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Prediction in Typical and Atypical Development

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Abstract
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Forming predictions about what is going to happen next is a crucial ability that develops early in life. Theory and some empirical evidence suggest that predictive abilities may be impaired in Autism Spectrum Disorder (ASD). The overarching aim of this thesis is to investigate early measures of prediction in relation to concurrent and later outcomes in typical and atypical development, with a particular focus on ASD and related behavioral problems.

In Study I, we used motion capture technology to examine prospective motor control and its relationship to executive functions in typically developing 18-month-olds. Our findings showed that motor control is associated with executive functioning in infancy.

Study II investigated motor control in infants at low and elevated likelihood for ASD and examined how these measures relate to later development. We found group differences as well as similarities in motor control in 10-months-olds with and without a familial history of ASD. Early motor measures were related to general developmental level, but not ASD symptomatology in toddlerhood.

Using eye tracking, Study III examined how infants with later ASD and neurotypical infants form predictions about visual object motion. Our findings indicated that infants with later ASD were able to form predictions about object motion and adapt to simple changes in motion patterns, and that their performance did not differ from the performance of neurotypical infants.

In Study IV, we surveyed parents about their experiences during participation in an infant sibling study of ASD as a first step to understanding the benefits and risks associated with this type of research. Parents were generally positive about their experiences both from their own perspective as well as, the child's perspective.

This thesis illustrates the potential of using advanced technology, such as motion tracking and eye tracking, to study and compare prediction in typical and atypical development. It points to the important role of prediction and motor control for child development, but fails to find a specific link to ASD.

Keywords: Prediction; Infancy; Developmental Psychology; Motor Development; Motor Control; Motion Tracking; Executive Functions; Embodied Cognition; Eye Tracking; Visual Motion; Predictive Coding; Autism Spectrum Disorder; Infant Siblings

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Prediction is very difficult.
Especially if it's about the future.

Niels Bohr, Nobel Laureate, 1885 – 1962

List of Papers

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

I Gottwald, J. M., Achermann, S., Marciszko, C., Lindskog, M., & Gredebäck, G. (2016) An Embodied Account of Early Executive-Function Development. *Psychological Science*, *27*(12):1600–1610, doi:10.1177/0956797616667447

II Achermann, S., Nyström, P., Bölte, S., Falck-Ytter, T (2020) Motor Atypicalities in Infancy are Associated with General Developmental Level at Two Years, but Not Autistic Symptoms. *Autism (forthcoming)*, doi:10.1177/1362361320918745

III Achermann, S., Falck-Ytter, T., Bölte, S., & Nyström, P. (2020) Updating Expectations about Unexpected Object Motion in Infants Later Diagnosed with Autism Spectrum Disorder. Manuscript submitted for publication.

IV Achermann, S., Bölte, S., Falck-Ytter, T. (2020) Parents' experiences from participating in an infant sibling study of autism spectrum disorder. *Research in Autism Spectrum Disorder*, *69,* 101454, doi:10.1016/j.rasd.2019.101454

The contribution of Sheila Achermann to the studies included in this thesis, namely Study I, II, III, and IV, was as follows. In Study I, Sheila Achermann contributed to the study design, collected and analyzed data, and revised the manuscript. In Study II, III, and IV, Sheila Achermann was responsible for data collection, analysis, and writing the manuscripts with contributions from co-authors.

Content

Abbreviations

ADHD	Attention Deficit Hyperactivity Disorder
ADI-R	Autism Diagnostic Interview-Revised
ADOS-2	Autism Diagnostic Observation Schedule, 2nd Edition
ANOVA	Analysis of Variance
AOI	Area of Interest
ASD	Autism Spectrum Disorder
CS	Comparison Score
DSM	Diagnostic and Statistical Manual of Mental Disorders
EASE	Early Autism Sweden
EEG	Electroencephalography
EL	Elevated Likelihood
EMG	Electromyography
HR-ASD	Heightened-Risk with ASD
HR-noASD	Heightened-Risk with no ASD
IQ	Intelligence Quotient
LL	Low Likelihood
LR	Low-Risk
M	Mean
MRI	Magnetic Resonance Imaging
MSEL	Mullen Scales of Early Learning
MU	Movement Unit
SD	Standard Deviation
SE	Standard Error
TD	Typically Developing / Typical Development
TU	Transport Unit

Introduction

From very early age, our environment requires us to constantly make predictions about upcoming events, whether we are intending to perform an action or if we are reacting to occurrences in our surroundings. Our actions are directed toward the future, which requires that we understand upcoming events, interpret regularities and extract information to form accurate predictions. Thus, predictions are a necessary requisite in order to act efficiently in our dynamic environment (Gredebäck, von Hofsten, & Boudreau, 2002; von Hofsten, 2004). For example, when catching a ball during play, we inherently predict the ball's position, velocity, and motion direction. In addition, we prepare our own bodily actions when visually detecting the ball's motion: planning the manual reach, and estimating the intersection point of the ball and the hand. These complex processes are fundamental to performing purposeful actions.

When it comes to social situations, similar complex processes take place. This happens in a conversation, for instance, when interpreting another person's intentions, emotions, and focus of attention. Who is going to say something next, and what is going to be said? Therefore, understanding social interaction and communication encompasses observing, listening, as well as looking and shifting one's gaze from one interaction partner to another or to an object (Von Hofsten, 2009). Taken together, the ability to form predictions is a crucial factor for learning and interacting, even in early development.

But what if the ability to form predictions is impaired? Recent literature points toward atypical predictions in autistic individuals (Lawson, Rees, & Friston, 2014; Pellicano & Burr, 2012; Sinha et al., 2014; Van de Cruys et al., 2014). However, few studies have investigated whether atypical predictive abilities are present in early development and are perhaps involved in the trajectories that lead to autism spectrum disorder (ASD). This thesis provides novel insight into the development of prediction and how early prospective control relates to outcomes later in life. By including studies of typically and atypically developing children, I am able to highlight different aspects relevant for developmental pathways.

Study I investigated prospective motor control using motion capture technology in relation to executive function in 18-month-olds. Study II took a similar approach by using motion capture technology to examine motor functioning in 10-month-old infants in relation to later ASD symptomatology. Study III longitudinally investigated how 10-month-old infants with later ASD formed predictions about visual object motion using eye tracking. Finally, Study IV took another perspective and discussed ethical considerations about prospective longitudinal studies of ASD.

I will begin by providing a theoretical background on prediction, the role of prediction in early development, and its relation to ASD. Next, I will introduce the aspects of prediction examined in the studies, namely prospective motor control and visual motion prediction. Finally, I will approach prediction from another perspective and discuss research efforts in finding early markers of ASD in order to further understand and eventually predict later diagnostic outcomes.

Prediction in typical and atypical development

Magicians make the unbelievable believable, the impossible possible, or the unpredictable predictable. Most of us enjoy a magical performance; however, what if our whole environment is "magical" or perceived as unpredictable? Not being able to predict what happens next and adapt to changes in the environment restricts our ability to navigate in the world. This may lead to feeling overwhelmed, having a lack of control over the situation, and will impede performance. Given the importance of prediction, it is not surprising that predictive abilities start developing as early as infancy.[1] In the context of this thesis, I refer to prediction in a broad sense, meaning that prediction includes a range of predictive abilities from predictive looking behavior to prospective motor control (see e.g., von Hofsten, 1993).

Role of prediction in early development

Already at 22 weeks of gestation, kinematic analyses revealed that a fetus performs coordinated actions regarding spatial and temporal characteristics of movements. This finding suggests that a fetus shows early signs of prediction and planning of actions (Zoia et al., 2007). This ability further develops throughout the first months after birth. Infants at around 12 weeks of age are

[1] In the literature, there is no clear consensus as to use of the terms "prediction" or "anticipation". While some differentiate the terms, others use them interchangeably. Here, I use "prediction" as an overarching term indicating processing toward future-directed actions and including actions elsewhere defined as anticipation or expectation.

already able to track objects with their gaze, suggesting basic knowledge in predicting how objects move in time and space (Agyei, van der Weel, & van der Meer, 2016; Rosander & von Hofsten, 2002, 2004).

Around the same age, infants start to reach prospectively for objects. Learning to reach is described as one of the most important transitions in development and enables the infant to explore and interact with its surroundings in entirely new ways (Corbetta, Thurman, Wiener, Guan, & Williams, 2014; Thelen et al., 1993; von Hofsten, 1991, 2004). The ability to prospectively plan and control motor actions is improved throughout the first year of life. At 10 months of age, infants can already perform complex motor actions that require predictive abilities (Claxton, Keen, & McCarty, 2003). In addition, infants around this age, not only behave in a predictive manner when it comes to their own actions, but they also predict what other people are going to do next (Falck-Ytter, Gredebäck, & von Hofsten, 2006; Rosander & von Hofsten, 2011).

Taken together, it is clear that already in infancy, actions are directed toward the future and based on assumptions about what happens next. This kind of prospective control develops early in life and emerges simultaneously with a variety of new skills (von Hofsten, 2004, 2007).

Prediction in autism spectrum disorder

Not being able to understand social and non-social cues in our environment and therefore not being able to predict what happens next, may have a profound effect on functioning in multiple domains. In ASD, theories that highlight the importance of prediction have recently been introduced. For example, it has been proposed that impairments in the ability to form predictions and use them efficiently could underlie the core symptoms of ASD (Sinha et al., 2014).

ASD is a common neurodevelopmental condition with core symptoms in two domains: social communication and interaction, and restricted and repetitive behaviors (American Psychiatric Association, 2013). Theoretically, impaired predictive ability could account for atypicalities related to ASD, such as impairments in social functioning, sensory hyper- or hyposensitivity, difficulties in motor performance, and problems with theory of mind (Sinha et al., 2014). All of these domains introduce a degree of uncertainty, depending on how one anticipates a stimulus, ranging from catching a moving object to predicting actions of another person. At the same time, predictive ability may also assist in explaining observed islands of proficiency in ASD. For instance, individuals with ASD have been shown to outperform neurotypical individuals in visual search tasks, block design tasks, static form

coherence, or mathematics. Such tasks are rule-based and often static, which reduces the uncertainty of outcomes and therefore may facilitate predictions for individuals with ASD (Sinha et al., 2014).

The theory of predictive coding has become increasingly popular in the literature, providing a framework of how we perceive our environment and how we form predictive models based on experiences. It has been suggested that the process of forming predictions (Pellicano & Burr, 2012) or how predictive models are treated (Van de Cruys et al., 2014) may be compromised in ASD. Impaired predictive abilities may result in not being able to respond to changes in the environment, as well as perceiving the environment as uncontrollable, unpredictable, or even magical.

In sum, prediction is a fundamental process that develops early in life, and alterations may be present in early development across multiple domains.

Prediction and motor control during action execution

Research efforts have increasingly been directed toward investigating prospective motor control across a variety of measures. In the following sections, I will introduce a more detailed view on new techniques used to assess motor control and associated findings, with a particular emphasis on studies related to ASD.

New techniques to assess motor control in infancy

Motor control is essential for an infant's development and for the infant's interaction with the environment (Bushnell & Boudreau, 1993; E. J. Gibson, 1988). The development of motor control is related to a variety of skills throughout development, such as cognitive functions (Libertus, Joh, & Needham, 2016; Mohring & Frick, 2013), but also social interaction and communication skills (Cannon, Woodward, Gredebäck, von Hofsten, & Turek, 2012; Falck-Ytter et al., 2006).

Previous literature on motor development in infancy has typically been based on retrospective home videos, parent report, or performance on broad standardized tests. These measures may not be sufficiently precise or valid to explain the fine-grained nature of motor control, and may therefore confound motor control with other behavioral characteristics. However, advances in technology have enabled researchers to perform detailed quantitative assessments. Precise timing measures, accelerometers, electromyography (EMG), or 3-dimensional (3D) motion tracking technology allow us to ex-

amine motor control in more detail. These methods may even uncover subtle findings not visible with more broad measures.

For example, analyzing kinematic profiles of manual actions helps us to understand the microstructure of movements. Through kinematic analyses, movements can be divided into separate movement units (MU). A movement unit includes an acceleration and a deceleration. The acceleration following the first deceleration marks the onset of the next movement unit (von Hofsten, 1991). For example, when an infant reaches, movements often start with a large first movement unit, which decelerate into small adjustments toward the end of the reach (Jeannerod, 1988; Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987). In young infants, however, more adjustments are needed during the manual action in order to reach successfully. With maturation, the number of movement units decreases, which is a measurement for the straightness and efficiency of the reach (von Hofsten, 1991; von Hofsten & Lindhagen, 1979).

