mouth or in a container attached to the participant's shoulder. When the target was the mouth the TD participants showed muscle activation before even picking up the object, suggesting an early preparation for mouth opening. In contrast, the ASD participants only activated their jaw muscles after picking up the object. Similarly, Fabbri-Destro and colleagues (2009) showed that seven-year-olds with ASD do not reach faster for an object that is to be placed in a large container as compared to a small container in a subsequent step, whereas TD children do. This indicates failure in the ASD group to chain separate action parts together into a global action during motor planning.

Until recently, motor impairments as a potential diagnostic risk marker for autism have received relatively little attention. Now, several groups have reported data from retrospective home videos, where early home videos of children who have received an ASD diagnosis are coded for early signs of motor impairment (e.g. Adrien et al., 1993; Esposito & Venuti, 2008; Phagava et al., 2008). Teitelbaum, Teitelbaum, Nye, Fryman and Maurer (1998) reported severe motor abnormalities in the first six to nine months in infants later diagnosed with ASD. Ozonoff and colleagues (2008) compared 54 children with ASD to 25 children with developmental delay and 24 children with typical development. It was found that children later diagnosed with ASD and developmental delay were delayed in motor maturity compared to the TD children. More recent research by Esposito, Venuti, Maestro and Muratori (2009) showed qualitative differences in early motor functioning in ASD beginning in infancy, by applying rigorous measures of posture and movement to the analysis of early home videos. Finally, Brisson, Warreyn, Serres, Foussier, & Adrien-Louis (2011) used retrospective home videos to examine predictive mouth-opening during feeding in infants who went on to receive an ASD diagnosis. It was found that ASD infants between four and six months of age have a prediction deficit during spoon-feeding, and thus open their mouths reactively (after the spoon touches the mouth).

Retrospective work is valuable but suffers from many limitations, for example selective parental memory. Concerning videotaped events, researches will be limited to the assessment of overt behavior caught on tape. All they above-mentioned studies also focus on gross motor impairments, since video quality is frequently not good enough to assess fine motor qualities.

Infants at elevated risk for ASD

Prospective sibling designs are becoming increasingly popular in the search for early autism markers. Genetics has a key role in the aetiology of autism (Lai et al., 2014). About 50% of the risk for ASD is explained by genetic factors (Sandin et al., 2014). Due to its heritability factor, the probability for an ASD diagnosis in infant siblings of children with ASD is at least tenfold compared to the risk in the general population (Constantino, Zhang, Frazier, Abbacchi, & Law, 2010). In a large prospective study by Sally Ozonoff and colleagues (2011), 18.7% of infants' siblings developed ASD, and the recurrence risk further increased with the number of affected older siblings, as well as in male infant siblings. It should further be noted that up to 50% of infant siblings can develop ASD *or* autism related concerns (i.e. BAP) (Ozonoff et al., 2011, 2014). This makes longitudinal studies of infants at high familial risk for ASD a feasible design. In these designs, infant siblings of children with a confirmed ASD diagnosis ('high-risk', HR) are typically compared to a group of children with no familial risk for ASD ('low-risk', LR). Using prospective sibling designs, several diverse impairments in infancy, both behavioral and neurocognitive, have been suggested as indicative of a later ASD diagnosis. (For reviews of prospective studies of HR infants, see Jones, Gliga, Bedford, Charman, & Johnson, 2014; Zwaigenbaum, Bryson, & Garon, 2013).

Prospective studies of HR infants are now starting to shed further light on motor development as a potential risk marker of ASD outcome. Several groups have examined performance on standardized measures of motor development using prospective designs. One commonly used measure is the Mullen Scales of Early Learning (MSEL; Mullen, 1995), which contain scales for assessment of both gross and fine motor abilities. Landa and Garrett-Mayer (2006) found that children who went on to receive an ASD diagnosis had lower gross and fine motor scores compared to non-diagnosed children at 14 and 24 months, but not at six months. Similarly, Ozonoff and colleagues (2010) observed differences between HR and LR groups on the fine motor scale that became significant between 10 and 18 months. Leonard, Elsabbagh, Hill, and the Basis team (2014) could also report generally poorer performance in the HR group compared to LR controls on the MSEL motor scales, even as early as seven months. In a case series report by Bryson and colleagues (2007), four six-month-old infant siblings of children with ASD who were themselves later diagnosed with ASD, presented with limited motor control and coordination according to the Autism Observation Scale for Infants (AOSI; Bryson, Zwaigenbaum, McDermott, Rombough, & Brian, 2008).

Flanagan, Landa, Bhat and Bauman (2012) examined head lag during a pull-to-sit task in six-month-olds at familial risk for ASD. Head lag by six months is very uncommon in typical development (Bly, 1994). The results showed that 90% of the infants who went on to get an ASD diagnosis showed head lag at six months, as compared to non-diagnosed HR children where head lag at six months was only present in 43% of the infants. It was concluded that head lag during pull-to-sit is likely to be indicative of neurodevelopmental disruption, and may be associated with autism risk. In future work, it will also be important to explore whether this group difference is due to poor postural stability or low muscle tone, or if the ability of these infants to predict the experimenters actions in pulling the child to sit might be compromised, leading to failure of predictive postural adjustment.

Libertus, Sheperd, Ross and Landa (2014) used a combination of the Mullen Scales (Mullen, 1995) and a free-play assessment to examine differences between HR and LR groups concerning reaching and grasping actions in six- and 10-month-old infants. Results showed significantly lower scores on the fine motor scale of the MSEL in all HR subgroups (HR no diagnose, HR developmental delay, HR ASD) compared to the LR group. Raw item (T-scores) analysis of the fine motor scale showed that items concerning object manipulation were what started to separate the groups. In the follow-up, free-play context, the HR group showed reduced grasping and object-exploration activity at six months. However, by 10 months, the infants in the HR group had caught up with the LR group, showing the same level of performance. The authors conclude that the lower fine motor and grasping scores found in the HR group seem to be part of an ASD endophenotype, that is, it might be an example of a trait that occurs more frequently in affected as well as unaffected family members of a risk group than in the general population. One important limitation with this study is that even though the HR infants scored lower than the LR controls, their overall fine motor scores were still within the range of typical development for that particular age. Thus, the differences are subtle and probably involve qualitative aspects that are difficult to quantify using standardized tests.

There is growing evidence that there is a prodromal phase of autism, lasting through late infancy, when diagnostic signs are not yet clearly visible (Elsabbagh & Johnson, 2010). In sum, both retrospective and prospective studies of infants who went on to receive a diagnosis of ASD have shown that motor problems can be noticeable very early in development, making this a potentially effective early risk marker.

Summary of Introduction

This introductory section has provided an overview of how manual motor development is profound during infancy. The first section stressed the importance of motor prediction for efficient reach planning and execution. The following three sections demonstrated some central prerequisites for competent reaching development, discussed in what way motor development can relate to our understanding of others and, finally, discussed how motor deficits might be implemented in neurodevelopmental disorders, respectively. Hence, motor development is important from many different perspectives, not only considering kinematic profiles or reaching motor milestones. It also seems to matter for typical cognitive and social development. This is an area of research that is somewhat overlooked.

Aims of the thesis

The overarching aim of this thesis is to study manual motor development in infancy from different perspectives: first, through examining a prerequisite for efficient reaching development, more specifically stereopsis; second with regard to understanding others' goal-directed reach actions, through assessment of the mu rhythm as a measure of mirror neuron activation; and, third, in relation to possible atypical development, with a specific focus on ASD. The common denominator of the three studies is the notion that motor ability is a central component of many psychological processes and that motor prediction is a key factor behind execution and understanding of reaching actions. This aspect of motor control is present in each study.

The aim of Study I was to compare reach-to-grasp actions for objects under binocular and monocular viewing conditions. The study was motivated by the fact that effective action planning and motor prediction is reliant on sensitivity to depth and distance information. We studied whether and in what way a lack of stereopsis would affect reach-to-grasp actions in infants using a new spinning paradigm. By removing binocular information, using an eye-patch, we aimed to see how this would affect reaching in terms of time to object contact and number of reaching errors committed.

The main purpose of Study II was to see whether there is neural evidence of a MNS in human infants who observe a goal-directed reach action. We aimed show the existence of MNS activity in infants observing a reach action that they can master themselves. Concerning adults, there is a large body of research suggesting that other people's actions can be understood and also predicted by mapping them onto one's own motor representation of those actions. At the time of conducting the study, a few studies had also shown similar results in slightly older infants (Southgate et al., 2010, 2009; van Elk et al., 2008). Using EEG, we measured the desynchronization of the mu rhythm as a marker for MNS activity.

The aim of Study III was to assess the ability of infants at risk for ASD to prospectively control their own reach-to-grasp actions. Study III was motivated by the body of evidence showing that individuals with ASD demonstrate specific problems with prospective motor control of actions, and the fact that little is known about the precise nature of motor deficits in young children with ASD, and even less in infants at risk for ASD. Accordingly, we assessed prospective motor control in younger siblings of children with ASD while they were catching a moving object.

Methods

Participants

Two different procedures were used to recruit infants in these studies. In Studies I and II infants were recruited through the vital birth records in Uppsala, Sweden. Parents of infants at appropriate ages were contacted through a letter informing them about the research conducted at the Uppsala Child and Babylab, and describing the particular study. Interested parents (mainly northern European middle class families) replied to the invitation and appointments were set up by telephone. In both Study I and Study II, families received a gift certificate worth approximately 10 euros in gratitude for their participation.

For Study III a slightly different recruitment procedure was partly used. The infants who served as the low-risk control group were recruited using the same method as described for Studies I and II. However, only infants with a typically developing older sibling were considered for recruitment in order to match the presumptions of the high-risk group. The children who had an older sibling with a diagnosis of ASD were recruited through the longitudinal projects website (www.smasyskon.se), clinical units and advertisements. Concerning this group, most families were primarily from the greater Stockholm area in Sweden. More than 90% of infants in both the low- and high-risk groups had parents who were born in Sweden.

In Study I, the final sample consisted of 72 infants: 29 six-month-olds (*M* age = 6.07 months; 16 female), 19 eight-month-olds (*M* age = 8.33 months; 9 female), and 24 10-month-olds (*M* age= 9.96 months; 9 female). An additional four infants (three eight-month-olds and one 10-month-old) were tested but not included in the final sample because they completed less than 15 reaching trials. The three age groups were chosen based on the varying degree of reaching experience at those ages. All infants were healthy and without any known visual problems.

In Study II, 32 healthy eight-month-old infants (*M* age = 8.21 months; 18 female) were included in the final sample. Two infants were excluded due to fussing or inattention, and two infants were excluded due to technical problems. All infants were able to successfully grasp an object presented to them.

In Study III a total of 45 10-month-old infants were included in the final sample. The high-risk (HR) group consisted of 29 infants (*M* age = 10.1 months, 13 female), and the low-risk (LR) group consisted of 16 infants (*M* age = 10.3 months, eight female). One additional HR infant (female) did not perform any trials and was excluded before data analysis. The groups were comparable in terms of mental age (according to the Mullen Scales of Early Learning; Mullen, 1995), and socioeconomic background (calculated on the basis of parental education and income, equal weighting). Each infant in the HR group had at least one older sibling with a community diagnosis of ASD. Four infants in the HR group were half-siblings of the child with ASD. LR infants had no relatives (up to the second degree) with ASD. To match the HR group, we required all LR siblings to also have at least one typically developing older sibling. One LR infant only had an older half-sibling. All infants included in the sample were born full-term (>36 weeks), and did not have any known or suspected medical or developmental concerns (including visual/auditory impairments). Participants were part of an ongoing longitudinal study that follows infants from 10 to 36 months of age. Families received a 20-euro gift certificate per testing day in gratitude for their participation.

Regional ethical committees approved all these studies and the parents signed informed written consents upon arrival at the lab in accordance with the 1964 Declaration of Helsinki.

Apparatus and procedure

Studies I and III were behavioral studies of reach-to-grasp performance, and the analyses were performed through offline coding of video recordings. Study II was performed using high-density EEG (128 channels).

Study I

In Study I, we assessed the importance of binocular information for reaching in infants. Reach-to-grasp behavior was evaluated in a dynamic reaching situation where binocularity was manipulated by patching either the left or the right eye. Individual infants participated in both a binocular as well as a monocular condition. In the monocular condition, one of the infants' eyes was covered with an eye-patch (Master Aid's Ortopad), which eliminated binocular information and obscured the view of the "covered" side of reaching space. Which eye that was patched was counterbalanced across subjects. Every session started with the binocular condition, followed by the monocular condition. Each condition consisted of four blocks, with seven trials in each block, giving each infant a maximum of 28 binocular and 28 monocular reaching trials. Infants had to complete at least 15 trials with binocular vision and seven trials (i.e. at least one full block) with monocular vision to be included in the final analysis.

The apparatus consisted of an upright magnetic whiteboard (60×91 cm), which was clamped to a wooden table. 15 small toy targets were used as reaching stimuli, and were placed on the whiteboard at seven positions varying from 0-28 cm to the left and right of midline in 9.3-cm increments. The toys were approximately 5×5×4 cm in size and had magnets affixed to their backs that allowed for easy attachment to and removal from the magnetic board. Two experimenters ran the study: the primary experimenter sat opposite the board and administered a spinning procedure (see below); the second experimenter was hidden behind a screen and placed the targets on the board at predetermined positions when the infants' back was facing the board.