By assessing kinematic profiles, Kahrs, Jung, and Lockman (2013) found differences in younger and older infants when banging a hammer-like object. Younger infants showed an inconsistent pattern with trajectories varying in distance traveled, straightness, and peak velocity. Older infants, however, banged objects in an efficient and consistent pattern, characterized by consistent length and velocity of hand trajectories. More recent studies suggest peak velocity of the first movement unit as a measure of prospective motor control[2] (Gottwald et al., 2017; Gottwald & Gredebäck, 2015). Prospective motor control is an integral component in the planning of goal-directed movements and entails the ability to adapt movements with respect to future goals or tasks (von Hofsten, 1993). For example, Gottwald et al. (2017) investigated how 14-month-olds adjusted their manual motor actions with respect to task goals and difficulty in a reach-to-place task. Kinematic analyses revealed that if task difficulty was high, infants performed reaches with lower peak velocity of the first movement unit.

Taken together, these findings suggest that infants are able to plan action sequences and prospectively control movements with respect to future action goals and task demands. In addition, the results highlight the many ways kinematic variables can be used to access the microstructure of manual motor actions.

[2] In this thesis, the term "prospective motor control" is used when describing the ability to control and plan motor actions. In the literature, both "predictive motor control" and "prospective motor control" are used. These terms are often treated as synonyms; however, Ledouit, Casanova, Zaal, and Bootsma (2013) have highlighted differences between the terms.

Studies on motor control in autism spectrum disorder

Although social impairments and restricted, repetitive behaviors are the core diagnostic features of ASD, motor control has been of special interest in the literature. Difficulties in motor control are frequently observed in autistic individuals (Fournier, Hass, Naik, Lodha, & Cauraugh, 2010; Green et al., 2009). However, several aspects regarding these findings are yet to be clarified. First, it remains unclear which aspects of motor control are affected early in life. Second, it has not yet been determined if the observed differences are unique to individuals with ASD, or are instead a reflection of comprised neurocognitive development.

In order to investigate early developmental trajectories, research has turned to studying infant siblings of autistic children (Elsabbagh & Johnson, 2010). Genetics play an important role in the etiology of ASD (Lai, Lombardo, & Baron-Cohen, 2014). Due to its heritability, the recurrence is higher in families with a history of ASD (Constantino, Zhang, Frazier, Abbacchi, & Law, 2010; Ozonoff et al., 2011; Sandin et al., 2014). Therefore, infant sibling studies offer a promising approach in studying early trajectories that lead to ASD.

Several studies have reported findings from infant sibling studies regarding early motor impairments in ASD. There is evidence suggesting differences in a variety of motor measures, ranging from atypicalities in postural control (Flanagan, Landa, Bhat, & Bauman, 2012), to lower performance on certain scales using standardized tests of fine and gross motor development (Landa & Garrett-Mayer, 2006), to differences in reaching behavior (Ekberg, Falck-Ytter, Bölte, & Gredebäck, 2016; Focaroli, Taffoni, Parsons, Keller, & Iverson, 2016; Sacrey, Zwaigenbaum, Bryson, Brian, & Smith, 2018). Nevertheless, some studies have failed to find clear group differences between infant siblings with familial history of ASD and infant siblings from neurotypical families (Iverson & Wozniak, 2007; Taffoni, Focaroli, Keller, & Iverson, 2019).

In a large infant sibling study of ASD, early differences in fine and gross motor measures in infants with familial history of ASD were not specific to infants who were later diagnosed with ASD. In addition, when interpreting the findings, it should be taken into account that infant sibling groups are characterized by a large heterogeneity and may include infants with a variety of developmental concerns (Iverson, 2018). Nevertheless, even if motor differences may not predict ASD specifically, motor differences may affect development in other domains, such as social communication, language, and cognition. Impairments in motor control may restrict infants' opportunities

for learning, which thus may affect the development of skills in other domains (Sacrey et al., 2018).

Prospective motor control in early development is of special interest in this thesis. In ASD, studies on prospective motor control have mainly included older autistic children. Thus, the early development of prospective motor control in ASD is not well understood. However, similar to the aforementioned findings on motor differences, evidence for impairments in prospective control is inconsistent. Previous studies on how infants, older children, and young adults with ASD execute manual motor actions show indications of differences in motor control, albeit the ability to perform motor tasks (Focaroli et al., 2016; Mari, Castiello, Marks, Marraffa, & Prior, 2003; Rinehart et al., 2006).

Taken together, evidence suggests that motor difficulties are a feature of the autism phenotype and should be considered in the evaluation of ASD (Licari et al., 2019). Early development of motor functioning, and prospective motor control should be studied further. Specifically, relying on broad standardized measures exclusively may not capture the subtle differences that are detectable with detailed measures that use advanced technology. Thus, to understand the underlying nature and subtle variations in motor development, kinematic analyses using motion tracking technology are motivated.

From movement to cognition

How we move influences what we perceive in our environment, how we interact with our environment, and how we form predictions. Achieving motor milestones in development, such as sitting, reaching, crawling or walking, changes the ways in which an infant can interact with the environment. For example, sitting unsupported improves an infant's visual exploration, reaching improves object manipulation and exploration, and crawling and walking create multiple new opportunities to learn from and interact with the physical and social world. Therefore, motor impairments in infancy may inhibit the learning that occurs during everyday actions in a crucial developmental period (Iverson, 2010, 2018).

There is evidence for a link between early motor measures and social, emotional and cognitive skills. Regarding social cognition, it has been shown that children with motor difficulties are less likely to be involved in social play with their peers (Bar-Haim & Bart, 2006; Smyth & Anderson, 2001). Not participating in social play may result in fewer opportunities for positive social interactions, not only in terms of social play but also for other types of social interactions. Individuals with motor impairments may miss out on the positive reinforcement that occurs during such interactions, and as a result

no longer engage in social activities (Sacrey et al., 2018). In addition, motor impairments are related to atypicalities in emotion recognition and comprehension (Cummins, Piek, & Dyck, 2005; Piek, Bradbury, Elsley, & Tate, 2008), providing evidence for the importance of motor skills in socio-emotional development.

Regarding cognitive development, it has been shown that manual exploration of objects increases 6-month-olds' ability to mentally rotate objects (Mohring & Frick, 2013). Furthermore, motor training at 3 months of age has been shown to improve attention focusing skills and object exploration at 15 months of age (Libertus et al., 2016). This provides further evidence for the link between motor control and cognitive skills.

Another set of skills within cognition is executive functioning. Executive functions can be defined as self-directed, higher-order cognitive processes that underlie the ability to set goals and act toward those goals (Barkley, 2012; Hendry, Jones, & Charman, 2016; Stephens, Watson, Crais, & Reznick, 2018). The core executive functions include inhibition, working memory, and cognitive flexibility (Diamond, 2013). Executive functions emerge early in life and show strong links to later academic achievement (Best, Miller, & Naglieri, 2011; Blair & Razza, 2007; Bull & Scerif, 2001). Difficulties in executive functions have been shown to be associated with neurodevelopmental conditions, namely attention deficit hyperactivity disorder (ADHD, Barkley, 1997) and ASD (Demetriou et al., 2018).

Empirical evidence indicates that executive functions are related to motor control. First, neural structures (i.e., prefrontal cortex and cerebellum) are regions associated with both executive functions and motor control (Barkley, 2012; Diamond, 2000). Second, in frequently co-occurring neurodevelopmental conditions, namely ADHD and ASD, impairments in both executive functions (Barkley, 1997; Demetriou et al., 2018) and motor control (Fournier et al., 2010; Kaiser, Schoemaker, Albaret, & Geuze, 2015) are often observed. Third, longitudinal studies have found associations between early motor milestones and executive functions in adulthood (Murray et al., 2006; Ridler et al., 2006). Fourth, there is evidence for an association between executive functions and motor control in development, indicating that motor measures are related to working memory and inhibition in childhood (Houwen, van der Veer, Visser, & Cantell, 2017; Piek, Dawson, Smith, & Gasson, 2008; Smith, Thelen, Titzer, & McLin, 1999).

In addition, theoretically, action planning requires different levels of control, such as higher-order cognitive control and low level motor control (Grafton & Hamilton, 2007; Hamilton & Grafton, 2007). There is reason to assume that higher-order cognitive planning and control, in an executive function

sense, is related to lower level motor control. Similarly, at a behavioral level, higher-order cognitive functions are involved in performing motor actions. For example, when catching a ball, a sequence of motor commands has to be planned and monitored in order to be successful. Unnecessary movements have to be inhibited and relevant movements have to be corrected and adjusted according to task demands. Arguably, motor control involves aspects of executive functioning, and executive functioning involves aspects of motor control.

Taken together, it is clear given the many links between motor control and cognition, the two domains should be understood and studied in concert. Along the same lines, the embodied cognition account proposes that cognitive processes are rooted in bodily movements, indicating that movements are crucial in shaping the mind (Wilson, 2002).

Predicting external physical events

Accurately perceiving and identifying events or objects in space and time is essential to guiding manual actions. Thus, we typically rely heavily on our visual system to guide motor actions. In this section, I introduce the development of visual perception for prospective control. Afterward, I will discuss findings on predictive looking behavior in typical and atypical development.

Predictive looking in infancy

Looking is an active process. By studying infants' looking behavior, we can understand how predictive abilities develop early in life. At around 2 months of age, a first early indicator of prospective control is measurable through infants' ability to track a moving object (Rosander & von Hofsten, 2002; von Hofsten & Rosander, 1996). This ability develops further during the following months. At around 6 months of age, infants follow objects with predictive head and eye movements (Jonsson & von Hofsten, 2003). Thus, it is clear that at this age, infants are able to take visually perceived constraints into account in order to guide motor actions (Jonsson & von Hofsten, 2003; van der Meer, van der Weel, & Lee, 1994; von Hofsten, Vishton, Spelke, Feng, & Rosander, 1998).

In our environment, certain objects may be behind others, or may temporarily be out of sight and then reappear again. At around 6 months of age, the ability to track a moving object persists despite temporary occlusion (Kochukhova & Gredebäck, 2007; Rosander & von Hofsten, 2004). It has been suggested that predicting visual motion despite temporary occlusion

occurs in at least two different ways. The first, in which infants predict the reappearance location of moving objects, occurs through basing their prediction on how objects generally move in time and space. If an object moves on a straight trajectory, it is likely that the object would continue on that trajectory, and the pre-occlusion path can be extrapolated. The second way, in which infants predict the reappearance after occlusion, occurs through basing their expectations on recent experience. If an object moves on a certain (non-linear) trajectory, it is likely that the object will continue to move on this trajectory (Kochukhova & Gredebäck, 2007).

In sum, 6-month-olds are already able to track moving objects, which allows them to predict an object's trajectory. Visual tracking is vital for prospective motor control because this information is used to guide goal-directed motor actions. This ability has been widely investigated in typical development. However, the development of visual motion perception in infants with later ASD is not fully understood, and the link to ASD symptomatology and diagnosis needs to be investigated further.

Studies on visual motion prediction in autism spectrum disorder

To address predictive looking behavior in ASD, von Hofsten, Uhlig, Adell, and Kochukhova (2009) investigated three predictive behaviors in three different tasks. First, a task that investigated how children track a moving object; second, an occlusion task that measured predictive gaze shifts to the reappearance of an object; and third, a social task on predictive gaze shifts when looking at a social interaction. Interestingly, autistic children tracked moving objects with smooth pursuit and showed predictive looking behavior similar to neurotypical children. However, the authors did find differences in the social task, since autistic children did not predict the dynamics of a social interaction in the same way as neurotypical children. Hence, it has been proposed that autistic children are able to form accurate predictions about external physical events, but that the impairment lies in forming predictions in a social setting. However, Falck-Ytter (2010) found no indication of such an impairment in a social predictive task of action observation. Autistic children showed predictive gaze shifts no different than neurotypical children. Nevertheless, prediction in social settings may underlie different mechanisms and may differ fundamentally from prediction of non-social events.

Recently, theories of predictive coding in ASD have become increasingly popular when describing observed differences in predictive abilities (Pellicano & Burr, 2012; Van de Cruys et al., 2014). The predictions we make about events in our environment are compared to incoming information from our senses, as well as and prior information from experience. This process, or aspects of it, may be comprised in ASD. For example,

Pellicano and Burr (2012) suggested that autistic individuals are less influenced by prior experience when forming predictions. Thus, according to this account, perception is seen as more accurate or "becomes too real" (Pellicano & Burr, 2012, p. 509), which has effects on how one perceives the environment.

On the other hand, Van de Cruys et al. (2014) suggested that predictive atypicalities in ASD are related to how information is processed when predictive models are compared to incoming information. Autistic individuals may assign atypically high weight to prediction errors (HIPPEA; High, Inflexible Precision of Prediction Errors in Autism). Prediction errors reflect a bottom-up process that is indicative of the mismatch between sensory input and predictions. In addition, prediction errors are dependent on top-down processing coming from predictions. These predictions, in turn, are based on previous prediction errors. Thus, the predictive coding account reflects a complex interplay of bottom-up and top-down influences to process information in our environment (Van de Cruys et al., 2014).

Van de Cruys et al. (2014) proposed that the way in which autistic individuals respond to prediction errors provides an explanation of the observed atypicalities in ASD. Giving precision of prediction errors a high weight will lead to more frequent updates of predictive models. This process is thought to be inflexible, and the weighting may not be flexibly adjusted to different environmental constraints. However, predictive abilities in ASD are not deficient per se, according to Van de Cruys et al. (2014). It is proposed that autistic individuals still form predictions and compute prediction errors correctly. When it comes to low-level processing, setting precision high by default may even act as an advantage (Van de Cruys et al., 2014).

Looking at empirical data, there is some support for impaired prediction in ASD (Lawson, Mathys, & Rees, 2017; Park, Schauder, Kwon, Bennetto, & Tadin, 2018). The evidence, however, remains inconsistent. For example, through measuring the pupillary response to an unexpected event when a prediction was violated, it was determined that autistic adults were less surprised than neurotypical adults (Lawson et al., 2017). On the other hand, no difference was found between autistic and neurotypical children in how statistical information was used to guide decision-making in a probabilistic learning task (Manning, Kilner, Neil, Karaminis, & Pellicano, 2017), or in a visual extrapolation task when predicting object motion (Tewolde, Bishop, & Manning, 2018).

In sum, some studies find differences between autistic and neurotypical individuals in visual motion prediction, and others fail to do so. Alterations in predictions should affect individuals across domains, which includes the

perception of visual motion. Moreover, as predictive abilities emerge early in life, it is surprising that few studies have investigated early motion prediction in young infants with familial history of ASD.

Infant markers of autism spectrum disorder

ASD is often diagnosed after the age of two. However, there is evidence for early manifestations of ASD before the age when a clinical diagnosis typically is given (Elsabbagh & Johnson, 2010). Therefore, studying early development is important in order to enhance our understanding of ASD and illuminate developmental pathways that lead to ASD. Research has thus increased efforts toward finding early markers with the potential goal of facilitating early diagnosis and timely treatment (Elsabbagh & Johnson, 2010).

Infant sibling studies of autism spectrum disorder

As already noted, prospective longitudinal studies of infant siblings of children on the autism spectrum are a popular approach to studying early manifestations of ASD. The foundation of this line of research lies in the substantial genetic component present in the development of ASD (Lai et al., 2014). In the typical population, prevalence estimates of ASD are indicated at 1.7% (Baio et al., 2018). In a population of infant siblings, on the other hand, prevalence estimates are indicated to be around 10–20% (Constantino et al., 2010; Ozonoff et al., 2011; Sandin et al., 2014). Infant sibling studies have provided novel insights into the early development of ASD, ranging from language and communication skills (Hudry et al., 2014; Iverson, 2018; Iverson et al., 2018; Sheinkopf, Iverson, Rinaldi, & Lester, 2012) to social interaction and orientation (Bedford et al., 2014; Elsabbagh et al., 2012; Nyström, Bölte, Falck-Ytter, & EASE Team, 2017; Thorup et al., 2016, 2018), to motor functioning (Bhat, Galloway, & Landa, 2012; Einspieler et al., 2014; Flanagan et al., 2012; Iverson et al., 2019) and neural atypicalities (Blasi et al., 2015; Bosl, Tager-Flusberg, & Nelson, 2018; Hazlett et al., 2017). It is believed that the new knowledge generated from these types of studies may help to improve early diagnosis and treatment in the future.

Benefit and risk estimation

Although infant sibling studies provide a promising approach for increasing our understanding of ASD, little attention has been brought to the ethically challenging aspects of this type of research (D. T. Chen, Miller, & Rosenstein, 2003; Fletcher-Watson et al., 2017; Walsh, Elsabbagh, Bolton, & Singh, 2011; Yudell et al., 2013; Zwaigenbaum et al., 2007).

ASD is a condition of heterogeneous nature, which makes research complex and multifaceted. Study protocols are extensive and include a variety of tasks aimed at assessing a broad range of behaviors. Thus, infant sibling studies often require significant time and commitment from participating families, which may be considered burdensome. In addition, another challenging aspect of infant sibling studies is putting the label "at risk"[3] on a large group of infants who have no behavioral signs of atypical development and have a high likelihood of typical development despite familial history of ASD. In a group of infant siblings of autistic children, the large majority will not receive an ASD diagnosis. However, it is presumed that even without a diagnosis, many of these infants will show some atypical behaviors. Nevertheless, parent surveys indicate that the recurrence rate of ASD is largely overestimated (Mercer, Creighton, Holden, & Lewis, 2006). Focusing on risk and impairments may at the same time increase stigmatization and cause parents' to experience guilt and distress (Broady, Stoyles, & Morse, 2017; Gray, 1993, 2002; Ludlow, Skelly, & Rohleder, 2012).

Taken together, infant sibling studies generate novel insights into developmental trajectories of ASD; however, the experience of the participating families' and the potential ethical challenges should not be ignored.

Key findings and knowledge gaps

Both prospective motor control and cognitive skills affect our actions in everyday life. These two key components are intertwined even in infancy. Planning and controlling actions can be understood at both a higher-order cognitive level and at a lower level of motor control. Furthermore, motor control involves some aspects of executive functioning (i.e., planning, inhibition, and working memory needed to perform actions), and hence, it is possible that executive function abilities are rooted in motor control. Nevertheless, the link between executive functions and motor control has rarely been studied in early childhood, nor have studies used the advanced technology available to examine kinematic profiles of motor actions.

Moreover, there is some evidence that mechanisms underlying prediction may function differently in autistic individuals. Nevertheless, the findings

[3] The "high risk" terminology is frequently used in the infant sibling literature. I am aware of the negative connotations of this terminology and the ongoing debate related to it. Although, ASD can involve severe difficulties in everyday life for some individuals, it should also be recognized that many autistic people consider ASD to be an important part of their identity (see Kapp, Gillespie-Lynch, Sherman, & Hutman, 2013). Therefore, in this thesis, the term "elevated likelihood" is used to account for neurodiversity in order to recognize both challenges and strengths in ASD.

are rather inconsistent, and little research has been conducted in early infancy using detailed measures and advanced technology.

Thus, it is currently not well understood how prospective motor control develops in infants with later ASD, and whether or not potential differences are an indicator for later ASD symptomatology. In addition, prediction of visual motion is important for perception and the development of prospective control; however, few studies have investigated this ability in infants with later ASD.

Finally, in light of promising new findings from infant sibling studies, more problematic aspects of this kind of research may have been overlooked. Little is known about what parents experience while participating in an infant sibling study of ASD. Thus, identifying the advantages as well as the disadvantages or potential risks for participating families is an important step for future ethical discussions.

Aims of the thesis

The overarching aim of this thesis is to investigate early measures of prediction related to concurrent and later outcomes in typical and atypical development, with a particular focus on ASD and related behavioral problems.

In study I, we investigated prediction in the motor domain. More specifically, we used 3D motion capture technology to examine prospective motor control and its relationship to executive functions in typically developing 18-month-olds. We expected that better ability to prospectively control actions would be associated with better performance in executive function tasks.

Using a similar approach as Study I, Study II investigated motor control in infants at low and elevated likelihood for ASD and examined how these measures relate to later development. We expected to find group differences in motor control at 10 months of age, and we anticipated that these differences would correlate with ASD symptomatology in toddlerhood.

The aim of study III was to investigate how infants with later ASD and neurotypical infants update expectations about visual object motion using eye tracking. We expected to find group (ASD vs. controls) differences related to how fast infants would adjust their looking behavior to unexpected visual events, and how these events affect their pupil size.

Studying infants at elevated likelihood for ASD is a popular approach to advancing our knowledge about early developmental pathways in ASD. However, very little is known about potential disadvantages and advantages from the perspective of the parents who participate in an infant sibling study of ASD. Therefore, in Study IV we surveyed parents about their experiences while participating in an infant sibling study as a first step to understand the benefits and risks associated with this type of study.

Methods

Participants

Study I

Participants in Study I were recruited from the Uppsala Child and Baby Lab's database of families who had previously expressed interest in participating in research studies with their child. For study participation, families received a gift voucher of 100 Swedish Crowns (≈ 10 Euro). All procedures in Study I were approved by the Regional Ethical Committee and conducted in accordance with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Written informed consent was obtained from all parents.

In Study I, the final sample included 53 18-month-olds (M = 543 days, SD = 9 days, 22 female). The total sample included 17 additional infants; however, they were excluded from the analyses due to incomplete task performance (n = 11), technical error (n = 4), or insufficient motion tracking data (n = 2). Thus, all infants in the final sample completed all experimental tasks (see Procedure Study I for details).

Study II, III, and IV

Participants in Study II, III, and IV were part of the ongoing, longitudinal Early Autism Sweden study (EASE; for a general overview, see http://www.eurosibs.eu/research; for an overview of the project in Sweden, see www.earlyautism.se). The EASE study includes infant siblings of autistic children who form the group known as elevated likelihood (EL), as well as infant siblings of families with no familial history of ASD, forming the group known as low likelihood (LL).

The infant siblings in this study undergo a multitude of assessments starting at the age of 5 months and up to the age of 6 years. Families who participated in the EASE study were recruited through multiple channels, including clinical units, advertisements, the project's website, as well as the above-mentioned database of families at the Uppsala Child and Baby Lab. Partici-

pating families received a gift voucher of 500 Swedish Crowns (≈ 50 Euro) after each visit to the lab.

The EASE sample is mainly comprised of middle-class families with similar socio-economic status from the greater Stockholm area. All infants in the EASE study were born at full term (> 36 weeks) and showed no confirmed or suspected medical problems (including visual and auditory impairments). All families provided written informed consent, and the study protocol was approved by the Regional Ethical Board. The EASE study is conducted in accordance with the standards specified in the 1963 Helsinki Declaration. All studies and analyses within the EASE project are preregistered internally.

Study II included 58 infants comprising two groups: (1) an EL group (n = 39, 20 females), and (2) an LL group (n = 19, 9 females). An additional subset of infants had to be excluded from the analyses due to technical errors or insufficient motion tracking data (see Procedure Study II for details). All infants included in the study completed data collection at both 10 and 24 months of age.

In Study III, the final sample included 90 infants with experimental data from 10, 14, and 18 months of age. In addition, a clinical diagnostic assessment was conducted at 36 months, after which the participants were assigned to three different groups: (1) an EL group with ASD (EL-ASD n = 19, 14 females); (2) an EL group without ASD (EL-no-ASD n = 47, 31 females); or (3) an LL group with neurotypical outcome (LL n = 14, 6 females).

Study IV included families who completed a questionnaire after the 18-month visit (n = 69, response rate: 67.0%) or after the 36-month visit (n = 19 families, response rate: 70.4%). The data sets for the different time points were distinct populations with no overlap. The study was comprised of parents of two groups: (1) infants with an older autistic sibling (EL, n = 43, 48.9%), and (2) infant siblings of families without a history of ASD (LL, n = 23, 36.1%). The total sample included an additional 22 families; however, for these families there was no indication of familial history of ASD (25.0%). Socio-economic status was estimated by parental income and education with no evidence supporting a group difference (EL, M = 7.08, LL M = 7.60, $p > .25$).