Infants sat in their parent's lap on an office swivel chair in front of the board. Parents were instructed to sit with their infants far out on their laps, to provide postural support by holding their child's hips, and to close their eyes before spinning around to face the board in order to limit their influence on infants' reaching. The second experimenter placed toys at infants' chest level, 9 to 12 cm perpendicular in distance from the center of the board. A few warm-up trials were run before the start of the actual experiment to confirm that infants understood the spinning and reaching task and to ensure that they were able to reach the toy at the extreme end positions.

At the start of each trial, the parent and infant faced away from the board toward the primary experimenter. The experimenter then spun the chair 180° to a position straight at board midline. The 180° spinning action took approximately two seconds (90°/second). Turn direction and object location were counterbalanced in the task, such that infants were presented with objects on the right and left side of the reaching space while rotating both in the clockwise as well as the counterclockwise direction. Infants were free to start reaching for the toys as soon as they began turning around. Infants were given approximately 10 sec to reach for the toy before the chair was spun away from the board, again facing the primary experimenter. Sessions lasted approximately 20 minutes.

Two digital cameras recorded the infants' manual actions. One camera, suspended above the whiteboard, recorded the actions from an overhead view. A second camera presented a side view from the right of the board. The side view camera had a wide-angle lens and presented a full view of infants' bodies. The two camera views were mixed together online onto a single synchronized video frame for later offline coding of the reaching behaviors. Figure 2 shows the experimental setup from the two camera views.

Figure 2. Still photo from the experimental setup showing an infant grasping a target toy positioned 28 cm from midline. The upper side of the whiteboard had markings of the pre-specified intervals where the toys were placed.

Study II

In Study II, we investigated mu rhythm desynchronizations in a group of eight-month-old infants. The study was performed using three conditions in a within-group design. The three conditions consisted of a baseline condition where the model sat passively for approximately four seconds (static condition), as well as two manual action conditions. In the first action condition (goal-directed action), the model grasped a toy train and moved it to the highest point of a short railway track. In the other action condition (non-goal directed action), the model simply placed his/her open hand on the table (see Figure 3). Except for the very first condition that for practical reasons was always a goal-directed action, these conditions were presented in randomized order by sometimes interleaving the static condition and sometimes not, or presenting the goal-directed or non-goal-directed conditions twice before proceeding to any of the other conditions.

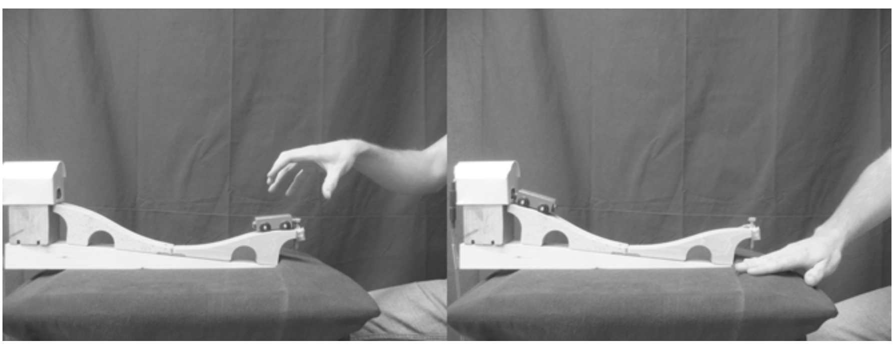

Figure 3. Example of models actions from the infants' viewpoint. Left: goal-directed action. Right: non-goal-directed action.

After measurements of the infants' skull, a high-density 128 channels EEG net (EGI Corp., Eugene, Oregon) of the appropriate size was applied to the infants' head, and adjusted with the reference electrode placed at vertex. The placement of the net usually took less than two minutes. The infants were then seated in a special baby seat (Bumbo Inc., South Africa) at approximately one meter from a scene where a live model demonstrated the three conditions. On a table, a short railway track with a toy train was placed (see Figure 3). This setup was used for presentation of the conditions. The three conditions were presented in a randomized order until the infants were no longer interested or started to fuss (range 10-49 presentations per event, M = 21.06; SD = 7.40). The model never presented any of the conditions unless the infants were attentive. Sessions lasted for approximately 15 minutes.

The EEG was time-locked by the model, using manual triggers hidden from the infants' view, when the hand either touched the toy or the table, or after approximately one second of sitting passively. The 128 EEG channels were sampled at 250 Hz, and an analogue hardware filter (EGI Netstation 3.5, Eugene, Oregon) band pass filtered the signal between 0.1 and 100 Hz during recording. The infants were videotaped using a small web camera that was placed on the table.

Study III

In Study III, we assessed whether and when the infants caught a ball that rolled toward them on a curvilinear path off an inclined tabletop.

Each infant was seated in a stable infant chair at a quadratic table (60×60 cm). The parent was seated right behind the infant. The experimenter was seated on the other side of the table across from the infant. This positioning allowed for interaction between the experimenter and the infant, and also for the experimenter to start the rolling motion of the ball toward the infant. Two toy rails were mounted on the tabletop as tracks, both from the left and right, for the ball to roll against (see Figure 4). The ball's diameter was four cm.

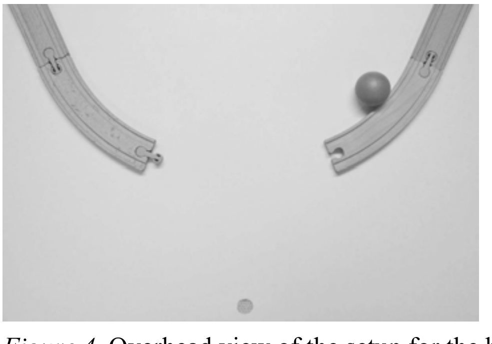

Figure 4. Overhead view of the setup for the ball-catching task.

At the start of each trial, when the infant was attentive, the experimenter let go of the ball at the edge of the tabletop on her side, and the ball started rolling toward the infant. The release of the ball was not accompanied by any type of social cue (e.g. vocalizing, facial expression change). The infant could watch the ball roll for approximately three seconds before the ball passed the rails and entered the reaching space (see definition below). The infant was free to initiate the reaching movement at any point. The trial was over when the infant either caught the ball or when it rolled off the table. Neither the experimenter nor the parent stopped the ball from rolling off the table. The study included two conditions, and was conducted using a within-group design. Two different inclination degrees of the tabletop were used, resulting in two different rolling speeds. The experiment always started with the slower rolling speed, at which the tabletop was inclined 2.8 degrees from the horizontal plane, resulting in a rolling speed of approximately 2.6 cm/sec when the ball entered reaching space (see Figure 9 in the section of the Results of Study III). In the condition with the higher speed, the tabletop was inclined 4.1 degrees, resulting in a rolling speed of approximately 3.6 cm/sec. The starting location of the ball (left or right side) was counterbalanced across trials. After a series of warm-up trials, where the infant became accustomed to the task, at least four trials with the slower rolling speed were presented, followed by at least four trials with the higher rolling speed. In total, each session lasted approximately 10 minutes. A video camera (Sony Handycam HD) was mounted above the table, recording a full view of the experimental setup, as well as the infant and the experimenter.

Since Study III is part of a longitudinal project, the particular experiment described here was conducted as part of a larger testing day. The ball-catching task was performed in the morning. The Mullen Scales of Early Learning (Mullen, 1995) was conducted with each infant by an experienced licensed psychologist to assess the infants' developmental level.

Data analysis

Study I

All recorded videos were coded offline using computerized video coding software (www.openshapa.org). A primary coder scored time to object contact (contact time), and reaching accuracy (number of contact errors) (dependent variables). Hand selection was also coded but will not be discussed in this thesis summary (see motivation under Study I). Contact time was defined as the time from when the chair stopped rotating at midline until the first contact with the object was made. Because infants were allowed to reach freely for the toy, even before the chair stopped rotating, contact time could be scored as either positive (contact with the toy was made after the chair stopped at midline, reactive reach) or negative (contact with the toy was made before the chair stopped at midline, predictive reach). A contact error was defined as the infant misjudging the position of the object on the board and contacting the board first with the same hand later used to contact the target. Interrater reliability was assessed on 25% of each infant's trials for the binocular condition and 50% of trials for the monocular condition, and concordance was very high (hand selection: $\kappa = .988$ ($p < .001$), contact error: $\kappa = .895$ ($p < .001$), contact time: $r = .998$).

Generalized linear models (GLIMs) with a logit link (e.g. Olsson, 2002) were used for the analyses. GLIMs are a broad class of statistical models that includes many commonly used models (including General Linear Models [GLM] which in turn include linear regression, analysis of variance and analysis of covariance). The classical applications of GLM rest on the assumptions of normality, linearity and homoscedasticity, whereas GLIM allow for modeling of data using other distributions than a normal distribution (Olsson, 2002). Reaching accuracy was treated as a binary variable (a contact error was made or not). In the analysis the infant was included as a random effect[2]. In addition, each combination of condition and block were also set as random effects. The fixed effects included condition, object position and rotation direction, along with all interactions. Age group was also treated as a fixed effect (constant within the age group). Post-hoc pairwise comparisons of least squares means[3] were adjusted for multiplicity using Tukey's method. Contact time was analyzed as a continuous variable using a mixed model approach. Subject and condition/block combinations were treated as random effects; condition, object position, age group, rotation direction, and all two-way interactions were used as fixed effects. The Glimmix procedure in the SAS (2008) package was used for the analyses. Two-tailed probabilities ($\alpha = 0.05$) were used.

Since each infant was exposed to multiple experimental conditions, mixed logistic models were warranted (Littell, Milliken, Stroup, Wolfinger, & Schabenberger, 2006). We used GLIM instead of traditional analyses of variance because each infant's useable trials were not distributed evenly across object positions, which can be accounted for with the mixed model approach. Moreover, since each infant was exposed to several trials in multiple conditions, performances on trials coming from one individual infant were likely to be more correlated with each other as compared to trial performances coming from another infant. Furthermore, ANOVAs do not allow the use of binary outcome measures.

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[2] A random effect is allowed to vary, and a fixed effect is constant across individuals (Kreft & de Leeuw, 1998). Fixed effects are estimated using least square means.

[3] Least square means are means that are estimated from a linear model. Least squares means are adjusted for other terms in the model (like covariates), and are less sensitive to missing data (Olsson, 2002).

Study II

After recording, the EEG data were transferred to the MATLAB v.7.2 environment and analyzed using the EEGLAB v5.03 toolbox. The data were re-referenced to an average reference and notch filtered (45-55 Hz) to remove line noise. The continuous EEG was then band pass filtered at 2-20 Hz to remove noise and to focus on the frequencies where most brain related signals appear. The data were then segmented into trials from one second before to one second after time-lock (touch of toy train or table, or after approximately one second of resting). A modified artefact rejection routine (removal of interpolation) for high-density EEG (Junghöfer, Elbert, Tucker, & Rockstroh, 2000) removed bad trials and sensors based on their maximum values, standard deviations and range values. After artefact rejection, where bad trials and channels were excluded from the dataset to prevent spreading of bad data when re-referencing, the data were transformed to average reference.

A natural-gradient logistic infomax independent component analysis (ICA) was performed on the data (the Runica algorithm, Delorme & Makeig, 2004), resulting in as many independent components as remaining channels minus one for each subject. ICA is a blind (i.e. used without the aid of information about the source signals or the mixing process) source separation technique that aims to find components that are most statistically independent of one another. However, ICA introduces a component selection problem, and it is of great importance to evaluate the quality of the ICA decomposition. In Study II this was done by visual inspection of scalp topographies, trial amplitudes and frequency spectrums from each independent component. After ICA, each subject's data can be expected to decompose into many different components, and only the components thought to reflect the mu rhythm should be considered in this analysis. Other components assumingly mask the signal of interest by introducing noise and brain signals not related to the MNS. To reduce noise and to focus on components with MNS properties, a two-step component selection procedure was performed as described below.

First, we excluded components that reflected artefacts by the following criteria: components with any abnormal ICA weight, > 2.7 *SD* of all weights within a component, were considered artefactual and excluded. The value of 2.7 *SD* was decided by visual inspection of all components to retain components with dipole like scalp projections and to exclude components originating from channel pops or movement artefacts. The validity of this value was assessed after the analysis, and was found to be relatively conservative. Also, the maximum absolute amplitudes of components were calculated to identify outlier values that could bias the subsequent frequency analysis. Trials with abnormal values (> 3 *SD*) were thus excluded. Components with fewer than 10 trials in any condition were also removed.

Second, we selected components related to mu rhythm desynchronization from the remaining components. Here we used the three conditions in the study design to solve the independent component selection problem. Frequency spectra of the three conditions were extracted, and components with a mu rhythm power peak greater than 1 dB in the static condition and a decrease in the power peak from this value greater than 1 dB for the two movement conditions together were selected for further statistical analysis. The definition of the mu rhythm frequency interval was based on previous studies of infant alpha rhythms (Marshall et al., 2002; Stroganova et al., 1999) and the 5-9 Hz band was used. This procedure selected components that showed mu rhythm desynchronization in the two action conditions, without making any distinction between them, relative to the static condition. In total, 43 components with 10-49 trials ($M = 21.06$; $SD = 7.40$) from each condition originating from 23 subjects were selected. Each subject contributed with 1-5 components ($M = 1.87$; $SD = 1.12$). If the ICA did not decompose any component with mu characteristics the subject was excluded[4]. The components that were not selected were subtracted from the raw EEG to create datasets pruned for noise, movement artefacts and brain activity that were not related to mu desynchronization. Since no distinction between the two action conditions was made at this point, it was possible to test them for statistical differences.