Procedures

Study I

Study I investigated manual motor behavior in 18-month-olds using an eight-camera passive motion tracking system (Qualisys Motion Capture Systems, Gothenburg, Sweden) at a sample rate of 240Hz. The study assessed prospective motor control during a reach-to-place action with varying difficulty levels (see *Figure 1*). We examined if infants prospectively controlled their current actions (i.e., reaching for the target), and their subsequent action (i.e., placing the target) at the beginning of the action sequence. Thus, the difficulty of the second action (i.e., placing) was manipulated by goal size and distance in order to investigate if the subsequent action influenced the first action (i.e., reaching). Our measure for prospective motor control was the peak velocity of the first movement unit of the first action (reaching). In addition to the kinematic data, a video camera filmed the entire experiment from a bird's eye view. The behavioral measures of executive functions (prohibition, working memory, and complex inhibition) included in Study 1 were analyzed using video coding (see *Figure 1*).

The prohibition task (Friedman, Miyake, Robinson, & Hewitt, 2011) was used to assess the ability to inhibit reaching for an attractive toy (i.e., glittering wand) for 30 seconds. The experimenter presented the toy for the infant and placed it within the infant's reaching space on the table. The experimenter shook her head and told the infant not to touch the toy.

The working memory task was a classic hide-and-seek task using a chest of four drawers. After a warm-up phase, four trials were performed where the toy was hidden in each of the four possible drawers. After a time delay of 5 seconds, the infant was encouraged to search for the hidden toy.

In the complex inhibition task (modified from Garon, Smith, & Bryson, 2014), the infant had to inhibit one action for another. An attractive toy (i.e., a color-changing duck) was hidden in a custom-built box behind a plexiglass window. In order to retrieve the toy, the infant had to inhibit a direct reach toward the plexiglass window and reach for a knob on top of the box instead.

Moreover, parents filled out the Vineland Adaptive Behavior Scales (Vineland-II, Sparrow, Balla, & Cicchetti, 1984) to assess gross and fine motor skills. During the experimental tasks, the infant sat on the caregiver's lap, and the caregiver was instructed not to interfere with the infant's behavior. The total procedure took approximately 30 minutes, including instructions and breaks.

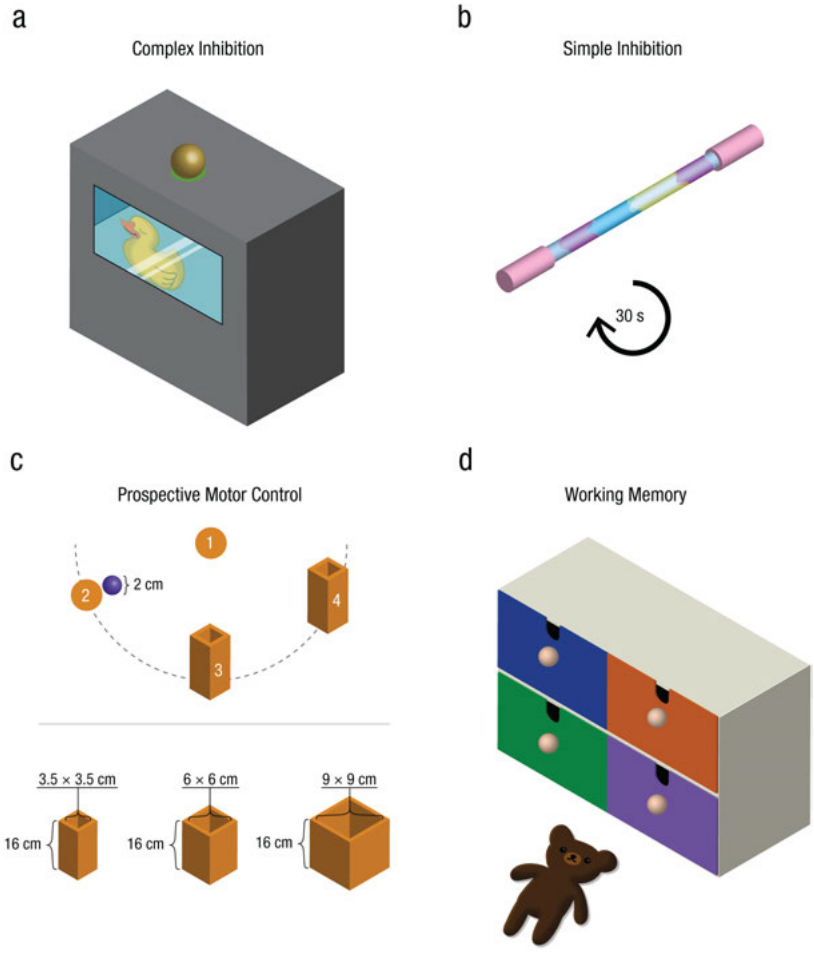

Figure 1. Setup and materials used in Study I. (a) Prospective motor control task: The first action was to reach for the target. Infant's hand was placed in the area marked as (1), while the target was placed in the area marked (2). The subsequent action was to place the target in a small, medium, or large cylinder (3). The cylinder was either placed at short or long distance from the target pick-up area; (b) Prohibition: The task was to inhibit the reach for the glittering wand for 30 seconds; (c) Working Memory: The task was to remember in which of the four different locations the toy was hidden after a time delay of 5 seconds; (d) Complex inhibition: The task was to open the window of the box in order to retrieve the toy. Opening the window required reaching and pulling the knob on top of the box.

Study II, III, and IV

The following studies were all part of the larger EASE project and therefore involved a similar protocol. Typically, families spent 4-5 hours in the lab and completed a range of assessments, including eye tracking, motion tracking, electroencephalography (EEG), magnetic resonance imaging (MRI), play observation, developmental assessments, and parent-child interaction. The testing day started in the morning, included a lunch and/or nap break, and was followed by an afternoon session. During all of the assessments, the caregiver was present with the infant.

Study II used motion tracking technology to investigate motor functioning in 10-months-olds during a interceptive action task. The experimental task and setup was the same as the one reported in Ekberg et al. (2016). The infant was seated in a high chair facing the experimenter at a table with an adjustable tabletop (60 x 60 centimeters, see *Figure 2*). The task was to catch a moving target (i.e., ball), which was rolling toward the infant along rail tracks that had been mounted on the upper left and the right side of the tabletop. At the start of each trial, the infant's attention was captured before releasing the ball in order to confirm that the infant was focused on the ball. During each trial, the infant could watch the ball roll down the tracks for approximately 3 seconds before it entered the infant's reaching space. At least four trials were completed, and the end of each trial was marked either by the infant catching the ball or by the ball rolling off the tabletop. This task was part of a larger motion tracking session, which took approximately 10 minutes.

The infant's manual actions were recorded using an eight-camera passive motion tracking device (Qualisys Motion Capture Systems, Gothenburg, Sweden) at a sample rate of 240 Hz. Passive reflective markers (.4 centimeters in diameter) were placed on the infant's hand between the index finger and the thumb. The ball had a diameter of 4 centimeters. In addition, Study II included assessments for autistic symptomatology (Autism Diagnostic Observation Schedule 2nd Edition, ADOS-2; Lord et al., 2012) and developmental level (Mullen Scales of Early Learning, MSEL; Mullen, 1995) at 24 months of age.

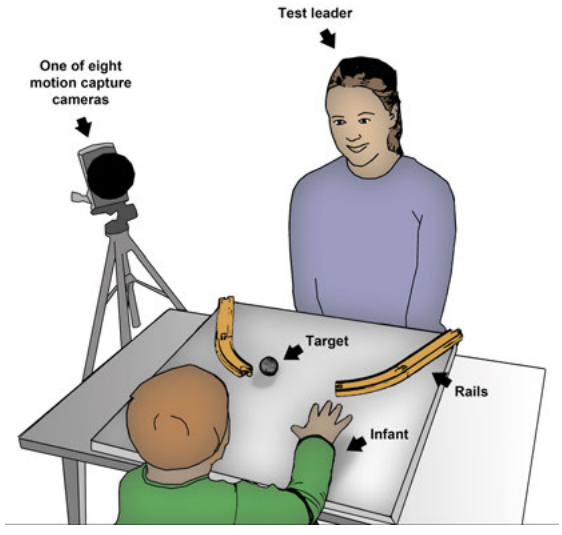

Figure 2. Sketch of the materials and setup included for the interceptive action task, showing an infant and test leader facing each other at a quadratic table with adjustable tabletop.

Study III used eye tracking to investigate how infants updated their expectations about object motion in light of novel visual information. With a visual motion task including temporary occlusion (adapted from Kochukhova & Gredebäck, 2007), we assessed predictions about the directionality of a moving target and how these predictions were updated over time.

Gaze data was recorded using Tobii corneal reflection eye trackers (Tobii AB, Danderyd, Sweden). During the recording, the infant sat on the caregiver's lap at approximately 60 centimeters distance to a computer monitor (screen size of 23", recordings displayed at a resolution of 1024 x 768 pixels). After a five-point calibration in every corner and the center of the screen, the recording started.

The stimulus examined in Study III consisted of a moving target, which started to move horizontally from the left side of the screen for 960 milliseconds. Then the target disappeared behind an occluder in the middle of the screen for 1120 milliseconds. Covered by the occluder, the target changed its trajectory 90° counter-clockwise to continue in this direction for another 960 milliseconds. Before the target reached the upper edge of the screen, it reversed its direction and continued to the starting point along the same trajec-

tory (see *Figure 3*). One trial lasted 3040 seconds and included 1 occlusion passage. Each infant was presented with 2 blocks consisting of 10 trials. The task investigated in Study II was part of a larger eye tracking session of approximately 8 minutes.

In addition to gaze data, Study III included a diagnostic assessment at the 36-months visit. The assessment was conducted by experienced psychologists and included information on medical history, developmental level (Mullen Scales of Early Learning, MSEL; Mullen, 1995), as well as autistic symptomatology using the Autism Diagnostic Observation Schedule 2nd Edition (ADOS-2; Lord et al., 2012) and the Autism Diagnostic Interview-Revised (ADI-R; Rutter, LeCouteur, & Lord, 2003).

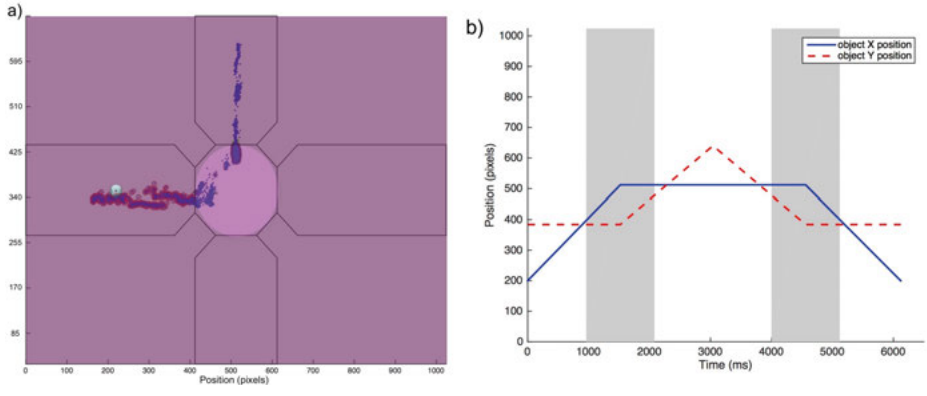

Figure 3. Illustration of the visual motion paradigm. (a) Gaze data plotted in blue and superimposed on the visual scene during the experiment. The areas of interest (AOIs) covered in the analyses are illustrated in black. (b) Illustration of the target's X- and Y-position plotted over time and displaying two occlusion intervals colored in grey.

In Study IV, we surveyed parents who participated in the EASE study about their experience during the study. The survey included both a rating of agreement with different statements, as well as opportunities for free text responses. Families received the survey after completion of either the 18-month visit or the 36-month visit. The survey was distributed in paper form, completed at the family's home, and sent back to the lab. Given the longitudinal character of the EASE study, the survey was voluntary and anonymous.

Measures and Analysis

Study I

The analysis of manual motor behavior was based on motion tracking data and video recordings. In a first step, video recordings were used to code the beginning and the end of the reaching and placing actions (QTM, Qualisys Track Manager, Qualisys, Gothenburg, Sweden). Three events were identified, which were defined as follows: (1) the last frame before the start of a reaching movement, (2) the first contact between the hand and the target, and (3) the last frame before releasing the target in the cylinder.

In Study I, the reaching movement was of interest. Thus, a valid reach was regarded as an extension of the right arm, initiating from the starting area toward the target and ended with the first contact with the target. In addition, for a trial to be included in the analysis, the reach and placement had to be direct, without breaks, interruptions or interference from the caregiver. For the placement movements, a valid placement included both successful and unsuccessful outcomes. Inclusion criteria for the analysis were completion of at least half of the first block (12 trials) and data from three valid trials per goal size. In order to judge trial validity, an interrater reliability analysis was conducted, resulting in high agreement (inter class correlation (ICC) was .97).