For statistical analysis, a time/frequency analysis using discrete wavelet transforms was performed on each component's (or channel's, in the case of raw data) conditions using the standard EEGLAB timef function which resulted in power maps with 200 time-points and 20 frequency bands. However, as we were mainly interested in the 5-9 Hz frequency band, this interval was averaged and the goal-directed and non-goal-directed conditions were compared with reference to this measure at every time point. As multiple significance tests inflate the risk of Type I errors, only clusters of 10 or more adjacent significant p-values ($p < 0.05$) were considered. The most prominent channel was then analyzed in further detail using pixel wise t-tests in all frequency bands between 2 and 20 Hz. To control for multiple testing of these 200x20 time/frequency points, only clusters of 20 or more adjacent p-values ($p < 0.05$) were considered significant. Two-tailed probabilities ($\alpha = 0.05$) were used. The statistical procedure was first performed channel-wise on the raw EEG datasets ($n = 32$), and then repeated on the pruned datasets ($n = 23$).

[4] Different reasons why some infants did not contribute with any mu components can be possible. First, the mu rhythm is subject to individual differences, and might not have developed yet in some subjects. Second, some minor artefacts that the ICA could not decompose could have contaminated the measurements. In either case the subject would not have any signal to contribute with, and would have to be excluded.

Study III

In Study III, prospective motor control was measured via reach latency, namely the time when the hand started to move relative to when the ball entered reaching space. Reaching space was defined as the area where the ball was within approximate reach for the infant, i.e. within the infant's arm length. This definition of reaching space was adopted from Hespos, Gredebäck, von Hofsten & Spelke (2009), and Spelke & von Hofsten (2001). More specifically, the ball was within reach for the infants once it passed the toy rails on the table (see Figure 9). Frame-by-frame software (Mangold International INTERACT, Arnstof, Germany) was used for the offline coding of the recorded videos. Trained observers (blind to group membership) registered the time from video recordings when the rolling ball passed the end of the tracks, and entered reaching space (ball entering reaching space). We further registered the point in time when the infants started to move their arm (reach initiation) and when the hand first made contact with the object (or came within two cm from the ball, here defined as catching the ball; see similar procedure in Hespos et al., 2009) (contact time). If the reaching movement was initiated before the ball entered reaching space, the reach was considered predictive (negative reach latency). If the reaching movement was initiated after the ball entered reaching space, this was considered a reactive reach (positive reach latency). In this context (like prior work using similar procedures on typically developing infants; Hespos et al., 2009; Spelke & von Hofsten, 2001), predictive reaches were considered to reflect prospective motor control. In order to control for other aspects of the reaching action, we also analyzed movement duration (defined as the time between reach initiation and contact time).

Inter-rater reliability was assessed on 12 (26%) randomly selected participants, and concordance was very high (ball entering reaching space: $r > .99$, reach initiation: $r > .99$, contact time $r > .99$).

Dependent measures in Study III were reach latency and movement duration. Independent t-tests with risk status (HR vs. LR) as the between-subjects factor was used, and single sample t-tests to measure whether average reach latency differed significantly from zero, with significant negative difference from zero meaning predictive reaches. Two-tailed probabilities ($\alpha = 0.05$) were used. There were no group differences in terms of performance at each rolling speed or concerning starting location (left or right side), thus, in all analyses data were collapsed across rolling speed and starting location.

Study I – The importance of stereopsis in infants' dynamic reaching

Study I is aimed at studying one presumption for typical development of reaching behavior and motor control, namely stereopsis as a prerequisite for efficient reaching development. As reviewed in the first part of the Introduction section, effective action planning and prediction is reliant on sensitivity to depth and distance information. Judging the correct distance to an object is crucial since it gives information about how long time you have to plan an action. More specifically, we studied whether and in what way a lack of stereopsis would affect reach-to-grasp actions in infants. In Study I, we manipulated access to binocular information in infants using an eye-patch, and it was investigated whether and how this would affect reaching in terms of time to object contact and reaching accuracy (number of contact errors committed). Hand selection was also an examined factor on its own in the study, but this variable will not be discussed in the thesis summary. The reason to exclude this factor for purposes of the summary is that in Study I, hand selection was not affected by removal of binocular information. Instead, hand selection was mostly determined by the object's position in the board (see Paper I). Infants of three different ages (six, eight and 10 months old) participated. The age groups were chosen to represent different stages of typical reaching development, through varying degrees of reaching experience (Carvalho, Tudella, Caljouw, & Savelsbergh, 2008; van Hof et al., 2006).

Planning and executing a reach is a dynamic activity. In order to successfully reach for something, the whole body needs to be correctly placed relative to the positions of objects in visual space, and arm movements need to be carefully planned. Manual actions also need to be planned in the context of changes in body position, because the whole body is typically involved in reaching movements in everyday life. Each step in this process relies on prediction to be successful. To reflect this, a new reaching paradigm was used in Study I. Infants sat on their parents' lap in a swivel chair that was rotated toward a flat vertical board on which small toys were placed at various positions along a horizontal line. This procedure created an experimental situation that is dynamic in a different way from what is conventionally used. In typical reaching experiments, infants are stationary and they reach for stationary or moving objects (Fagard, Spelke, & von Hofsten, 2009; van

Hof, van der Kamp, & Savelsbergh, 2006; von Hofsten, 1979, 1983). In the present study, we moved the infant rather than the object. This manipulation creates a rich source of vestibular and proprioceptive information in addition to the global visual flow created by the motion of the subject, but it also places greater demands on prospective control. Furthermore, in previous studies of infant reaching, objects have traditionally been placed at infants' midline (e.g. Berthier & Keen, 2006) or at locations near the left and right shoulders (e.g. Rönnqvist & Domellöf, 2006; van Hof et al., 2006). In the present study, object placement varied across the horizontal reaching space. Infants were free to initiate reaching whenever they wanted – even before the chair had stopped rotating.

Based on previous work, we hypothesized that reaches performed under monocular conditions would have longer times to object contact, and be less accurate, especially in the six- and eight-month-olds (Braddick, 1996; van Hof et al., 2006). We also expected that covering one of the eyes would selectively impair time to object contact and reaching accuracy with the hand on the partly occluded side; that is, covering the right eye should impair reaching with the right hand, and it should take longer to complete the reach with this hand, independent of object location. Finally we hypothesized that covering the right or left eye would selectively impair time to object contact and reaching accuracy toward the covered part of the visual field, independent of hand use.

Results

The dynamic reaching paradigm worked well with a high rate of attempted reaches (95% of all presented trials). The exclusion criteria described above resulted in 48 infants being analyzed for the monocular condition (24 six-month-olds, 14 eight-month-olds and 10 10-month-olds) (out of the 72 who contributed data to both conditions). All statistical inferences (GLIM results) are based on the 48 infants who contributed data to both conditions.

Table 1 shows least square mean values for all levels of the fixed effect variables in the mixed model examining average time to object contact. This model revealed a significant effect of condition (F (2) = 3.74, p = .026), with longer contact time in the monocular condition compared to the binocular one. There was also an effect of object position on average contact time (F (6) = 19.93, p < .0001), with longer contact times at the extreme end positions both to the right and left (±28 cm). In addition, there was an interaction effect between condition and object position (F (1) = 3.32, p < .0001), such that during the monocular trials, contact times were longer at the positions on the patched side of reaching space. Contact times were also longer at the extreme end positions, independent of the positioning of the patch. No significant differences in contact times were found among the three age groups or between rotation directions of the chair ($Fs < 1.0$).

Table 1. Least square mean values for all levels of the fixed effect variables in the model examining average time (in s) to target contact. Position -28 cm is furthest to the left.

	M	*SE*
Condition		
Binocular	1.60	.09
Right eye patched	1.86	.15
Left eye patched	1.96	.16
Position		
-28 cm	2.48	.17
-18.7 cm	1.52	.16
-9.3 cm	1.42	.15
0 cm	1.18	.15
9.3 cm	1.46	.15
18.7 cm	1.71	.15
28 cm	2.88	.16
Age (months)		
6	1.94	.12
8	1.78	.16
10	1.70	.19
Rotation direction		
Clockwise	1.77	.11
Counter-clockwise	1.84	.11

Given the significant effect of condition on contact time, follow-up analyses on only monocular trials were carried out to examine the effects of which eye was patched and effects of rotation direction of the chair on contact time. For a more detailed result, separate analyses were performed for reaching with the right and left hands, respectively[5]. A mixed model analysis examining the interaction between rotation direction and patched eye (left or right) with respect to contact time for right hand reaching confirmed a significant interaction (F (1) = 5.85, p = .016). For right hand reaches, contact times were longer when the patched right eye was leading (turning clockwise). For left hand reaches, the pattern looked different (Table 2 shows least square mean contact time estimates (in seconds) for all levels of this analysis). A mixed model examining the interaction between rotation direction and patched eye with respect to contact time for left hand use showed no signifi-

[5] This analysis is not connected to the hand selection factor (see Paper I) that will not be discussed in the thesis summary. This analysis was performed only on monocular trials and does not reflect a choice of hand, but rather the contact time when reaching with the hand that is more or less visible.

cant effect ($F < 1.0$). Thus, when infants reached with their left hand, there were no differences in contact time due to whether the unpatched eye was leading during chair rotation or not.

Table 2. Least square mean time estimates (s) to object contact in the mixed model examining the interaction between rotation direction, patched eye, and hand selection with respect to contact time (in s). SE values shown in parentheses.

	Right hand		Left hand	
	Left eye	Right eye	Left eye	Right eye
Clockwise	2.02 (.405)	2.10 (.386)	2.72 (.391)	1.29 (.385)
Counter-clockwise	1.80 (.425)	1.20 (.401)	2.53 (.370)	1.40 (.375)

It should be noted that a number of reaches had a negative latency (5.4% in the binocular condition, and 6.9% in the monocular condition), that is, the infants made contact with the object before the chair had stopped at midline. 22% of all reaches were completed within 600 ms after the chair stopped.

Table 3 shows least square mean values for all levels of the fixed effect variables in a generalized linear model examining frequency of contact errors. The model revealed a significant difference between conditions (F (2) = 4.35, $p = .013$). Infants committed more contact errors in the monocular than in the binocular condition. The same model showed that contact errors did not vary across object position or rotation direction of the chair (Fs < 1.6). The frequency of contact errors did, however, vary across the three age groups (F (2) = 27.99, $p < .0001$), with the six-month-olds making more mistakes overall as compared to the eight- and 10-month-olds. There was no interaction between age and condition in this respect ($p = 0.236$).

Table 3. Least square mean values for all levels of the fixed effect variables in the model examining proportions of trials with contact errors. Position -28cm is furthest to the left.

	M	*SE*
Condition		
Binocular	.10	.01
Right eye patched	.18	.04
Left eye patched	.16	.04
Position		
-28 cm	.14	.04
-18.7 cm	.08	.03
-9.3 cm	.18	.04
0 cm	.16	.04
9.3 cm	.16	.04
18.7 cm	.17	.04
28 cm	.15	.04
Age (months)		
6	.45	.05
8	.07	.02
10	.07	.03
Rotation direction		
Clockwise	.16	.03
Counter-clockwise	.13	.02

Since the omnibus analysis for contact errors showed a significant result for condition, follow-up analyses on only monocular trials were carried out to examine the effects of which eye was patched and the object's placement on the board on the proportion of trials with contact errors. We first examined whether the infants committed more contact errors with the hand on the same side as the patch (independent of the object's placement on the board). A GLIM showed no significant interaction between patched eye and hand use with regard to frequency of contact errors with the ipsilateral hand ($F < 1.0$). No other interaction effects were found.

Finally, it was examined whether the infants committed more contact errors while reaching for objects that were placed on the side of the board partly occluded by the patch (independent of hand use).[6] No significant interaction was found between patched eye and the object's position on the board with regard to frequency of contact errors ($F < 1.0$). Thus, the infants did not make more contact errors when the object was placed on the side of the board that was partly occluded by a patch. However, a significant interaction

[6] To have sufficient power for this analysis, object locations from -28 to -9.33 cm were binned together to represent object placement on the left side of the board, and object locations from +9.33 to +28 cm were binned together to represent placement on the right side of the board. Objects at 0 cm were regarded as placed at the midline position.

effect was found between patched eye and rotation direction of the chair (*F* (1) = 4.12, *p* = .043). Infants committed more contact errors when the unpatched eye was leading during the rotation. When the right eye was leading and unpatched (chair rotating clockwise), the least square mean value was .219 (*SE* = .076); when the right eye was leading and patched, it was .136 (*SE* = .054). When the left eye was leading and unpatched (chair rotating counterclockwise), the least square mean value was .263 (*SE* = .075), and .191 (*SE* = .065) when the left eye was leading and patched.

Conclusions Study I

By using a dynamic reaching situation, we examined the role of binocular information in infants for the control and development of reach-to-grasp actions. As hypothesized, the main results show that when performing reaching actions under monocular circumstances, infants perform slower reaches across all tested age groups, and they also make more contact errors. The six-month-old infants committed more contact errors overall as compared to the two older age groups. This result is reasonable since these infants have had less reaching experience (Carvalho et al., 2008). Further, results from the 'time to object contact' variable show that reaches to a certain extent could be planned during the rotation of the chair. Object contact was repeatedly made before the chair stopped, or at a time after it stopped that was shorter than the time it takes to plan and execute a reach (see General discussion section).

One hypothesis was that reaching should be impaired toward the covered part of the visual field, independent of hand use. The results are in line with this regarding time to object contact, but not concerning reaching accuracy. In order to show the impairing effect of monocularity on number of contact errors, it is necessary to take the rotation direction of the chair into account. Infants committed more contact errors when the unpatched eye was leading during the rotation. Rotation direction also needs to be considered for results regarding the hypothesis that reaching should be impaired with the hand on the same side of the patch, independent of object placement. Only when the interaction between rotation direction and patched eye is examined, does the impairing effect of monocular vision become evident. The dynamic reaching paradigm was needed to show the interaction effects between patching and turn direction. Arguably, the paradigm introduces a more ecologically valid reaching situation. In everyday life, objects are rarely placed right in front of us. It is much more common to turn around to reach for things that are placed at different distances and also at different positions across reaching space (Land, 2004). However, the passive rotation of the trunk and head introduces a complex summation of visual and vestibular information as shown by Bresciani, Gauthier, Vercher and Blouin (2005) and Bortolami, Pigeon, Dizio, & Lackner (2008), which places greater demands on prospective motor control. Further experiments are needed to evaluate reaching while in motion, preferably in combination with a motion tracking system.

To conclude, stereopsis seems to be an important prerequisite for efficient and correct reaching. When depth and distance information provided by binocular vision is removed, reach-to-grasp actions in infants become slower and less accurate. Monocularity also gives a smaller visual field, which can also contribute to slower reaches as it might take longer to discover an object under these conditions. The longer times to object contact during monocular trials specifically imply that the predictive planning part of the action is less effective when depth and distance information is compromised.

Study II – Assessing the infant MNS using mu rhythm desynchronization

Study II takes the perspective of how motor development can aid in the understanding of others' goal-directed actions. If the MNS hypothesis, namely understanding the actions of others by transferring that information onto your own motor representations of that action, is valid, it implies that you need to be able to master a certain action in order to understand it. It follows from this that the development of children's understanding of other people's actions should be parallel to their own motor development. Accordingly, the overarching aim of Study II was to find neural evidence of MNS activity in human infants who observe a goal-directed action that they can master themselves. At the time this research was conducted, this was an important study to implement, since empirical neurophysiological data on the infant MNS was very meager (Bertenthal & Longo, 2007; Kilner & Blakemore, 2007; Lepage & Théoret, 2007). Several studies on this topic have followed since (for reviews, see Cuevas et al., 2014; Marshall & Meltzoff, 2011; Saby & Marshall, 2012).

As outlined in the Introduction, MNS activity has earlier been identified in adults by analysis of the mu rhythm (e.g. Muthukumaraswamy & Johnson, 2004a; Pineda, 2005). In Study II, we assessed the mu rhythm at the frequency band of 5-9 Hz by using high-density EEG. The infant rhythm of 5-9 Hz shows strong resemblances with the adult mu rhythm, and it has therefore been suggested as being the infant mu rhythm (Marshall et al., 2002; Stroganova et al., 1999). Since this signal was expected to be weak and masked by surrounding noise, the use of independent component analysis (ICA) decomposition was motivated to extract the signal of interest.

In an earlier study, a similar method was used on six-month-old infants and adults to extract mu rhythm activation elicited by video presentations of an actor performing goal-directed as well as non-goal-directed actions (Nyström, 2008). In that study, the mu rhythm suppression was not significantly different between conditions in the infant group. In relation to the study by Nyström (2008), the present study was improved in two ways. First, eight-month-old instead of six-month-old infants were studied, since infants of this age have more reaching experience than six-month-olds, and should thus produce a more robust mu rhythm desynchronization when watching someone else perform a reaching action. Second, in this study we used a live display instead of video recorded stimuli. A few studies have found that live actors elicit a stronger MNS activation as compared to video stimuli (Järveläinen, Schürmann, Avikainen, & Hari, 2001; Ruysschaert et al., 2013; Shimada & Hiraki, 2006). We hypothesized that the mu rhythm would desynchronize more when the infants observed a goal-directed action that they can perform themselves compared to observing a non-goal-directed action as well as a static scene.

Results

The experimental design was very successful as indicated by the, for EEG studies, extremely low exclusion rate. It is not uncommon for an attrition rate of close to 50% in infant EEG studies (Stets, Stahl, & Reid, 2012). In this study, only two infants out of 34 were excluded because of insufficient data.

Looking at the raw EEG data, we found no significant desynchronizations in any of the analyzed channels (see Figure 5).

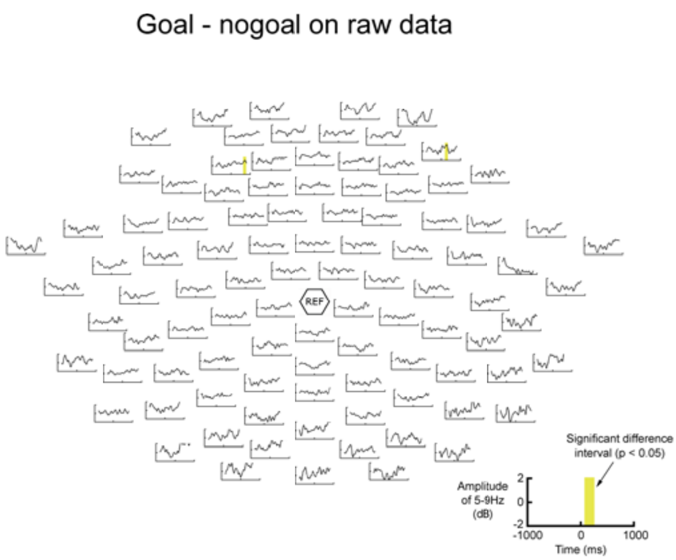

Figure 5. Mean amplitude differences of the 5-9 Hz frequency band between the goal- and non-goal-directed conditions in the raw datasets. Each curve map represents a channel and the layout describes the spatial relations between the sensors on the scalp (nose pointing upwards). Significant differences between conditions are marked with yellow intervals ($n = 32$, $p < .05$, adjusted for multiple testing). No channels with significant desynchronization were found in the raw datasets (cf. Figure 6).

Contrary to this, in the analysis of the selected components, the pixel wise *t*-tests between the goal-directed and non-goal-directed conditions showed a significant desynchronization of the mu rhythm band for the goal-directed condition approximately at the time when the hand touched the object. A global power minimum of -1.6 dB was found 10 ms after time lock (p = .0007). This minimum is found in a significant difference interval between the goal- vs. the non-goal-directed conditions starting approximately 60 ms before time of touch, and remaining until 55 ms after time of touch. Thus, the activation is predictive. The channels with the largest difference between the goal-directed and the non-goal-directed movement conditions were located on the right frontal lobe and in central areas, as shown in Figure 6. Two more channels with significant desynchronization were located in the left frontal lobe (over prefrontal cortex) and finally two over the occipital lobe.

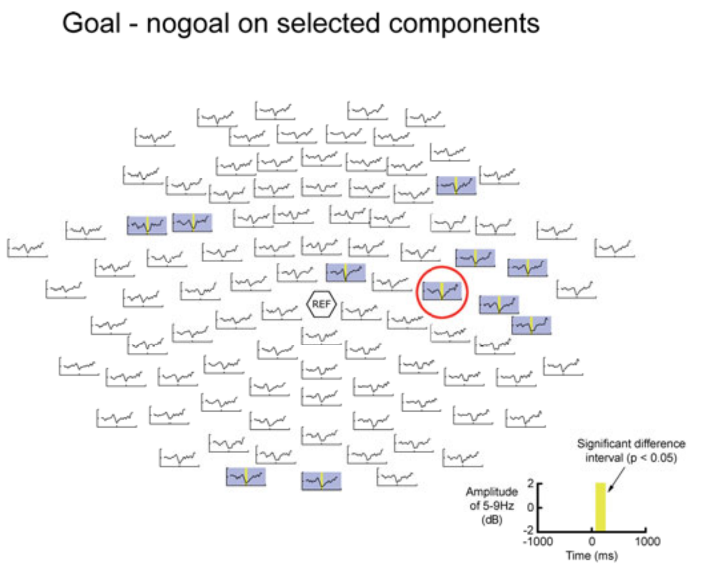

Figure 6. Mean amplitude differences of the 5-9 Hz frequency band between the goal- and non-goal-directed conditions in the pruned datasets containing only the selected independent component projections. Each curve map represents a channel and the layout describes the spatial relations between the sensors on the scalp (nose pointing upwards). Significant differences between conditions are marked with yellow intervals ($n = 23$, $p < .05$, adjusted for multiple testing), and channels with significant desynchronization are shaded. The most significant channel is marked with a red circle, and presented in more detail in Figures 7 and 8.

A magnified view of the most significant channel (marked with a red circle in Figure 6) is presented in Figure 7, which also shows the amplitudes of 5-9 Hz for all conditions.

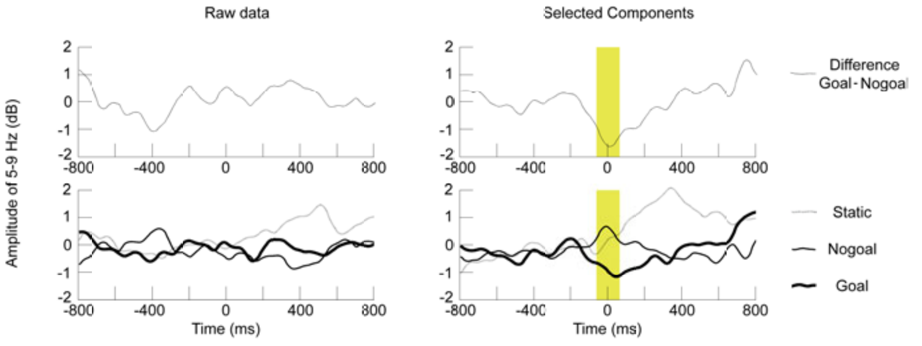

Figure 7. A presentation of the separate conditions of the most significant channel (marked with a red circle in Figure 6). The left column shows data from the raw datasets, and the right column shows data from the pruned datasets containing only independent component projections. 0 ms indicates time of touch of the object/tabletop. The yellow interval marks when the significant differences between conditions occur in time.

The detailed time/frequency analysis of the most significant channel is presented in Figure 8. The difference between the goal-directed and non-goal-directed condition had a global minimum of 1.6 dB 10 ms after the hand touched the object at 6.8 Hz (p = .0002).

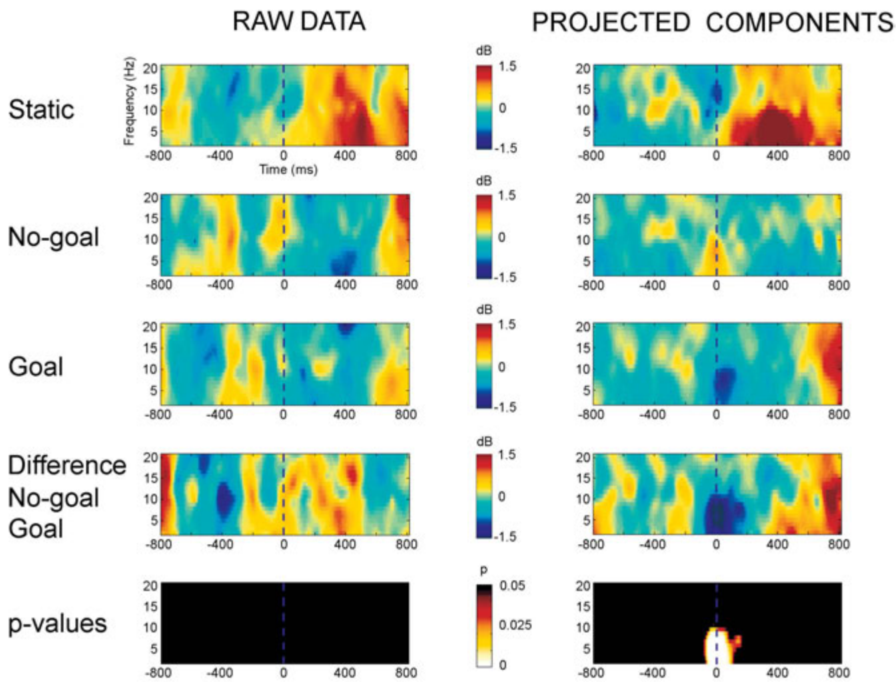

Figure 8. A presentation of the separate conditions in the most significant channel (marked with a red circle in Figure 6) using the detailed time/frequency decomposition returned by the EEGLAB Timef function. The left column shows data from the raw datasets, and the right column shows data from the pruned datasets containing only selected independent component projections. Blue values indicate more desynchronization. The bottom row shows the point wise statistical t-tests' *p*-values (left plot $n = 32$, right plot $n = 23$), threshold at alpha = .05, and adjusted for multiple comparisons (200 * 20 tests) by removing significant clusters smaller than 20 pixels. 0 ms (dashed line) indicates time of touch of the object/tabletop.