Motion tracking data was further analyzed to extract the dependent variable of peak velocity of the first movement unit. Data as interpolated in the Qualisys Track Manager, extracted, and implemented in TimeStudio (http://timestudioproject.com; Nyström, Falck-Ytter, & Gredebäck, 2015). Data was further filtered for x-, y-, and z-coordinates in order to remove outliers. In a next step, 3-dimensional velocity was calculated and movement units were semi-automatically defined. The criteria for a movement unit were a minimal peak distance of 1 sample (i.e., 4.18 milliseconds), and a merge threshold of 8 samples (i.e., 33.34 milliseconds). In addition, trials with less than 50% data, incomplete first movements, or noisy data were excluded. All remaining trials underwent visual inspection to confirm the selected threshold as appropriate. Finally, the peak velocity of the first movement unit was inferred and computed as an average for each infant.

In addition to the motion tracking data, executive function measures were obtained through the video recordings. The coding was validated through an interrater reliability analysis, which resulted in high agreement across all three executive function measures (ICC .92 - .99).

For the prohibition task, the infant's waiting time was calculated in seconds. If an infant did not touch the glittering wand, a trial would last a maximum of 30 seconds. After 30 seconds, all infants were encouraged to grab the wand. A total of 67 infants (96%) contributed with valid data.

In the working memory task, the number of searches (i.e., opening of drawers) was of interest. The highest possible score was obtained if the infant was successful on the first try (4 points), and the lowest score was obtained if the infant was not successful after four attempts (0 points). For the analyses, an infant had to contribute at least one valid trial. Subsequently, the mean score of the four test trials was determined for each infant. Thus, a total of 63 infants (90%) contributed with valid data.

The complex inhibition task was scored as follows: full points (2 points), for opening the box by reaching toward the knob, 1 point for reaching toward the window and then reaching toward the knob, and 0 points for only reaching toward the plexiglass window, reaching toward the window after a reminder from the experimenter, or no reach toward the knob at all. To be included in the analyses, an infant had to contribute at least one valid trial. Subsequently, the mean score for all trials was calculated for each infant. A total of 65 infants (93%) contributed with valid data.

Finally, data was analyzed using bivariate correlations to examine the relationship between the variables and *t*-tests to investigate gender differences. In addition, a hierarchical regression was run to investigate the contributions of control variables (i.e., age, gender, fine and gross motor skills), as well as the measures of executive functions on peak velocity of the first movement unit.

Study II

Similar to Study I, the analysis of manual motor behavior was based on a combination of video recordings and motion tracking data. In the first step, video recordings were analyzed with a frame-by-frame video coding software (Mangold International INTERACT, Arnstorf, Germany), consistent with prior research on the task (Ekberg et al., 2016). The beginning and the end of the reach were coded, as well as the hand used (right, left, bimanual). In addition, the outcome of the reach was coded as either a *reach* (i.e., contact with the ball or within 2 centimeters), or *other* (e.g., unsuccessful reaches, no reach attempt, experimenter errors, or interrupted reaching movements). Subsequently, the category *other* was excluded from the analysis to ensure high-quality data. Video coding was completed by blinded coders and showed high interrater reliability (Cohen's kappa = .89, $p < .001$, 95% kappa confidence interval = .82 - .97).

In the next step, motion tracking data was extracted and implemented in TimeStudio (Nyström et al., 2015). The processing of the motion tracking data was in line with prior research (Gottwald et al., 2016; Gottwald et al., 2017; Grönqvist, Strand Brodd, & von Hofsten, 2011). Data was interpolated and filtered to decrease noise on the velocity profile. In Study II, the transport unit (TU), which is the largest movement unit toward the target, was of special interest. Thus, movement units were automatically extracted by taking every local minimum as the onset of a movement unit (see *Figure 4*). In addition, a merging threshold for on-line adjustments was defined as a peak velocity of less than 8 millimeters / second above the adjacent minimum. This processing allowed the removal of artifacts and filtered out a disproportionate amount of movement units. In addition, trials with less than 50% motion tracking data were excluded.

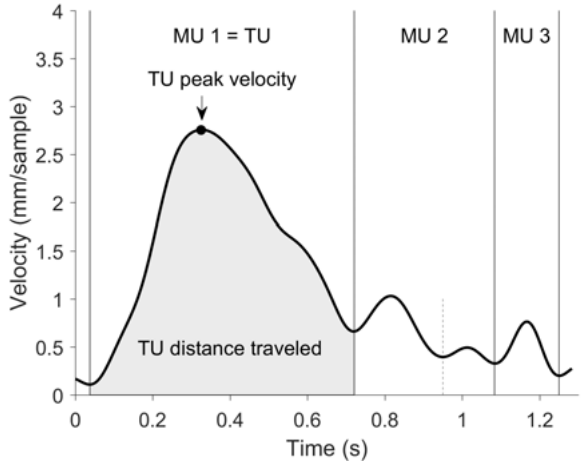

Figure 4. Example of a reach. The velocity profile of one participant during a reach is illustrated and divided by movement units (MUs). The shorter, dashed line shows a small local minimum that was merged with the adjacent MU according the predefined thresholds. In addition, the first MU in this example is also the transport unit (TU), the largest MU toward the target.

The next step was to combine the video and motion tracking data. The final sample consisted of 58 infants, who contributed at least three valid reaches. The total sample was initially larger, but a subset of infants had to be excluded due to missing data and technical problems.

The following motor variables were calculated based on the transport unit: (1) motor planning (i.e., the ball's position (in millimeters, distance to target) at the beginning of the transport unit); (2) prediction (i.e., intersection of the

ball's and the hand's trajectory during the transport unit, in milliseconds, time of prospective aiming); (3) peak velocity of the TU (in millimeters / sample); (4) distance traveled during the TU (in millimeters / sample); (5) the straightness of the approach path during the TU (1 would indicate a straight approach); and (6) the number of movement units used in the reach. The data was analyzed using Linear Mixed Models for each of the 6 motor variables. While group (elevated / low likelihood) and slope (flat / step, not included in this analysis) were treated as fixed factors, subject was treated as a random factor with random intercept ("dv ~ group + slope + (1|subject)").

In addition, longitudinal relations of early motor variables and later ASD symptomatology and developmental level were investigated using Pearson correlations.

Study III

Raw gaze data was extracted and analyzed in MATLAB (R2015a, Mathworks Inc. CA, USA) using custom written scripts. As a first step, events were identified for the occlusion passage (i.e., frame at which target disappeared and reappeared), which created a window of interest for the analysis. Trials with less than 50% of data prior to this window of interest were excluded. In addition, infants had to complete at least four trials to be included in the analysis. Next, all trials underwent visual inspection by a coder blind to group status and infant identity. This procedure was completed in order to remove trials containing missing data close to the occlusion event, noisy data, or movement artifacts. In addition, gaze data was manually transposed to enable the AOIs to cover as much gaze as possible, as well as accounting for gaze calibration drifts during the recording.

In the next step, gaze velocity was calculated and plotted in order to manually identify the gaze shift toward the respective AOI after occlusion. The pupillary responses were defined as the change in pupil size in response to the reappearance of the target after occlusion. The change in pupil size was calculated by a simple equation of the pupil size after occlusion (i.e., an interval after the saccade + 2000 milliseconds) relative to a baseline pupil size prior to the occlusion passage (i.e., saccade after occlusion – 1000 milliseconds). Data for the pupillary responses were derived from the left eye in order to avoid artifacts in case the eye tracker lost track of one of the eyes.

The focus of Study III was predictive and adaptive behavior; therefore, we investigated gaze shift latencies and pupillary responses, measuring both across trials within each testing session and across ages (10, 14, and 18 months). The dependent variables included *adaption rates* (across trials,

operationalized as the slope of a linear regression within each participant) and *developmental change* (across ages, operationalized as the slope of linear regression over the different time points). Taken together, we investigated the dependent variables in following subsections: (1) first trial gaze shift latency, (2) adaption rate of gaze shift latency, (3) first trial pupil response, and (4) adaption rate of pupil response.

After processing the gaze data in MATLAB (R2015a, Mathworks Inc. CA, USA), the dependent variables were extracted and analyzed in JASP (JASP Team, 2019, Version 0.9.0.1), using Bayesian *t*-tests and ANOVAs. Bayesian statistics, in contrast to frequentist statistics, allowed us to estimate the strength of evidence for both the working hypothesis, as well as for the null hypothesis. Furthermore, Bayesian statistics provided richer data on the difference of means and standard deviations, the power of the test, and the influence of outliers.

Study IV

The questionnaire administered in Study IV assessed the parents' satisfaction with the study, the child's perceived satisfaction, and the parents' motivation for participating. Parents were instructed to rate their agreement with a series of statements, ranging from completely agree, to partially agree, or don't agree. Moreover, there was the option to leave comments in open text boxes. Parents were asked to further comment on study participation, offer suggestions, and give recommendations to other families (see *Table 1*).

The ratings of the statements were quantified on a three–point scale. The open comments were analyzed by categories determined by putative topics of interest for infant sibling studies. The categories included (1) positive perception of study participation and research in this area, (2) feedback about the child's development, (3) positively perceived child experience, (4) negatively perceived child experience, (5) burdensome questionnaires, and (6) burdensome experimental measures. The analysis of open comments was validated by an interrater reliability analysis including two independent raters (Cohen's kappa = .80, 95% kappa confidence interval = .73 - .87).

Table 1. Questionnaire items

	Item
1 a	My overall impression of participating in the study is positive.
b	Comments on the overall impression
2 a	I believe that my child perceived participating in the study as positive.
b	Comments on the child's experience
3 a	I believe that I have received good and relevant information about the study's aim and content.
b	Comments on the information received
4	I can recommend other families participate in the study.
5	What would you like to tell other parents about participating in the study?
6	Do you have any suggestions on how to make study participation easier?
7	Do you have any further comments?

Study I

Background

Infants plan their manual motor actions in multiple steps, and they adapt movements with respect to future goals (Y. P. Chen, Keen, Rosander, & von Hofsten, 2010; Claxton et al., 2003; Gottwald et al., 2017). Thus, assessing motor actions using fine-grained measures allows us to understand infants' ability to plan actions in order to reach goals. Planning abilities in infancy are inherently related to executive functions. In addition, accounts of embodied cognition suggest the possibility that executive functions may be grounded in prospective motor control (Wilson, 2002). This means that prospectively controlling motor actions may build the foundation for the development of higher cognitive functions (Diamond, 2013; Miyake et al., 2000).

In line with the embodied cognition account, we wanted to investigate the link between prospective motor control during an action sequence and executive functioning in 18-month-old infants. To measure prospective motor control, we used the fine-grained measure of peak velocity of the first movement unit. To assess executive functions, we examined three age-appropriate tasks, measuring prohibition, working memory, and complex inhibition. We expected that infants' performance in the prohibition task and in the working memory task would be positively associated with the peak velocity of the first movement unit. For the performance in the complex inhibition task, we did not expect to find a correlation, as cognitive abilities required to perform this task are not thought to be fully developed at 18 months of age (Garon, Bryson, & Smith, 2008). In addition, we were interested in assessing whether individual differences in executive function performance were related to prospective motor control.

Results

Prospective motor control

In the final sample, infants contributed 25 trials on average, of which approximately 50% were considered valid trials. A velocity analysis revealed that the mean peak velocity of the first movement unit was 563.12 millime-

ters / second (range = 363.42 – 815.14 millimeters / second, *SD* = 87.25 millimeters / second). There were no indications of gender difference observed ($t(51) = -.66$, $p > .25$).

Executive functions

In the prohibition task, infants waited 7 seconds on average (range = 0 – 30 seconds, *SD* = 11.64 seconds). Seventeen infants touched the wand immediately, while 9 infants waited the maximum time.

In the working memory task, infants contributed on average 3.77 valid trials out of a maximum of 4 trials (*SD* = .81). The average score was 2.79 out of 4.00 possible points (range = .75 – 4.00 points, *SD* = .72 points).

Finally, in the complex inhibition task, infants on average performed 3.81 valid trials out of a possible 4 trials (*SD* = .81) and scored 1.28 out of 2.00 possible points (range = .00 – 2.00 points, *SD* = .68 points).