Conclusions Study II

The results from Study II clearly show that when selected components are analyzed, the mu rhythm of eight-month-old infants desynchronize more when they observe goal-directed actions as compared to when they observe non-goal-directed actions. The desynchronization pattern is very similar to what has previously been observed in adults (Muthukumaraswamy & Johnson, 2004b) and in those cases linked to activation of the MNS. Importantly, the activation is predictive, becoming significant around 60 ms before time of touch. Also, the approximate localization of activation sources fits well with results from previous adult MNS studies (e.g. Pineda, 2005). This would imply that at eight months of age, infants display a rather mature MNS. The study was one of the first to successfully display neurophysiological activation of the MNS in infants of this age. Since then, converging evidence has been published (Marshall et al., 2013, 2011; Paulus, Hunnius, & Bekkering, 2013; Paulus, Hunnius, van Elk, & Bekkering, 2012; Reid et al., 2011; Saby et al., 2012), showing that the infant MNS is functional in a comparable way to the adult MNS. Marshall and Meltzoff (2011), and Cuevas and colleagues (2014) have also published review papers of studies on the infant MNS assessed with EEG.

The present result on mu rhythm desynchronization indicates that the links between action production and action perception are not just conceptual but actually correspond to common brain processes. It has been argued that the development of the MNS either precedes or develops in concert with the attainment of new motor, and possibly also social, skills. The achievement of a motor milestone often foregoes a significant change in cognitive functioning (Jones et al., 2014). Plenty of work has been done, which suggests that, as infants become more proficient in the motor domain, they rapidly develop social skills requiring understanding of other peoples' actions (e.g. pointing, Tomasello, Carpenter, & Liszkowski, 2007; deferred imitation, Barr, Rovee-Collier, & Campanella, 2005).

Conclusively, it appears like the MNS can serve as a uniting link between motor development and social cognition. By mastering a certain action, it becomes possible for an individual to understand when other individuals are performing that action, and through this predict (Ambrosini et al., 2013; Falck-Ytter et al., 2006; Kanakogi & Itakura, 2011; Kilner et al., 2004; Marshall et al., 2013; Paulus et al., 2012; Southgate et al., 2010, 2009) the behavior of others. The results from Study II support the MNS hypothesis by showing neural activation in eight-month-old infants when they merely observe someone else perform an action that they can master themselves.

Study III – Prospective motor control in infants at risk for ASD

Study III takes the perspective of how deficits in motor ability might relate to atypical development. As outlined in the Introduction, there are several neurodevelopmental disorders that include motoric issues. Study III is focused on ASD, since this pervasive developmental disorder has clear implications for both the motor as well as the social cognition domain. Study III was further motivated by the body of evidence showing that individuals with ASD demonstrate specific problems with prospective motor control of actions. Studies on adults with ASD have shown that they often display longer reaction times before starting a reaching movement compared to typically developed controls (Glazebrook et al., 2008). Further, in a series of studies individuals with ASD have demonstrated reactive rather than prospective changes in muscle activity during load-lifting tasks (David et al., 2009; Schmitz et al., 2003), reduced interceptive skills (Green et al., 2009; Whyatt & Craig, 2013b; Whyatt & Craig, 2012) and reduced ability to prospectively plan their own actions with respect to future goals (Cattaneo et al., 2007; Fabbri-Destro et al., 2009; Hughes, 1996). It has also been argued that impaired prospective motor control can result in problems in interacting socially with others (Cattaneo et al., 2007; von Hofsten & Rosander, 2012).

The specific aim of Study III was to assess the ability of infants at familial risk for ASD to prospectively control their own reach-to-grasp actions. All high-risk (HR) infants had an older sibling with an ASD diagnosis. Little is known about the precise nature of motor deficits in young children with ASD, and even less in infants at risk for ASD, but based on earlier ASD literature it can be expected that problems with prospective control may be particularly pronounced in children with ASD, and possibly in HR infants as well. The performance of the HR group was compared to performance of a group of low-risk (LR) infants. Based on earlier research (e.g. Glazebrook et al., 2006, 2008; Schmitz et al., 2003; Whyatt & Craig, 2013b), we hypothesized that, compared to the LR group, the HR group would show reduced prospective control while catching a moving object. 10-month-old infants were presented with a task requiring them to reach and grasp a ball rolling on a curvilinear path off an inclined tabletop. Similar tasks have previously been used to assess prospective control in typically developing infants (Hespos, Gredebäck, von Hofsten, & Spelke, 2009; Spelke & von Hofsten, 2001; von Hofsten, 1980), and in older children with ASD (Whyatt & Craig, 2013b), but has never hitherto been used to assess motor performance in infants at elevated risk for autism.

Study III was performed as part of a large ongoing longitudinal project (Projekt Småsyskon/Early Autism Sweden [EASE]) that examines the development of younger siblings of children with an ASD diagnosis. Up to 50% of HR infants can be expected to receive an ASD themselves, or develop significant ASD-related problems (Ozonoff et al., 2014). The younger siblings in the project are assessed between five and 36 months of age, and tested using a wide range of experimental tasks, standardized assessments and brain imaging techniques such as EEG and MRI. At 36 months, all participants will be diagnostically screened for ASD. The ultimate goal of the project is to look for early behavioral indicators or biomarkers that can be predictive of a later ASD diagnosis. The experimental tasks include a motor assessment block, where the ball catching task presented here is one of four. The other three tasks consist of receiving and giving a toy, placing a toy in a bucket and finally banging an object on a table surface. The whole motor block is documented using video recordings in combination with a motion capture system (Qualisys AB, Gothenburg, Sweden). The data from the motion capture recordings is used for answering other questions than the one being addressed in Study III (see section on Future directions).

Results

Infants in the HR and LR groups attempted to reach for the ball equally often (HR M = 11.9 trials, SD = 3.1; LR M = 11.1 trials, SD = 2.4), $t(43) = .939$, $p = .353$, $d = .29$, and they were equally likely to catch the ball (HR M = 85%, SD = 18%; LR M = 86%, SD = 15%), $t(43) = .103$, $p = .919$, $d = .03$.

In the trials where the ball was caught, the mean reach latency was -201 ms (SD = 187 ms) in the LR group and -13 ms (SD = 356 ms) in the HR group. Negative latencies are defined as predictive reaches. The reach latencies in the two groups differed significantly from each other, $t(40) = 2.25$, $p = .030$, $d = .71$ (equal variances not assumed, adjusted p-value is reported). A single sample t-test showed that reach latency for the LR group significantly differed from zero, $t(14) = 4.16$, $p = .001$, $d = 2.22$, whereas the same test for the HR group did not differ from zero ($p > .5$; see Figure 10). That is, infants in the LR group started moving their arm predictively, 201 ms before the ball entered their reaching space, whereas infants in the HR group initiated their reach just as (-13 ms) the ball entered the same space.

We found no group differences in movement duration, (LR M = 1.05 sec, SD = .16, HR M = .97 sec, SD = .22), $t(40) = 1.18$, $p = .245$, $d = .37$ and also no significant correlation between reach latency during catches and performance on the FM scale of the MSEL (r = .099, p = .534). The same was true for the other subscales as well (all p's > .05).

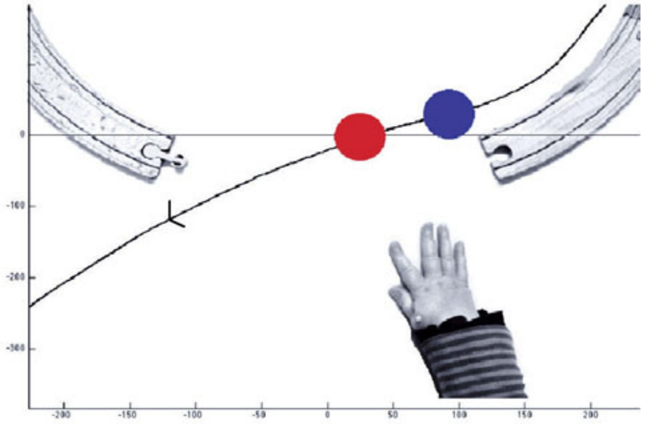

Figure 9. Illustration of the catching task, with a superimposed representative ball trajectory in 2D. Y-axis shows Y coordinates in mm. 0 mm on the Y-axis marks the first point in space where the ball can be reached (positive values indicates the ball is outside reaching space). Red ball indicates approximate movement initiation in the HR group, and blue ball represents the LR group. Arrow indicates movement direction.

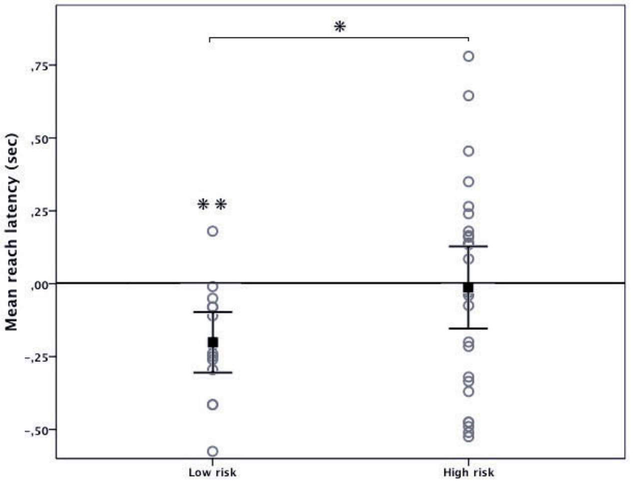

Figure 10. Mean reach latency in sec for the two groups. Error bars represent 95% confidence intervals. Circles represent individual data points. *p < .05 (independent t-test), **p < .01 (single sample t-test).

Conclusions Study III

The results from Study III confirm the results of many earlier papers on the development of reach-to-grasp actions (e.g. von Hofsten, Vishton, Spelke, Feng, 1998; Hespos et al., 2009; Spelke & von Hofsten, 2001; von Hofsten, 1980); that infants expected to develop typically reach for moving objects in a predictive manner. Such prospective motor control plays a critical role for infants' ability to act effectively on objects in the world (von Hofsten, 2004). Concerning infants at elevated risk for ASD, our results show that they, on the other hand, perform reactive reaches, thus not initiating their movements toward a moving object before it enters their reaching space. There is also a significant difference in reach latency between the two tested groups. The results are in line with our hypothesis.

This finding provides important new insights into the specific nature of motor impairments possibly linked to ASD susceptibility early in life. We suggest that problems with prospective motor control are overrepresented in infants at risk for ASD, even though it is important to note that the design of Study III does not allow for conclusions that these findings are specific to ASD. Nevertheless, this scenario would be in line with the view that impairments in prospective control mechanisms can cause a problematic developmental cascade, affecting areas beyond motor functioning (Wolpert, Doya, & Kawato, 2003) (see also General discussion section).

Follow-up diagnostic assessment of these infants at 36 months will show whether reduced prospective motor control can be used as a predictive diagnostic marker for ASD diagnosis. A plausible outcome is that the infants who perform most poorly on this task will be overrepresented among those that ultimately will receive an ASD diagnosis.

Conclusively, these results provide information to the notion of how deviations from normal motor development, in this case reduced motor control, can relate to neurodevelopmental disorders. Study III wad solely focused on ASD, but the current study provides strong motivation for further examinations of prospective motor control both in infants at risk for ASD, and other developmental disorders frequently co-occurring with ASD, such as ADHD or developmental coordination disorder.

General discussion

The overarching aim of this thesis has been to study manual motor development in infancy from three different perspectives. The three empirical studies that comprise this thesis contribute more information regarding the importance of manual motor development from different perspectives. Study I takes on a basic research point of view, through examining the importance of stereopsis for the development of efficient dynamic reaching. The main result of Study I is the fact that, under monocular viewing conditions, infants at different ages, and thus with varying degrees of reaching experience, perform slower and less accurate reach-to-grasp actions than during binocular viewing conditions. Study I uses a new dynamic reaching paradigm, where the infants are moved and the object is static. A rotating procedure is needed to show the interaction effects of turning in a certain direction, and the coverage of one eye, to fully understand the impairing effects that monocular vision has on reaching actions during movement. Further, longer times to object contact during monocular trials specifically imply that the predictive part of the action is less effective when depth and distance information is compromised. The second examined perspective is with regard to how the capacity of performing reaching actions might support the understanding of other peoples' actions in infancy, by means of the mirror neuron system. The main result of Study II is the finding that, at eight months of age, infants seem to have a mirror neuron system (MNS) that function in a similar way to the adult version. MNS activation, operationalized by mu rhythm desynchronization, is found over the infants' motor cortex while they are simply observing an action that they can master themselves. This activation is predictive, indicating that the infants also anticipate the observed action and its goal. Study III takes on a more clinically applied view of the importance of manual motor development, through assessing prospective motor control in infants at elevated familial risk for ASD. The main result of Study III is that infants at high-risk of receiving an ASD diagnosis present with reduced prospective motor control at 10 months of age. These high-risk infants produce reactive rather than predictive reaches while catching a moving object. In contrast, low-risk controls perform predictive reaches, thus initiating their arm movement toward the object before it is even reachable. There is also a significant group difference with regard to reach latency, with the high-risk infants being slower to initiate reaches on average.

Besides the fact that motor ability is a central component of many psychological processes, a common denominator for the three empirical studies is the fact that motor prediction is a key factor behind being able to timely execute and understand reaching actions. To a varying degree, this aspect of motor control is present in each study.

In the following sections, I will elaborate more on the findings from the presented empirical studies, and also discuss them in relation to earlier theoretical and empirical work. This more general discussion will end with a section concerning future directions, where I will present some ideas on how to continue the work I started here.

When two eyes are better than one

Study I represents a basic research perspective by looking at one important prerequisite for performing efficient reaching actions. Knowledge like this is essential for the understanding of how motor development might influence other psychological areas. Several of the prerequisites that were pinpointed in the Introduction as important for developing competent reaching skills are reflected in the design of Study I. The dynamic reaching paradigm places significant demands on postural control as well as eye-hand coordination. But the focus of Study I, hence the variable that was manipulated, was on the importance of stereopsis for infants' (dynamic) reaching.

Timing

As has already been pointed out, the monocular condition resulted in slower reaches, measured by longer times to object contact. Further, object position on the board also had a significant effect on the time to object contact. Contact times were longer when the object was placed at the extreme end positions. It is probable that these longer times to object contact were due to the fact that it took longer for the infants to discover the object when it was placed in the outer borders of the visual field. Interestingly, for right hand reaches, contact times were longer when the right eye was covered and leading during the chair rotation. In contrast, when infants reached with their left hand, there were no differences in whether the covered eye was leading during the chair rotation or not. This coupling between the right hand and the right eye might, in fact, be a precursor to more established hand laterality in later development (e.g. Fagard & Lockman, 2005).

Contact time is defined in Study I as the time between the end of the chair rotation and infants' first contact with the object. If contact with the object was made after the chair stopped rotating, the reach can be considered reactive. Accordingly, if contact with the object was made before the chair stopped, it can be considered a predictive reach. Results from this measure shows that reaches, to a certain extent, were planned during the rotation of the chair (5.4% of all reaches were predictive in the binocular condition, and 6.9% in the monocular condition). Further, as was pointed out in the Conclusions section of Study I, several reaches were executed at a time after the chair stopped that was shorter than the time it takes to plan and execute a reach. To program a reach takes around 250-400 ms (Berthier & Robin, 1998; von Hofsten et al., 1998), and to execute a reach takes around 500 ms up to 1 s (Rönnqvist & Domellöf, 2006; von Hofsten, 1983). Thus, a conservative estimate of the minimum time to program and execute a reach is about 600 ms (300 ms for programming and 300 ms for execution). In the present study, 22% of the reaches were completed within 600 ms of the chair stopping and 38% were completed with 1 s.

Loftus and colleagues (2004) suggest that stereopsis gives online information of the hand relative to the target, and interpret slower reaches during monocular viewing conditions as being the system's attempt to decrease the error at grasp. Of special importance to this thesis, this specifically implies that prospective motor control of the action is less effective when depth and distance information is compromised, such that the visual sensory feedback used in computational forward models (e.g. Miall & Wolpert, 1996; Wolpert & Flanagan, 2001) might be less informative under monocular viewing conditions.

Accuracy

In contrast to results on the contact time variable in Study I, no main effect of object position was observed on the number of contact errors. This result suggests that the infants did not have more difficulty performing reaches for objects far out in the periphery, as compared to objects placed at or around midline. At the same time, infants showed longer times to object contact at the extreme end positions. Thus, these longer contact times could account for the fact that the number of contact errors committed at the extreme ends was not larger.

Few age effects were found in Study I. We hypothesized that the effects of monocular vision would be more pronounced in younger infants. We did find that the six-month-olds made more contact errors overall, thus, independent of condition. This is probably due to the fact that the youngest infants did not manage to compensate for the increased difficulties introduced by monocular vision by taking longer time to complete the reach, to the same extent as the older infants. However, no interaction effects were found between condition and age. The reason for this is probably that temporarily wearing an eye patch makes reaching so much more challenging, thus resulting in the monocularity effect showing to a similar extent in all age groups tested.

Surprisingly, infants committed more contact errors when the unpatched eye was leading during the rotation. This result might be explained by the fact that, under these circumstances, the object becomes visible earlier. As a result, infants may have produced prematurely predictive reaches, resulting in more imprecise reaching movements.

The dynamic reaching paradigm

How does patching of one eye affect the visual field in a rotating situation? Is the result only poorer depth perception due to monocular viewing, a manipulation of peripheral vision, or both? In the described dynamic paradigm, the analyses comparing turn direction and eye patched address this concern; the comparison of patched versus unpatched eye tells us about the effect of removing binocular information. The interaction of eye patched with turn direction provides information on removal of part of the visual field. There were differences between conditions in contact time and contact errors. Yet, for both measures, the condition effect was qualified by interactions with patched eye and turn direction. To be able to examine this difference satisfactorily, a comparison would have to be made between a monocular patching condition and one where peripheral binocular vision is restricted (for example using side blinders). In this latter manipulation, one would preferably also vary how far out in the periphery vision would be occluded.

The dynamic reaching paradigm presented in Study I works very well. Infants find the rotating procedure engaging, and the design also introduces more challenges (such as maintaining postural control). In some sense, this situation also resembles more of a natural reaching situation, since reaching for objects in everyday life rarely means that they are placed right in front of us, and self-locomotion is also very common during reaching. One improvement that could be made to this setup is to introduce a motion tracking system to complement the video recordings. In this way, more detailed information could be gathered regarding, for example, reaching trajectories and number of movement units made by the participants. Another example where the use of such a system could have been fruitful is when assessing head turns. Regarding some of the results from the monocular condition of Study I, it is possible that the infants turned their heads to compensate for the induced visual constraint. With a motion capture system, this possibility could have been examined further, since movements and velocities of both the infants' heads and arms can be captured with millisecond accuracy.

The results of Study I can have practical implications for infants and children that for different reasons need to wear an eye-patch during awake hours, for example to correct for strabismus or amblyopia. It can be expected that, while wearing the patch, their reaches might be slower and less accurate. Indeed, in a review paper by Webber and Wood (2005), it is argued that reduced stereoptic vision due to amblyopia can result in impairments in visuomotor skills, such as object manipulation. These effects can be suspected as even more pronounced while wearing the patch, since you then cover the healthy eye.

Understanding others through your own motor system

Study II represents the link between motor development and social cognition by examining how the ability to perform reaching actions relates to our ability to understand the reaching actions made by others.

In Study II we used a live model paradigm while measuring desynchronization of the mu rhythm using high-density EEG. The reason for choosing a live paradigm instead of a televised version was in part due to studies showing that live paradigms elicit a stronger MNS activation compared to video recordings (Järveläinen et al., 2001; Ruysschaert et al., 2013; Shimada & Hiraki, 2006). In some sense, letting a live model present the actions instead of presenting them on a screen, is making the setup more socially oriented. Further, in comparison to showing recorded acts on video, a live paradigm is also more flexible during data collection. Since drop out rates using infant EEG are usually very high (close to 50% in many studies [Stets et al., 2012]), one apparent strength with a live setup is that you can fit the presentation of trials to when the infant is attentive. You can also attract the infants' attention by saying their name or making funny noises. The live setup turned out to work very well, with only two out of 34 participants being excluded due to fussing or inattention.

Positioning and timing of activation

Making claims about source localization using EEG is a difficult enterprise, and one should be aware of the fact that positioning of activated channels on a scalp does not necessarily reflect activation coming from corresponding parts of the brain. Nevertheless, presenting scalp topographies showing activated channels is common in EEG research, and I would like to comment on the positioning on the scalp of the channels that showed significant mu rhythm desynchronization when looking at selected independent component projections (see Figure 6). Nine out of 11 significant channels were located at central areas, where the mu rhythm desynchronization has been assessed in previous studies (see e.g. Pineda, 2005). Marshall and colleagues (2011) found desynchronization during execution trials as restricted to central electrode sites in 14-month-olds, while action observation was associated with broader desynchronization activation across frontal, central, and parietal regions. A comparison like this cannot be made in Study II, since it did not involve an execution condition (see further discussion below). An interesting feature of the results of Study II is that seven of the nine sources in the premotor area were situated on the right hemisphere whereas Hari and colleagues (1998) as well as Southgate and collegues (2010) found higher activation on the left side. Nishitani and Hari (2000) found bilateral activation. One reason for this difference in lateralization across different studies may be that the activation may be task dependent. Further, one argument that might be made regarding the obtained results is that the activation found could reflect posterior alpha waves within the same frequency band (Marshall et al., 2002; Saby & Marshall, 2012). Posterior alpha waves are assumed to index information concerning visual motion. One reason against posterior alpha signals confounding the results is that visual differences between the tested conditions were minimized. All objects were present in the scene in all conditions, and the time-locking of the EEG occurred when the hand had decelerated and touched the toy train or the table.

The desynchronization activity measured in Study II was closely time-locked to when the model touched the object. Thus, the obtained significant activation during the goal-directed action was synchronized to the touch of the object. This is important since it fits well with the notion that mirror neurons are tuned to the goal of the action, and supports the hypothesis that it was indeed the presented goal-directed stimulus that elicited the mu rhythm desynchronization. It would have been much more difficult to argue that the mu rhythm desynchronization is related to MNS activation if there had been no timing of the reach toward the object.

While on the subject of timing, and of special importance to this thesis, it is interesting to note that the measured activation is predictive, becoming significant around 60 ms before time of touch. This means that the infants anticipate the goal of the model's goal-directed action, implying that they have some form of understanding of the actions and its aim. This predictive timing of the infant response is very similar to what has been observed in adults (Kilner et al., 2007, 2004). Analogous to the results of Study II, Southgate and colleagues (2009, 2010) also showed a predictive activation in the mu rhythm with nine-month-old infants, providing more evidence for online goal prediction in infancy. What the relation between the MNS and computational forward models of motor prediction might look like is discussed at the end of this section.

One important issue is whether any other self-movements by the subjects could cause mu rhythm desynchronization and thereby contaminate the measurements? Naturally, the infants did move occasionally but these movements were evenly distributed over the whole recording session, and any resulting unwanted mu rhythm desynchronization would just reduce the grand averages (similar to artefacts in conventional ERP recordings). The exact time-locking of the signal further implies that the significant effects are not related to randomly occurring movements by the infant. It needs to be noted that even though both the timing, positioning of activated sources and the apparent modulation of activation to goal-directed actions support the idea that the measured desynchronization is indeed related to MNS activity, the results of Study II would need to be replicated in order to draw any firm conclusions concerning the infant MNS.

Action execution and action understanding

The capacity to reach for and grasp an object was tested in all infants participating in Study II. Since all babies were able to perform this action successfully, there is a possibility that they could understand the actions made by the model in terms of translating what they saw to their own motor representations of the observed action. This corresponds well with the MNS hypothesis. As outlined in the Introduction, many studies have shown a correspondence between individuals' experience of or capacity to perform certain actions, and the amount of MNS activity that is recorded (e.g. Calvo-Merino et al., 2005; Cannon et al., 2014; van Elk et al., 2008). This implies that infants will learn to understand more complex motor acts made by others as they themselves learn to perform more complex behavior. However, the exact way in which motor skills and mirror neurons co-develop is by no means explained by the results of Study II, nor was this an objective.

One caveat of Study II is that it did not involve a condition where the infants executed the same movements as they watched the model perform. The main reason why no such condition was included is that making the infants reach for the toy train in a similar way as the adult model did would have induced too many motion artefacts to the EEG recording. It is very challenging to find a task that infants at this young age can be instructed to imitate in a systematic way without making exaggerated movements. Southgate and colleagues (2009, 2010) used an execution condition in their studies with nine-month-old infants. However, the execution task in those studies was not identical to the action that the infants watched a model perform. The task used in the work by Southgate and colleagues simply comprised a simple reach-to-grasp action. The object to grasp was presented right in front of the infants, using a mechanical claw. The activation recorded during this action was used as a reference mu frequency band for each individual infant, which was later concentrated on during the recording of the observation condition. These studies represent one extra step toward a firmer link of neural overlap between action execution and action observation, but the claim would have been even stronger if the executed and observed actions had been identical.

Action understanding is a complex concept, such that goals can be comprehended on different levels (e.g. Woodward & Gerson, 2014). Goals can be seen as having an inbuilt hierarchy, where there are proximal goals (e.g. reaching for a particular object, where the goal then is to obtain the object), and distal goals, defined as relating to more complex intentions (e.g. reaching for a coffee cup with the goal of drinking coffee to feel less tired) (Hunnius & Bekkering, 2014). When talking about goals in this particular thesis, I have referred to the proximal goal type. This would correspond to a '*what*'-level of action understanding, whereas the distal goal type corresponds more to a '*why*'-level of understanding. Hence, action understanding in the context of this thesis does not require a representation of possible higher-order intentions. With regard to action or goal understanding, there has been critique of the MNS hypothesis, challenging the view that action experience is crucial for the correct encoding of other peoples goals. It has been claimed that infants can understand the intentions of others without having any experience with that particular action, through for example rational or teleological reasoning. At the heart of this principle is the fact that goals are usually attained in the most efficient way (e.g. Gergely & Csibra, 1997, 2003). Advocates of this view argue that infants apply rational principles to actions they observe and, by assessing the efficiency of the means used to achieve the specific goal, they are able to infer it. In this way, goal understanding can be possible without the corresponding recruitment of a corresponding motor representation (as argued by direct-matching or motor resonance theories). Using EEG measurements of the sensorimotor cortex, Southgate and Begus (2013) showed that infants at nine months recruit their motor system whenever a context suggests an up-coming action. This is the case even when the predicted action is not possible to execute, hence the infants could not have had any experience performing it. The conclusion was drawn that motor activation is the result of, rather than the cause of, goal understanding (Southgate & Begus, 2013). One possibility that can be argued is that the role of the motor system in action understanding lies more in action prediction (Southgate, 2013). Further support for this view can be gained from studies showing that goal familiarity is more important than action familiarity when considering motor system involvement (Gazzola, Rizzolatti, Wicker, & Keysers, 2007). Thus, to argue that the brain sometimes uses motor simulation in action perception is not very controversial; rather, the discussion here concerns more the ontogeny, scope and function of the MNS in social cognition. This dispute is by no means resolved yet, and Study II was not designed to evaluate the value of truth to these different standpoints.