No indications of gender differences were found in the prohibition task ($t(51) = -.98$, $p > .25$), and the complex inhibition task ($t(51) = -.21$, $p > .25$). However, in the working memory task, we found a gender difference: girls reached higher scores ($M = 3.03$, $SD = .64$, $n = 22$) compared with boys ($M = 2.63$, $SD = .74$, $n = 31$, $t(51) = -2.06$, $p > .045$).

Correlations

We found significant correlations between prospective motor control and simple inhibition ($r = .31$, $p = .026$, see *Figure 5*), as well as between prospective motor control and working memory ($r = .39$, $p = .004$, see *Figure 5*). A higher peak velocity in the first movement unit was associated with a better performance in the prohibition task and the working memory task. No significant correlation was found with complex inhibition, gender, age, or fine / gross motor skills.

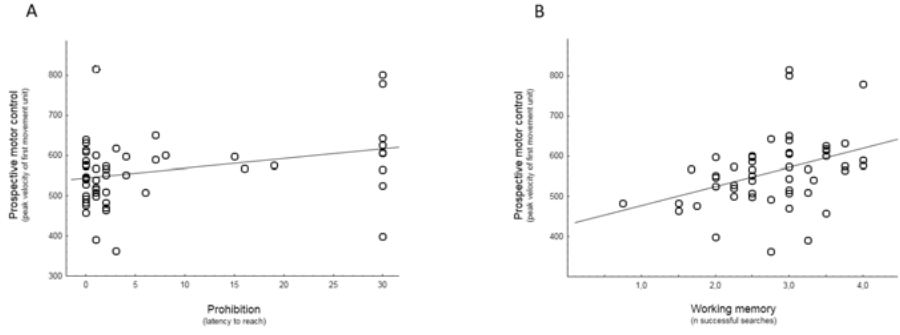

Figure 5. Correlations between (A) prohibition and peak velocity of the first movement unit, and (B) working memory and peak velocity of the first movement unit.

Hierarchical regression analysis

The subsequent analysis was completed in two steps. In the first step, the predictors included fine and gross motor skills, age, and gender. In this hierarchical regression model, none of these variables contributed to the relationship between prospective motor control and executive functions. In the second step, we added prohibition, working memory, and complex inhibition as predictors. This hierarchical regression model provided a significant result ($F(7, 45) = 2.29$, $p = .044$) and explained 26% of the variance in the peak velocity of the first movement unit. Both prohibition ($\beta = 0.29$, $p = .03$) and working memory ($\beta = 0.35$, $p = .013$) made independent contributions to the relationship (see *Table 2*).

Table 2. Coefficients of the hierarchical regression analysis of the reaching velocity of the first movement unit in two steps

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

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

Discussion

Study I showed that motor control and executive functioning are related in early infancy. Performance in both the prohibition and the working memory task was positively related to prospective motor control. However, performance in the complex inhibition task was not significantly related to prospective motor control. This finding was expected because we assumed that simple executive functions (i.e., prohibition and working memory) would be associated with low level motor control, but not with complex executive function tasks (i.e., complex inhibition). For example, Garon et al. (2008) describes two forms of inhibition: simple and complex inhibition. Simple inhibition includes withholding or delaying a response as in our prohibition task, whereas complex inhibition includes not only inhibiting a response, but also holding a rule in mind, and responding according to this rule. Simple inhibition and working memory emerge during the second half of the first year of life (Holmboe, Bonneville-Roussy, Csibra, & Johnson, 2018). Complex inhibition, on the other hand, develops later and can be measured from 18 months of age. However, most of the tasks on complex inhibition are recommended only from the age of 24 months and onwards (Garon et al., 2008; Garon et al., 2014).

A hierarchical perspective on executive function development would assume that simple executive functions develop first and present the building blocks

of more complex executive functions (Garon et al., 2008; Garon et al., 2014). Extending this hierarchical model, it is possible that prospectively controlling motor actions is associated with simple forms of executive functioning, but not directly with complex executive functions. Simple executive functions would then lay the foundation for more complex forms of executive functions. In other words, in Study I, we proposed an embodied perspective on executive function development in which the executive function ability to plan and control actions emerges in early infancy with the ability to prospectively control motor actions.

Study II

Background

Motor impairments have frequently been reported in autistic individuals and are considered to be a feature of the autism phenotype (Fournier et al., 2010; Licari et al., 2019). Understanding motor development is crucial because motor control is closely related to a variety of cognitive skills throughout development, ranging from social cognition (Gerson & Woodward, 2014), attention and object processing (Libertus et al., 2016), object completion (Soska, Adolph, & Johnson, 2010), mental rotation (Mohring & Frick, 2013) to executive functions (Gottwald et al., 2016). Thus, impairments or delays in these abilities and social situations resulting from impaired motor functioning will have a profound effect on development. This signifies the importance of studying early motor control in order to illuminate typical as well as atypical motor development.

Previous research on motor development in ASD is marked by a large variability regarding the types of movements examined, as well as the methods and assessments used. Early studies typically relied on parental reports, retrospective home videos, or broad tests of motor performance that may not have been precise enough measures of motor control.

Studying infant siblings of autistic and neurotypical children will help understand the development of motor control early in life, as well as offer insight into how motor control is related to the development of other skills and ASD, in particular. Therefore, Study II investigated motor control in 10-month-old infants at elevated likelihood (EL) and low likelihood (LL) for ASD when performing an interceptive action task. Using 3D motion tracking technology, we expected to find group differences in kinematic variables when infants performed manual motor actions. In addition, in the longitudinal analyses, we hypothesized that differences in motor performance were related to ASD symptomatology in toddlerhood, and that this relationship could not be explained by a general developmental delay.

Results

Kinematic variables in infancy

A linear mixed model demonstrated that the initiation of the reach occurred later in the group of infants with an older autistic sibling than in infants without history of ASD (EL group M = 284.91 mm, SE = 5.50, 95% CI [263.23, 306.60], LL group M = 296.16 mm, SE = 5.53, 95% CI [285.29, 307.03], $F(1, 375) = 4.18$, $p = .042$, see *Figure 6*).

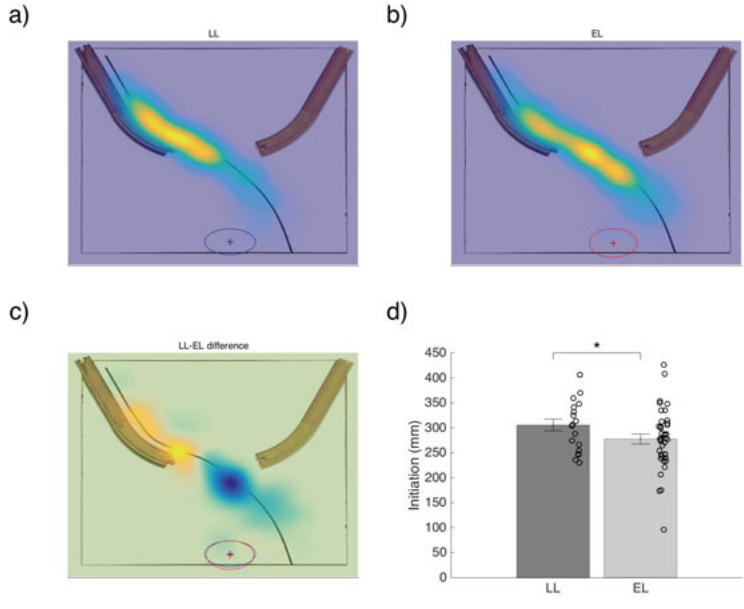

Figure 6. Initiation measured by the distance to the target (in mm) at onset of the transport unit. Heat maps display the target's position on the trajectory relative to when the transport unit started. The mean hand position is market by +, whereas ellipses show standard deviation in x and y dimensions. (a) Normalized heat map for the LL group; (b) Normalized heat map for the EL group; (c) Normalized difference map highlighting EL-LL differences; and (d) Initiation as a function of group. *p < .05.

Linear mixed models showed that the peak velocity of the transport unit was lower in infants at elevated likelihood for ASD (EL group M = 1.77 mm/sample, SE = .07, 95% CI [1.48, 2.07], LL group M = 1.94 mm/sample, SE = .08, 95% CI [1.80, 2.10], $F(1, 392) = 5.19$, $p = .023$). Similarly, the distance traveled during the transport unit was lower in the EL group compared to the LL group (EL group M = 177.89 mm, SE = 7.13, 95% CI

[149.81, 205.97], LL group *M* = 196.85 mm, *SE* = 7.15, 95% CI [182.79, 210.90], $F(1, 392) = 7.06$, $p = .008$). However, the linear mixed models indicated no group differences in the number of movement units used during the reach (EL *M* = 2.12, *SE* = .06; LL *M* = 2.18, *SE* = .06; $F(1, 407) = 1.00$, $p > .25$), or the straightness of the transport unit (EL *M* = 1.26, *SE* = .02; LL *M* = 1.27, *SE* = .02; $F(1, 392) = .23$, $p > .25$, see *Figure 7*).

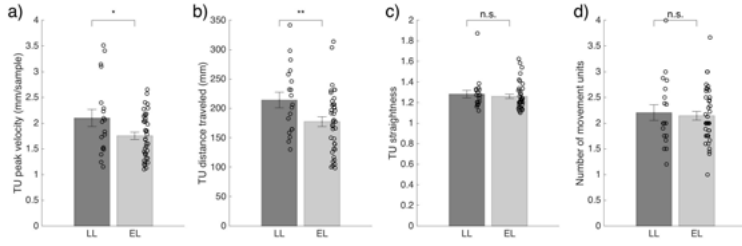

Figure 7. Kinematic analysis of movement units (MU) illustrated by averaged individual data points. (a) Peak velocity of the transport unit (TU) for the LL and EL group; (b) Distance traveled during the transport unit (TU) for the LL end EL group; (c) Number of movement units (MU) during the reach for the LL and EL group; and (d) Straightness of the transport unit for the LL and EL group. *p < .05. **p < .01 in main analyses. Error bars represent standard errors.

No group differences were found regarding predictive aiming (EL *M* = 677.06, *SE* = 36.68; LL *M* = 648.79, *SE* = 36.86; $F(1, 224) = .59$, $p > .25$, see *Figure 8*).

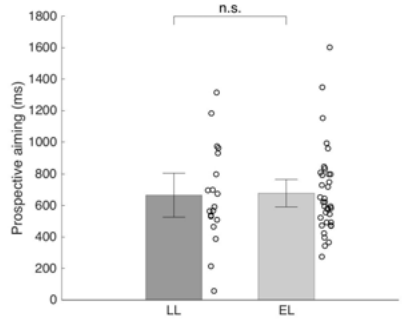

Figure 8. Predictive aiming in infants with low likelihood (LL) and elevated likelihood for ASD (EL), operationalized according to how far along the future trajectory of the target the reach was aimed (in ms). Circles represent averaged individual data points. Error bars represent standard errors.

Correlations

There was no indication of a relationship between any of the motor measures at 10 months and ASD symptomatology (ADOS Comparison Score) at 24 months. Regarding developmental levels at 24 months, we found that a lower Early Learning Composite Score on the MSEL was associated with a higher number of movement units during a reach at 10 months (r = -.323, p = .017; *Figure 9a*) in the whole sample. Including group, number of MUs and the interaction term (group*number of MUs) in a regression analysis with the MSEL score as the dependent variable, we found a significant effect of group (β = 1.28, $t(53)$ = -2.83, p = .007), number of MUs (β = .68, $t(53)$ = -3.56, p < .001) and an interaction effect (β = .97, $t(53)$ = 2.11, p = .040; *Figure 9a*).

A higher MSEL score was related to longer transport units (distance traveled) (r = .329, p = .015; *Figure 9b*). The regression analysis with distance traveled during the transport unit as dependent variable did not show any significant interaction terms.

There was no significant correlation between peak velocity of the transport unit and MSEL score. However, a regression analysis with group, TU peak velocity and the interaction term (group*TU peak velocity), and MSEL score as dependent variable, showed a significant effect of group (β = -1.21, $t(53)$ = -2.66, p = .010) and interaction (β = .88, $t(53)$ = 2.07, p = .044; *Figure 9c*). None of the remaining motor measures (straightness of the TU, prospective aiming, and initiation) showed significant interaction effects involving group.