The MNS and computational forward models

What does the relation between a computational model of motor prediction and the MNS look like? I would like to argue that these two mechanisms are by no means mutually exclusive. A forward computational model might well serve as an underlying mechanism for action understanding/prediction as suggested by the MNS theory. Thus, motor prediction during action production and action observation could possibly be based in the same underlying system for prospective motor control. There are behavioral and computational studies that suggest that several systems in the CNS, such as those responsible for oculomotor and postural control, perceptual processing and mental imagery have access to predictions of the motion of the arm (Davidson & Wolpert, 2005). As outlined in the Introduction, Wolpert and colleagues suggests that the concept of internal forward models can provide a unifying framework for motor control and social interaction (Wolpert &

Flanagan, 2001; Wolpert, Doya, & Kawato, 2003). The suggested link between these systems is intriguing, since mirror neurons are cells, and internal forward models described in computational theories of motor prediction constitute brain networks. So, the information is handled on different levels, but it is possible that the forward computational models can aid and underlie the creation of the mirror neuron network.

Impaired motor control in relation to ASD

Study III represents the link between impairments in motor development and elevated risk for neurodevelopmental disorders. The logic behind this link, which is also connecting Study II and Study III, is that if motor development matters for social cognition, does motor impairment during development then later influence abilities to socially interact with others?

The results of Study III show that infants at familial risk for receiving an ASD diagnosis perform reactive reaches while catching a moving object. This quite striking difference in comparison to the low-risk control group cannot be explained by general developmental delay in the high-risk group, considering there are no group differences on any of the subscales of the Mullen Scales of Early Learning (Mullen, 1995), which is a widely used standardized developmental test. In a related vein, we find no significant correlation between reach latency and performance on the fine motor scale of the MSEL and also no group differences on this measure. The lack of correlation between reach latency and the fine motor scale is likely due to the fact that most of the items in the MSEL fine motor scale require handling of static objects, and in cases like these, timing of movements will not be crucial. I would like to argue that, when measuring prospective control during reaching, we are tapping into the microstructure of motor performance. This level of detail is not assessed by established developmental tests.

As can be seen in Figure 10, a number of infants in the high-risk sample perform reaches that are comparable in reach latency to those of the low-risk controls. Given that most siblings in the high-risk group are not expected to develop ASD or other related atypicalities (Ozonoff et al., 2014), this result is not surprising. It will be very interesting to see what the outcome will look like for the high-risk siblings of Study III at the diagnostic follow-up that will be performed at age three years. It might just be the case that the infants who perform worst on this task (i.e. the slowest reachers) will be the ones who develop ASD or ASD-related concerns.

As mentioned in the Methods section, the ball catching task is part of a larger motor assessment block included in the EASE project. The whole motor block is recorded using a motion-tracking system complementing the video recordings. The reason why no motion-tracking data was analyzed with regard to Study III is that we were particularly interested in the aspect of prospective motor control, and the data from the video recordings sufficed for making these analyses. Thus, the recordings from the motion-tracking system will be used to answer other questions (see Future directions). Further, there were no group differences concerning movement duration, rendering no support for the view that action execution should be impaired in this sample. If the high-risk group had reached with a larger number of movement units and/or less straight reach trajectories, this should have resulted in longer reach durations. However, if there had been group differences with respect to movement duration, the recordings from the motion-tracking system would have been very helpful in disentangling the reasons for such an effect.

In relation to Study I, I argued that using the rotating paradigm introduces a more ecologically valid reaching situation compared to more traditional experimental paradigms where the subject is stationary and the object is being moved. In Study III, the latter, more conventional, setup is used. The reason for this is that there are studies showing that individuals with ASD rely more on proprioceptive information at the expense of visual input (Cascio, Foss-Feig, Burnette, Heacock, & Cosby, 2012; Haswell, Izawa, Dowell, Mostofsky, & Shadmehr, 2009; Izawa et al., 2012) (see also further discussion below), and since the pivoting paradigm introduces a complex summation of visual and vestibular information (Bortolami et al., 2008; Bresciani et al., 2005) we chose not to use this setup in Study III. If infants at risk for ASD were to rely more on proprioception when planning their reaches, then rotating the subject would likely have obscured the results.

Prospective sibling designs

So far the prospective studies of ASD that exist have failed to identify behavioral markers below six months of age (Ozonoff et al., 2010; Rogers, 2009), (but see Brisson et al., 2011). These results suggest that behavioral signs of autism are not present at birth, as originally suggested by Kanner (1943), but rather emerge over time through a process of diminishing skills in various key developmental areas. Concerning early signs of motor impairments specifically, one can turn to previous longitudinal studies that have focused on standardized test items (such as the MSEL) on motor development. Consistently lower scores have been found in high-risk samples (Landa & Garrett-Mayer, 2006; Ozonoff et al., 2010), but these group differences have been difficult to show before 12 months of age (but see Leonard et al., 2014; Libertus et al., 2014). One reason why we do not find any group differences on the gross and fine motor scales of the Mullen test might be that the infants tested in Study III are simply too young for such group differences to be detected. Nonetheless, early motor impairment is a promising venue for early ASD risk screening in high-risk samples.

There are many advantages to earlier diagnoses of ASD. Children who get an early diagnosis benefit more from intervention, through reduced burden-of-suffering and enhanced quality of life (Zwaigenbaum, 2010). Early detection research will hopefully also generate new treatment strategies to reduce or maybe even prevent long-term disability (Dawson, 2008). Family and societal costs related to ASD across the lifespan can also be reduced (Jacobson & Mulick, 2000). Prospective sibling designs, where the younger siblings of a child with ASD is systematically assessed, are very helpful regarding early detection research, and this method has several significant advantages (Rogers, 2009). Due to the genetically inflated recurrence risk, the assessment of high-risk siblings does not require testing of as many participants as would be necessary if one were to sample from the normal population. Hence, this type of prospective screening is more effective both time- and cost-wise. Studies like these also offer the opportunity to validate existing neurodevelopmental models of ASD against experimental evidence (Gliga, Jones, Bedford, Charman, & Johnson, 2014). However, as with all things, this method is not without its drawbacks. First, it is difficult to draw conclusions that the findings coming from sibling studies are specifically related to ASD, at least when outcome data are not yet available. Another disadvantage is that parental concerns may influence participation rates, thus inflating numbers of recurrence rate. Finally, generalizability of results might be limited due to possible genetic differences between single-incidence and multiple-incidence families (Ozonoff et al., 2011).

Potential explanations for motor difficulties in ASD

Several different sources suggest that motor impairment is potentially a key aspect of ASD, rather than being a 'secondary-level' deficit. One suggestion is that these problems are due to specific impairments with perception-action coupling rooted in an underlying difficulty with temporal control (Whyatt & Craig, 2013a). In particular, children with ASD have been found to display an inability to adapt the temporal characteristics of their movements to external spatial constraints. For example, while catching a moving ball, one needs to visually pick up information from the ball movement to predict when and where the ball will arrive, and simultaneously control the movement of the catching limb in order to intercept the ball's path at the right time and the right place (Green et al., 2009; Whyatt & Craig, 2013b). This line of thought also fits with Wolpert and colleagues' idea about internal forward models, where information from sensory signals (e.g. visual or audio) is combined with information on the current state of the joints in order to make reliable predictions about upcoming states (Miall & Wolpert, 1996; Wolpert, 1997). Thus, problems with predictive ability in ASD might be due to issues with perception-action coupling.

Might it be the case that children with autism actually perceive the world differently compared to typically developing children? There are several lines of research demonstrating that individuals with ASD make use of sensory input in a different way as compared to typically developing individuals. Milne, Swettenham and Campbell (2005) published a review paper concluding that individuals with ASD have reduced sensitivity to visual motion, and that this impairment can be generalized across many types of motion, for example response to optic flow, coherent motion and biological motion. Falck-Ytter, Rehnberg and Bölte (2013) assessed viewing preference for point-light displays in three-year-old children with autism and typically developing controls. Results showed that the children with autism did not orient to either biological motion or audio-visual synchrony, whereas the typically developing children did. These results indicate further evidence for difficulties with integrating sensory signals in ASD. Concerning proprioception, research suggest that this sense is intact in ASD (Fuentes, Mostofsky, & Bastian, 2011), and even that individuals with the disorder have a much stronger than usual association between motor commands and proprioceptive feedback (Cascio et al., 2012). Haswell and colleagues (2009) showed that greater reliance on proprioceptive feedback in ASD lead to more severe problems in social functioning and imitation. If there is some anomaly in how individuals with ASD perceive the world already at a sensory level, this will inevitably affect planning of new movements and predictive motor control at following points in the perception-action loop. Some researchers even go to the somewhat extreme end of calling autism a 'disorder of prediction' (Sinha et al., 2014). According to the authors of this review paper, the world can appear 'magical', if you lack the ability to predict what will happen next. Sinha and colleagues (2014) suggest that predictive impairments might lead to many of the more salient traits seen in ASD, such as difficulties with theory-of mind and insistence of sameness.

Which brain processes can relate to the problems with prospective control seen in ASD? The fact that predictions of upcoming events seem compromised suggests that the cerebellum is involved, since one of the main functions of the cerebellum is to handle timing of voluntary movements. Indeed, several brain imaging studies have shown the presence of cerebellar abnormalities in ASD (Brambilla et al., 2003; Courchesne, 1997; Haas et al., 1996). Interestingly, it has also been suggested that the forward models of object and arm dynamics are stored in the cerebellum (Davidson & Wolpert, 2005; Kawato et al., 2003). Further, the cortico-cerebellar loop, a pathway in the brain that is central for prospective control of action, has been argued to be compromised in ASD (von Hofsten & Rosander, 2012). Another neural network popularly associated with ASD is the MNS. Since the MNS has been strongly connected to social cognition, and problems in this area are a core diagnostic symptom of ASD, it is not difficult to see why an impaired MNS seems like a strong candidate for a neurobiological explanation of ASD. Several different brain-imaging techniques have been used to demonstrate impairment in classical MNS brain areas in ASD (e.g. Dapretto et al., 2006; Iacoboni & Dapretto, 2006; Martineau, Cochin, Magne, & Barthelemy, 2008; Oberman et al., 2005; Théoret et al., 2005), but there are behavioral findings to challenge this link (e.g. Falck-Ytter, 2010; Hamilton et al., 2007; Leighton, Bird, Charman, & Heyes, 2008). Braadbaart and colleagues (2013) suggest that instead of a specific deficit in mirror neurons, the reduced mu desynchronization seen in ASD might be explained by a more general deficit in visuomotor integration, and Boria and colleagues (2009) suggest that a possible MNS deficit in ASD might be more related to a chain-based mirror mechanism (i.e. more concerning neural networks, cf. Cattaneo et al., 2007), rather than malfunctioning of mirror neurons per se. Thus, the discussion concerning the 'broken mirror hypothesis' of ASD is still the subject of controversy. In addition, both the MNS and the cortico-cerebellar loop rely on distal cortical connections, which have been evidenced as weak in individuals with ASD. Wolff and colleagues (2012) demonstrated that long-range connections are weak in ASD, starting off as overdeveloped during the first year of life, and then clearly underdeveloped at 24 months.

Comorbidity in ASD

It is clear that ASD is a heterogeneous, complex syndrome and that single-cause explanations will by no means suffice. Here the focus of discussion has been on the possibility that prospective motor control and predictive ability might be a suitable candidate for some of the impairments seen in ASD. However, to pinpoint one isolated cause or an isolated risk marker for this disorder is difficult, if not impossible. As has already been pointed out, the relation between the performance of high-risk infant siblings at a young age, and their actual risk of receiving a diagnosis themselves, is complicated. Until we have the outcome data on which of the sibling participants actually become diagnosed with ASD, it is unclear whether the results of Study III are specific to ASD or neurodevelopmental disorders more generally. It is likely that the outcome evaluation at age three years will show that different diagnostic categories are present in the high-risk cohort. This has to do in part with the fact that comorbidity in ASD is very common (Lai et al., 2014), and that the broader autism phenotype is more common in family members of individuals with the disorder (Bailey et al., 1998; Bolton et al., 1994). Thus, finally I would like to comment on the relation between ASD and other neurodevelopmental disorders presenting with motor issues, and specifically concerning Attention Deficit/Hyperactivity Disorder (ADHD).

Motor disorders with high comorbidity with ASD include developmental coordination disorder, stereotypic movement disorder and Tourette's disorder (Lai et al., 2014). ADHD is not an explicit motor disorder, but neither is ASD. Nonetheless, both ASD and ADHD commonly present with motor impairments. One of the new features of DSM-5 (APA, 2013) is the possibility to have both a diagnosis of ASD and ADHD at the same time. It is common for individuals with ASD to also have symptoms of ADHD, whereas the other way around is more unusual (Mayes, Calhoun, Mayes, & Molitoris, 2012). There are both overlapping and discriminating symptoms of ASD and ADHD, however, when the disorders are considered in their more 'pure' form, differences in neuropsychological and clinical profiles are fairly evident (Gargaro, Rinehart, Bradshaw, Tonge, & Sheppard, 2011).