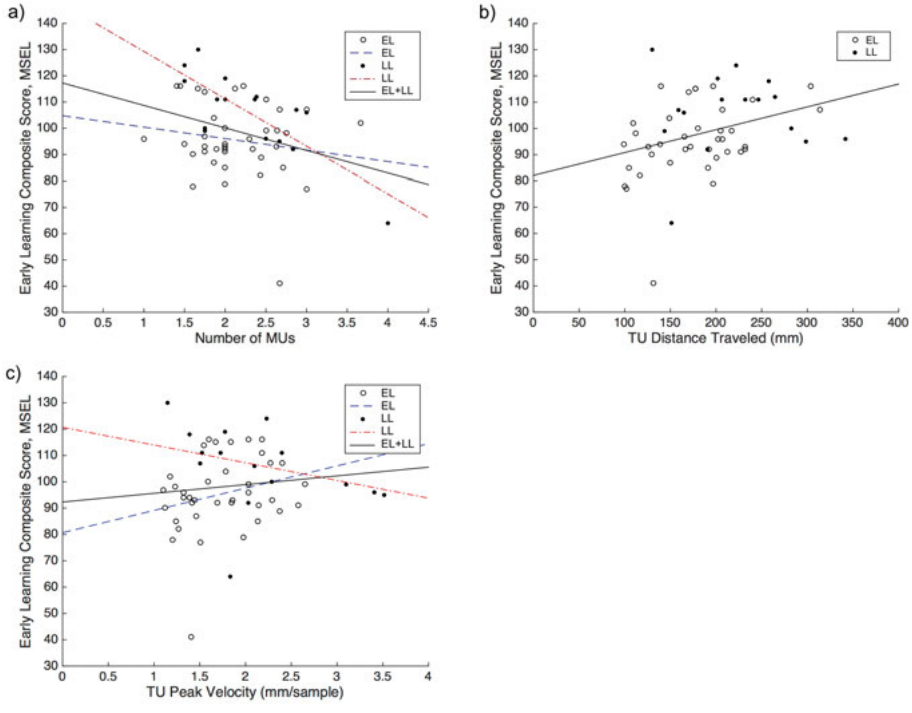

Figure 9. Motor measures at 10 months in relation to developmental level at 24 months. (a) Scatterplot of number of movement units (MU) against Early Learning Composite Score on the MSEL; (b) Scatterplot of distance traveled of the transport unit (TU) against the MSEL score; and (c) Scatterplot of the peak velocity of the transport unit (TU) against the MSEL score. Separate regression lines are displayed for the EL (blue, dashed) and LL group (red, dash dotted). Open circles represent trials of EL infants; full circles represent trials of LL infants.

Discussion

The findings of Study II highlight previously unrecognized and subtle differences in an interceptive action task not observable with traditional methods. Using advanced motion tracking technology, we found differences as well as similarities in motor control between infants at 10 months of age with and without familial history of ASD. Interestingly, there were no indications of significant associations between early measures of motor control and ASD symptomatology in toddlerhood. Nevertheless, certain aspects of motor control were related to general developmental level at 24 months. Taken together, our results suggest a complex pattern of similarities and differences in early motor control, and confirm the efficacy of using fine-grained methods to illuminate developmental pathways including motor trajectories in neurodevelopmental conditions.

Study III

Background

Making predictions about what is going to happen next is essential in order to act efficiently in our dynamic environment. Infants learn early in life how to make predictions about upcoming events (von Hofsten, 2004). For instance, at around 3 months of age, infants are able to track moving objects and predict how these objects are moving in time and space (Rosander & von Hofsten, 2004). Visual motion prediction is a common paradigm used to investigate predictive abilities in infancy. Recent theories of predictive coding have highlighted that prediction may be compromised in ASD. However, the evidence remains inconsistent, as some studies find support for atypicalities in autistic individuals regarding predictive abilities (Lawson et al., 2017; Park et al., 2018), while others do not find differences between neurotypical and autistic individuals (Manning et al., 2017; Tewolde et al., 2018).

Prediction is regarded as a fundamental ability throughout development and potential alterations should be present early in life. Using a visual motion paradigm, we examined how infants with a subsequent diagnosis of ASD (EL-ASD group) and neurotypical infants (LL and EL-no-ASD group) reacted to temporarily occluded objects that moved in an unexpected, but regular motion pattern. In order to investigate how infants update expectations in light of new information, we examined both gaze shift latencies and pupillary responses. We hypothesized that over trials all infants, regardless of diagnostic outcome, would show adaption, indicated by faster gaze shifts toward the object, and that the pupil size would become less affected over trials. In addition, given the notion that autistic individuals show an atypical balance between bottom-up and top-down processes, which is essential for forming predictions in new situations, we investigated group differences on the first trial, adaption over trials, and developmental change across ages.

Results

First trial gaze shift latency

A Bayesian ANOVA including the gaze shift latency on the first trial showed support for the null hypothesis, suggesting no differences between the EL-ASD, EL-no-ASD, and LL group at 10, 14, and 18 month of age. In addition, we found no indication of group differences in first trial gaze shift latency regarding developmental change across ages and the average across ages (see *Table 3* for descriptive statistics and Bayes Factors).

Adaption rate of gaze shift latency

A Bayesian one sample *t*-test against 0 showed strong evidence for a decrease in gaze shift latency over trials (BF_{10} = 16.87, strong evidence for H_1, n = 89, M = -4.33, SD = 12.39), irrespective of group and age. Then, using Bayesian ANOVAs including the adaption rate of gaze shift latency at 10, 14, and 18 months, we found most support for the null hypothesis. There was no indication of a group difference at 10 and 14 months of age. However, at 18 months, we found moderate support for the alternative hypothesis. When comparing the groups in pairs, the analyses showed moderate evidence for a difference between the EL-no-ASD and the EL-ASD group (BF_{10} = 8.256), anecdotal evidence for a difference between the EL-no-ASD and LL group (BF_{10} = 1.214), and anecdotal evidence for the null hypothesis when comparing the LL and the EL-ASD group (BF_{01} = 1.701). Regarding developmental change and the average across ages, we found moderate support for the null hypothesis, suggesting that there were no group differences in terms of adaption rates (see *Table 3*).

First trial pupil response

Unexpectedly, testing the average pupil response on the first trial against a baseline value gave anecdotal evidence for the null hypothesis (BF_{01} = 2.382). This finding suggested that the first trial pupil response did not differ from baseline. Using Bayesian ANOVAs, we found moderate support for no group differences in terms of first trial pupil responses at 10, 14, and 18 months. Similarly, there was no indication of group differences in the first trial pupil response regarding developmental change and the average across ages (see *Table 3*). The results suggest that the pupillary responses after the first trial were similar in all groups.

Adaption rates of pupil response

A Bayesian one sample *t*-test against 0 tested the average adaption rate of the pupil response, irrespective of group and age. The result showed that the

average adaption rate was close to 0 (BF_{01} = 16.87, strong evidence for H_0, n = 89, M = -.03, SD = .03). In addition, by using Bayesian ANOVAs, we found moderate support for the null hypothesis in terms of adaption rates at 10, 14, and 18 months, developmental change across ages, and the average across ages (see *Table 3*). The findings indicate that there were no differences in pupillary responses between the EL-ASD, the EL-no-ASD, and the LL group.

Given the unexpected null result for a general effect on the pupil response on the first trial, as well as the lack of adaption over trials, we used an additional Bayesian one sample *t*-test including the average adaption of the pupil response from the first to the second trial. Due to potential luminance differences during the baseline and the testing phase, we assumed that including two trials could provide better experimental control. The result showed a clear decrease in pupil response over the first two trials (BF_{10} = 21.59, strong evidence for H_1, N = 89, M = -1.81, SD = 5.05), indicating pupil dilation during the first trials in response to the initial unexpected object motion.

Table 3. Descriptive statistics (n, M, SD, BF_{01} [a,b]) for gaze shift latency (in ms) and pupillary response (in %, relative to baseline value of 100%) displayed for each group (low likelihood, LL; elevated likelihood no ASD, EL-no-ASD; elevated likelihood and ASD, EL-ASD).

	LL (29, 14 females)			**EL-no-ASD** (47, 31 females)			**EL-ASD** (14, 6 females)			
Gaze shift latency	***n***	***M***	***SD***	***n***	***M***	***SD***	***n***	***M***	***SD***	***BF_{01}***
First trial										
At 10m	21	301.4	145.4	28	267.1	108.6	8	256.7	139.6	4.24*
At 14m	19	225.9	71.2	26	224.7	81.3	6	181.2	62.2	3.45*
At 18m	15	186.2	77.5	28	208.7	90.7	12	160.5	74.7	2.34
Developmental change	21	-15.8	36.3	31	-5.3	21.1	10	-10.1	20.5	3.35*
Average across ages	28	252.9	95.5	40	232.3	76.3	13	197.0	67.9	1.93
Adaption rates										
At 10m	25	-2.12	16.07	36	-8.25	13.83	9	-4.79	10.71	2.42
At 14m	22	-3.79	9.80	33	-.95	13.17	7	-4.65	16.41	4.51*
At 18m	20	-2.24	9.74	35	-7.37	9.57	12	1.83	8.60	4.72[c]
Developmental change	25	-.21	2.82	37	-.32	1.78	10	0.52	2.17	5.11*
Average across ages	29	-2.31	10.35	46	-6.42	14.65	13	-1.78	6.03	3.02*
Pupillary response	***n***	***M***	***SD***	***n***	***M***	***SD***	***N***	***M***	***SD***	***BF_{01}***
First trial										
At 10m	25	98.4	5.9	36	97.8	8.1	9	96.2	7.3	5.93*
At 14m	22	98.7	8.3	34	98.7	6.1	7	95.7	6.7	4.62*
At 18m	20	100.7	5.0	37	102.0	6.0	12	99.7	5.9	4.01*
Developmental change	25	.2	1.3	38	0.4	1.2	10	.8	1.1	3.70*
Average across ages	29	99.3	5.3	48	99.4	6.0	13	97.1	5.1	4.66*
Adaption rates										
At 10m	25	.016	.32	36	.023	.30	9	.008	.16	7.16*
At 14m	22	.069	.40	33	.120	.33	7	-.054	.28	3.98*
At 18m	20	-.128	.28	35	-.023	.37	12	.042	.37	3.52*
Developmental change	25	-.018	.08	37	-.004	.08	10	-.010	.04	6.20*
Average across ages	29	.029	.24	48	-.004	.22	12	-.019	.24	6.70*

[a] BF_{01} describes the likelihood of the data under H_0, BF_{01} = 1-3, anecdotal evidence for H_0
[b] BF_{01} describes the likelihood of the data under H_0, BF_{01} = 3-10, moderate evidence for H_0
[c] This *BF* refers to the likelihood of the data under H_1, BF_{10} = 3-10, moderate evidence for H_1

Discussion

Our findings indicated that all infants, regardless of later diagnostic outcome reacted similarly to unexpected patterns of object motion. We found no indication of group differences between infants with later ASD and neurotypical infants in measures of gaze shift latencies and pupillary responses. Using Bayesian statistics allowed us to provide support for the null hypothesis, strengthening the assumption that there were no differences between the groups. Thus, our results suggested that the ability to update representations about regularities in the world in light of new information may not be function differently in infants with a subsequent diagnosis of ASD. Nevertheless, this does not exclude the possibility of atypicalities in other aspects of prediction in ASD.

Study IV

Background

In neurodevelopmental conditions, it is crucial to understand developmental pathways and identify early markers associated with the condition. In ASD, research has increasingly been directed toward studying infant siblings of autistic children (Elsabbagh & Johnson, 2010). While prevalence estimates for ASD in the typical population are indicated to be around 1.7% (Baio et al., 2018), the estimates in infant siblings are around 10 – 20% (Constantino et al., 2010; Ozonoff et al., 2011; Sandin et al., 2014). In consideration of novel and promising findings from infant sibling studies, potential risks or disadvantages may easily be overlooked.

Infant sibling studies are different than typical infant studies in that they require a great deal of time and commitment from participating families. In addition, due to the study's focus on potential atypical development, this type of study may increase parents' concerns about their child. Further, infants and families may experience stigmatization. This is especially important to consider since most of the infant siblings will not develop ASD themselves. Therefore, giving these infants an "at risk" label may change the attitudes of parents and other people toward the infants. Altogether, it is important for ethical discussions to take into account both positive and potential negative aspects of infant sibling studies. To our knowledge, no previous study has investigated parental experience while participating in an infant sibling study of ASD. We took a first step into illuminating this unexplored area by surveying parents about their experiences while participating in an infant sibling study of ASD.

Results

Quantitative analyses

The large majority of parents (n = 82, 93.2%) stated that their overall experience was positive, and the remaining parents (n = 6, 6.8%) partially found the study experience to be positive (see *Figure 10a*).