Motor issues in ADHD mainly involve exaggerated motor activity due to problems with inhibition, thus the problem then lies at a level of executive functioning (Johnson, Gliga, Jones, & Charman, 2014; Van Waelvelde, Oostra, Dewitte, Van Den Broeck, & Jongmans, 2010). (This can be compared with Tourette's disorder that involves problems with motor inhibition directly at the level of the motor cortex (Ziemann, Paulus, & Rothenberger, 1997).) Similarly to ASD, children with ADHD show delays in achieving motor milestones, and compared to typically developing children, they also have problems with manual dexterity and balance, slower reaching speed and inferior reaching accuracy when reaching in the absence of visual feedback (Johnson et al., 2014). Reiersen, Constantino and Todd (2008) showed that children with a combination of ADHD and motor problems were more likely to have high levels of autistic traits. Finally, Izawa and colleagues (2012) examined the specificity of motor issues during motor learning in ASD as compared to ADHD. It was found that, when learning to perform a novel task, children with ASD rely over-selectively on proprioceptive cues at the expense of visual input, thus replicating their earlier finding (Haswell et al., 2009). In contrast, children with ADHD integrated visual and proprioceptive cues during learning, but had larger trial-to-trial variability.

Conclusions

In order to understand shared and distinct clinical pathways to ASD and other neurodevelopmental disorders, it is feasible to perform prospective longitudinal studies of infants who are likely to later develop different conditions. I would like to suggest that early motor delay or motor impairments can be considered a possible red flag for later disorders. Early interventions concerning motor issues could potentially hinder a possible developmental cascade, affecting areas beyond motor functioning. Disturbances in motor processes could compromise how children engage socially (Cattaneo et al., 2007; Haswell et al., 2009), if their reduced ability to prospectively control their own actions also compromises their ability to encode the goals of actions made by others. A constant lagging in action understanding makes it difficult to interact in a smooth manner. For example, if your predictive ability to judge what other people are doing is somewhat delayed, this might extend to difficulties with staying in pace in the social 'dance', including skills such as turn taking and eye contact.

A note on sex differences

No sex differences were found in any of the three studies included in this thesis. Also, the number of boys and girls was similar in all studies. Nonetheless, the possibility for sex differences in relation to the examined variables of the studies is still interesting to consider. Cunha and colleagues (2015) very recently published a paper examining how situational factors (such as posture), and maturational factors (such as gender) affect reaching at its very onset. Three-month-old infants participated, and the results showed that a reclined position facilitated reaching in terms of straighter reach trajectories, and, interestingly enough, it was also found that girls were more efficient reachers as compared to boys at this age. The girls reached more often than the boys, and performed straighter and faster reaches using fewer movement units. At the same time, there were no differences concerning the length of the reach, indicating that girls have better feed-forward motor control than boys at this age (Cunha et al., 2015). There was a weak correlation between these results and anthropomorphic measures, such that girls had less length and weight of the forearm as compared to boys, but similar upper arm volumes. These results indicate that it is important to take maturational factors, including sex differences, into account when examining reaching performance.

Concerning sex differences in relation to ASD, the risk of receiving an ASD diagnosis is more than four times higher among boys than girls (CDC, 2014). Despite this consistent difference in diagnosis rate, there is little research available that examines sex differences in early diagnostic features of ASD. Most studies report on the large female-to-male ratio in diagnostic rates, and the possible reasons for that. It is likely that several sex-differential genetic and hormonal factors contribute to this difference (Werling & Geschwind, 2013), but one other suggestion is that females are in fact under-diagnosed, possibly due to the fact that the DSM-IV-TR diagnostic criteria were developed and tested using a predominantly male sample (Reinhardt, Wetherby, Schatschneider, & Lord, 2014), making the criteria less sensitive to sex differences in the manifestation of ASD. With regard to high-risk samples it is likely that sex differences in children who do get a diagnosis are too subtle to detect at an early age (Reinhardt et al., 2014), but research that systematically assesses the ASD phenotype across age and developmental level should definitely consider possible sex differences.

Future directions

One important direction for future research is to more firmly establish the correlates between action perception and action production in infancy. In Study II we used the mu rhythm as a marker of MNS activity in eight-month-olds, but only using an observation condition. To fully explore the MNS hypothesis in infancy, a performance condition will be important. EEG is a useful method for this, but an execution condition will also impose methodological challenges due to an increased number of movement artefacts. It is hoped that these issues can be solved by carefully choosing a suitable action as well as appropriate analysis intervals. Another alternative would be to integrate EEG recordings with for example EMG. A solution like this would allow for better artefact rejection. Another possibility is to use other neurophysiological measures suitable for infant studies, such as near-infrared spectroscopy (NIRS). NIRS uses the BOLD-signal as a measure of brain activity (similar to MRI), and thus has worse timing resolution as compared to EEG, but a lot better spatial resolution. NIRS is also less sensitive to motion artifacts compared to EEG. The same designs as the ones just suggested could also be used to examine the functioning of the MNS in siblings at elevated familial risk for ASD.

Motor skill is built on a range of sub-competencies (Gowen & Hamilton, 2013; Wolpert & Ghahramani, 2000). Nevertheless, when motor issues are discussed in relation to the early developmental disorders, such distinctions are frequently ignored. Thus, one important direction for future research is to dismantle the various sub-compartments of ‘motor skill’ in order to see which are, and which are not, related to a particular developmental disorder. This entails moving beyond standardized scales of motor function. Rather, what seems to be needed are new experimental paradigms that tap into specific (sub-) functions, and which are suited for infants and young children (such paradigms already exist for older populations; see e.g. Izawa et al., 2012; Stoit et al., 2013). One example of such a paradigm would be to specifically assess younger siblings’ ability to prospectively plan their movements with regard to different goals states. For example, do infants at risk for a neurodevelopmental disorder reach faster for an object that will be placed in a large versus a small container (cf. Claxton et al., 2003; Fabbri-Destro et al., 2009)?

Future research in the area of motor impairments specifically in relation to ASD should clarify whether the early motor impairments seen in the disorder and in siblings of children with ASD are uniquely linked to ASD, or whether they are linked to developmental disorders frequently co-occurring with ASD. These questions will be partly answered by following up the current sample of Study III, which is likely to include children with a range of different outcomes (Ozonoff et al., 2014). Nevertheless, the inclusion of just one type of risk group (siblings of children with ASD) will limit the conclusions. Ideally, in order to address the specificity question, one should assess different risk groups, and conduct a comprehensive and unbiased follow-up assessment of categorical as well as dimensional outcomes.

Finally, it would be important to broaden the study of motor development in relation to ASD to include qualitatively different types of actions. For example, concerning motor execution, infants frequently bang objects repeatedly on surfaces – a behavior that could be conceived as a basic, early emerging percussive behavior later employed in tool use (Kahrs, Jung, & Lockman, 2013; Kahrs & Lockman, 2014; Kahrs, Jung, & Lockman, 2012, 2014) but which also has a clear repetitive aspect. Thus, banging behavior can possibly be related to the higher frequency of stereotyped and repetitive behavior seen in ASD (Loh et al., 2007; Thelen, 1996). From this perspective, studying the relation between early repetitive banging and later ASD outcome is a very interesting aim. As mentioned in the description of Study III, the motor assessment block in the EASE project includes a session where the infant is encouraged to freely bang an object on a table surface. Some preliminary analyses from this task have been made, showing that the high-risk group have higher mean velocities at impact as compared to the low-risk controls ($t(45) = 1.56$, $p = .05$, $d = .47$) (10- and 14-month-olds collapsed). We speculate that the higher velocities at impact performed by the high-risk group indicate failure to prospectively decelerate the movement in preparation for impact. The high-risk siblings also have larger individual strike variability concerning velocity at impact ($t(45) = 1.49$, $p = .02$, $d = .44$), thus, they are more variable in their applied force while banging. Besides velocity, we are also analyzing other variables, namely straightness ratio and angle of impact (cf. Kahrs et al., 2012), as well as stroke amplitude and area of impact. None of these variables showed any significant group differences using the current sample. Notably, these kinds of analyses cannot be made without recordings from a motion-tracking system. More data are needed before we can draw any firm conclusion regarding reduced prospective motor control while banging. Data collection and more final analyses concerning this work are currently ongoing.

Final conclusions

Manual motor development is profoundly important during infancy. Evidently this applies to several different viewpoints, not only with regard to locomotor achievements or considering kinematic profiles. The main contribution made by this work is the insight that it is important to take motor aspects into account when considering (social) cognitive development and social interaction. This certainly applies with respect to normal development but also regarding development that in some way deviates from the standard trajectory, as with the case of neurodevelopmental disorders. Suggestions have been given on how to further investigate the specific role of manual motor behavior to normal psychological development, and perhaps even more centrally, with regard to neurodevelopmental disorders that presents with both motor as well as social and/or cognitive difficulties, such as ASD.

Summary in Swedish

Den här avhandlingen handlar om den roll som utveckling av motoriska färdigheter spelar för perceptuell, kognitiv och social utveckling under spädbarnsåren. Fokus ligger på manuell motorisk utveckling, det vill säga förmågan att kunna sträcka sig efter och gripa föremål. Av alla motoriska färdigheter är gripning nog den som spelar störst roll för typisk utveckling av psykologiska förmågor. Genom att sträcka sig efter och gripa föremål lär sig det lilla barnet mycket om olika egenskaper hos objekt, men det för även med sig tillfällen att kunna socialisera med andra. Genom att observera andras griprörelser kan spädbarn dessutom lära sig att förutsäga resultatet av andras handlingar. Det övergripande syftet med avhandlingen är att studera vikten av manuell motorisk utveckling ur olika perspektiv; för det första genom att undersöka en viktig förutsättning för effektiv griputveckling, mer specifikt stereopsis eller binokuläritet, för det andra genom att beakta förståelsen för andras målinriktade handlingar, genom att mäta desynkronisering av myrytmen som ett mått på spegelneuronaktivitet, och för det tredje i relation till möjlig avvikande utveckling, med särskilt fokus på autismspektrumtillstånd (AST). De gemensamma nämnarna för de tre empiriska studier som genomförts är dels tanken att motorisk förmåga är en central komponent i flera psykologiska processer, och dels att motorprediktion är en nyckelaspekt till effektivt utförande av egna griprörelser samt förståelse av andras griprörelser.

Syftet med Studie I är att undersöka hur snabbt och korrekt spädbarn utför griprörelser när de får titta med båda eller endast ena ögat. Denna studie motiverades av det faktum att effektiv planering av handlingar och motorprediktion är beroende av tillgången till information om djup och avstånd. Resultaten visar att både sex, åtta och 10 månader gamla spädbarn utför långsammare och mindre exakta griprörelser när de har ena ögat täckt. Det faktum att det tog längre tid för barnen att slutföra rörelsen med ena ögat täckt tyder specifikt på att motorprediktion är mindre effektivt när tillgången till information om djup och avstånd är begränsad.

Syftet med Studie II är att se om man kan finna neurala bevis för ett spegelneuronssystem hos spädbarn som endast observerar en vuxen som utför en målinriktad griprörelse som de även klarar av att utföra själva. Forskning på vuxna föreslår att andra människors handlingar kan förstås och även förutses genom att man överför det man ser på sina egna motoriska representationer av dessa handlingar. Med hjälp av EEG mätte vi desynkronisering av

myrytmen som ett mått på spegelneuronaktivitet hos åtta månader gamla spädbarn. Resultaten visar att barn i denna ålder verkar ha ett spegelneuronssystem som fungerar på liknande sätt som vuxnas, då myrytmen desynkroniserade mest vid observation av en målinriktad griprörelse. Aktiveringen var även prediktiv, vilket tyder på att spädbarnen kunde förstå och förutsäga målet med den observerade handlingen.

Syftet med Studie III var att undersöka förmågan hos småsyskon till barn med AST att prospektivt kontrollera sina egna griprörelser när de fångar en rullande boll. Studie III motiverades av forskningsresultat som visar att individer med AST har särskilt svårt att prospektivt kontrollera sina egna handlingar, och det faktum att man känner till väldigt lite om motorisk problematik hos barn med, eller med förhöjd risk att få, AST. Resultatet visar att, jämfört med en kontrollgrupp som inte löper förhöjd risk att diagnostiseras med AST, så är 10 månader gamla småsyskon till barn med AST långsammare på att börja röra sin arm, och de utför även reaktiva istället för prediktiva griprörelser. Småsyskonen började alltså inte röra sin arm mot den rullande bollen förrän den kommit inom räckhåll. Kontrollgruppen däremot, börjar röra sin arm mot bollen på ett förberedande sätt.

Sammantaget är det viktigaste bidraget med den här avhandlingen insikten om hur viktigt det är att beakta manuell motorisk förmåga när man utvärderar både typisk, men även avvikande, kognitiv och social utveckling. Slutsatserna från de respektive studierna tyder även på att motorprediktion är en nyckelfaktor bakom effektivt utförande av egna, samt förståelse av andras, målinriktade griprörelser.

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