Similarly, the majority of parents (n = 65, 73.9%) perceived that participating in the study was a positive experience for their child, while a quarter of parents (n = 23, 26.1%) perceived it as partially positive from their child's perspective (see *Figure 10b*).

A large majority of parents (n = 83, 94.3%) stated that they would recommend others to participate in the study, while the remaining parents (n = 5, 5.7%) partially agreed (see *Figure 10c*).

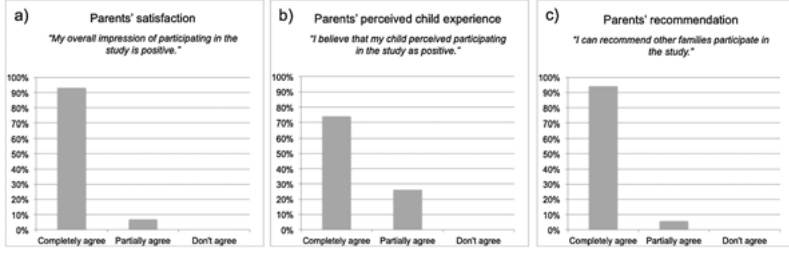

Figure 10. Parents' rating of (a) study satisfaction; (b) perceived child experience; and (c) study recommendation.

Regarding parental experience, perceived child experience and study recommendation, we found no indications of group differences in the ratings of families with and without history of ASD.

Open comments

In the open comments, the main themes were the importance of research in this area, as well as following and receiving feedback about the child's development. Concerning the actual testing, some parents stated that their child enjoyed the tasks, while others found that some tasks were boring and tiresome for the child. Furthermore, some parents mentioned that they perceived the large number of questionnaires as a burden.

Discussion

This study is a first step in understanding families' experiences while participating in an infant sibling study of ASD. Parents in our study were mainly positive about study participation from their own as well as their child's perspective, and they recommended other families participate in the study. Furthermore, there were no indications of differential experiences with regard to familial history of ASD. While the number of questionnaires was burdensome for some parents, there were no potential risks or disadvantages

identified in our findings. Nevertheless, it is important to investigate families' experiences further and in depth, as well as to validate these conclusions in future studies.

General discussion

Movements, perception, and cognition are intertwined, forming a functional system for us to act efficiently in our environment. Just as when we watch a magic trick and are surprised by an unexpected outcome, we are constantly influenced by previous experience, adapt and change in response to environmental volatility, and learn from novel occurrences in the world. These perceptual mechanisms develop early in life and allow infants to form predictions about upcoming events in time and space. Thus, prediction is essential for successful interactions with our ever-changing, dynamic environment. However, it is not only perceiving that is important for prospective motor control, but also interpreting incoming information from different senses.

In turn, motor control is fundamental for development and affects how we perceive and interact with the world (Bushnell & Boudreau, 1993; E. J. Gibson, 1988). Impaired motor control provides infants with fewer opportunities for learning from their own actions and for maneuvering efficiently in the world (Adolph, 1997; Campos et al., 2000). Therefore, it is not surprising to find that early motor measures are related to the development of other skills.

The overarching aim of this thesis is to investigate different aspects of prediction and its relationship to concurrent and later outcomes in typical and atypical development, with a particular focus on ASD and related behavioral measures. The studies comprising this thesis illuminate the importance of early forms of prediction and how predictive abilities shape development.

In the following sections, I will elaborate further on the findings of the four studies and discuss them in relation to prior theoretical and empirical work. Next, I will outline the clinical implications of the findings, discuss limitations, and explore avenues for future directions.

Assessing motor control in typical and atypical development

Study I and II investigated kinematic variables of motor control in infancy using motion tracking technology. Analyzing detailed and precise measures of motor control allowed us to tap into the microstructure of movements and to unfold subtle features of movements not observable with traditional methods. While Study I focused on the peak velocity of the first movement unit as marker of prospective motor control, broadly construed. Study II took a more detailed approach. Specifically, in Study II, the term *motor control* was broken down into motor planning, spatiotemporal prediction, and motor execution.

In both Study I and II, movement unit analysis was used to shed light on how infants have planned in advanced to perform an action, as well as how they in fact executed the action. Some studies have investigated the first movement unit of a manual action (i.e., as in Study I), and others (i.e., as in Study II) have investigated the transport unit, which is defined as the largest movement unit toward a target. There may be some discrepancies; however, the transport unit has been showed to be the first movement unit in most reaches after 7 months of age (von Hofsten, 1993). Thus we consider these measures as largely synonymous. The advantage of using the transport unit is that it is, per definition, the largest movement unit, making quantification of its properties more reliable than other, smaller, movement units. While Study I highlighted the link between prospective motor control and executive functions, Study II found longitudinal relationships of early kinematic variables and later developmental level in toddlerhood. Thus, at a general level, both studies found links between motor control, defined in terms of movement unit properties, and aspects of cognition.

In Study I, infants with higher peak velocities in the beginning of their motor actions showed a better performance in executive functioning tasks on prohibition and working memory. This result led us to propose an embodied perspective on executive function development, in that executive functioning is grounded in motor control (see discussion further below).

Along the same lines, measures of motor control in infancy have been shown to be positively related to executive functioning in adulthood (Ridler et al., 2006). Specifically, the earlier the motor milestones of standing and walking were reached in infancy, the better were working memory and categorization abilities in adulthood. These longitudinal correlations may be affected by various other factors, such as the individual's characteristics and environment. Nevertheless, the discovery of such long-term associations highlights the importance of early motor measures for development.

Study II investigated early motor control and longitudinal associations with autistic symptomatology and developmental level in infants with and without familial history of ASD. Movement unit analysis revealed a complex pattern of similarities and dissimilarities in motor measures at 10 months of age. More specifically, infants with familial history of ASD showed a lower peak velocity and shorter distances in the transport unit compared to infants from neurotypical families. However, the straightness of the reaches and the amount of movement units during a reach were no different in the two groups.

In addition, we investigated motor planning, more specifically, by focusing on the initiation of the movement. Motor planning occurs before a movement has started and can be defined as the "process of converting a current state and a desired state into a sequence of motor commands" (Gowen & Hamilton, 2013). Thus, the current state (i.e., position of the hand) and the desired state (i.e., hand catches the ball) have to be detected and turned into motor commands (i.e., move hand towards the ball, move fingers, open hand to grasp…). We found that infants with a familial history of ASD started to reach toward to ball later compared with infants without familial history of ASD.

Next, we focused on spatiotemporal prediction more narrowly, defined as how much ahead of time along the ball's future trajectory the reach was aimed at the onset of the transport unit. We found no indication of differences between infants with and without familial history of ASD in terms of this measure.

Also, there were no indications of group differences in terms of successfully performing the task, defined as successfully catching a ball. These findings highlight that the variations we found in infants with a familial history of ASD are rather subtle and not necessarily indicative of a deficit.

Taken together, while we found some differences in motor control between infants with and without history of ASD at 10 months of age, these early motor measures were not related to ASD symptoms in toddlerhood. This finding suggests that the kinematic measures assessed in Study II are not specifically linked to ASD and may rather reflect a subtle general developmental atypicality (given its link to the MSEL). By following infants from an early age until diagnosis and by including additional groups of infants with other concerns (e.g., ADHD, language impairments, or developmental delay), the issue of specificity can be more fully addressed.

Prior to ours, only a few studies have examined motor control with detailed kinematic measures in older autistic children or children with familial histo-

ry of ASD. There is some empirical evidence that points toward differences in kinematic profiles, such as longer movement preparation and duration, lower peak velocities, longer deceleration, or a variability in the time to reach peak velocity (Dowd, McGinley, Taffe, & Rinehart, 2012; Focaroli et al., 2016; Forti et al., 2011; Mari et al., 2003). However, in a recent longitudinal study, Taffoni et al. (2019) did not find any motor differences between toddlers with and without familial history of ASD in a shape sorter task. Movement durations, acceleration patterns, and vertical as well as horizontal errors during the manual actions were similar in both groups. The somewhat inconsistent evidence suggests that motor differences early in life in ASD are rather subtle and probably variable across children and sub-groups of ASD.

Going forward, advances in technology will enable novel means to investigate motor control in ASD early in life. For example, iPad gameplay could identify motor patterns related to ASD with high accuracy (Anzulewicz, Sobota, & Delafield-Butt, 2016). Inertial movement sensors embedded in touch-sensitive tablets could be employed to record kinematic profiles and gesture forces to examine motor patterns in young children. Thus, using tablet devices for scientific purposes provides a promising approach for new research due to their portability, accessibility, and ecological validity (Anzulewicz et al., 2016).

Predicting visual motion in infants with later autism spectrum disorder

In Study III, we used a visual motion paradigm to investigate how infants with later ASD and neurotypical infants reacted to temporarily occluded objects that violate initial expectations about object motion. The findings suggested that infants, irrespective of clinical outcome, reacted similarly to unexpected patterns of object motion in terms of gaze shift latencies and pupillary responses. Thus, updating representations about regularities in the world in light of novel information may not function differently in infants with later ASD, at least within the context of Study III.

Despite the fact that we did not find any indications for atypical predictive abilities in infants with later ASD, we do not exclude the possibility that other aspects of prediction may be atypical in ASD. For example, when a prediction was violated, autistic adults were less surprised than neurotypical adults, as measured by their pupil response to the unexpected event (Lawson et al., 2017). On the other hand, no difference was found between autistic and neurotypical children in how statistical information was used to guide decision in probabilistic learning task (Manning et al., 2017).

From a predictive coding standpoint (Van de Cruys et al., 2014), predictions in ASD are not deficient per se. Rather the atypicalities lie in predictions under uncertain circumstances, such as volatile environments (Van de Cruys et al., 2014). Arguably, it is more difficult to make predictions in a social context compared to predicting object motion. The dynamics of social situations are complex due to a higher degree of uncertainty and changes in social contingencies (Barrett, Mesquita, & Gendron, 2011). Often, meaning is interpreted between the lines or what is said is not what is meant.

According to the HIPPEA (Van de Cruys et al., 2014, see Introduction), the brain registers differences in incoming sensory information, and at the same time, needs to decide which of these differences are informative and which differences should be discarded. In the rich context of social situations, precision should be tuned down. However, in the case of inflexible adjustments of the precision of prediction errors, individuals may become overwhelmed with the available information in social settings. Therefore, high precision of prediction errors in social situations may lead to observed social atypicalilties in ASD (Van de Cruys et al., 2014). Importantly, while prediction may be particularly problematic in social contexts in ASD, the putative atypicalities in prediction are not thought to be limited to social settings.

Study III does not suggest that there are basic problems with prediction in ASD early in life. However, it has to be noted that our task was not designed to test specific implications of the predictive coding account (Van de Cruys et al., 2014). Study III investigated a rather simple visual motion prediction task where after an initial violation of expectation, infants were presented with the same regular motion pattern. This task may not have elucidated a high degree of uncertainty, and instead reflected lower level processing. In such cases, where precision is set at a high level, autistic individuals may not show any atypicalities in visual perception (Van de Cruys et al., 2014). Future research should therefore include associative learning tasks, in which individuals have to figure out rules and flexibly adapt to changes in those regularities. This type of research will shed further light on predictive abilities in ASD, and also test assumptions of the predictive coding account.

Taking an embodied perspective on development

In Study I, we argued for an embodied perspective on the development of executive functioning. We suggested that both motor control and executive functioning stem from the same motive, namely to control actions. Thus, the ability to control basic actions would arise first, and then the ability to cognitively control more complex actions (i.e., "classical" executive functions) would emerge. According to an embodied perspective, bodily movements

play a central role in shaping the mind, and cognitive processes are rooted in movements (Wilson, 2002). We thereby recognize the key roles of perception and action for cognition. This notion differs from classical accounts of cognition, which suggest that the material body and the immaterial mind are separate entities (Wilson, 2002).

It has been proposed that cognition in ASD may be "less embodied" than in neurotypical individuals (Eigsti, 2013), and that impairments in the motor domain observed in neurodevelopmental conditions may underlie atypicalities in cognitive processing. Motor atypicalities are highly prevalent in ASD (Fournier et al., 2010; Licari et al., 2019). Similarly, atypicalities in executive functioning in ASD have been frequently described (Demetriou et al., 2018). It is possible that early motor atypicalities may interfere with opportunities for learning and for linking motor actions to other information in the environment, which may result in cascading effects for cognition and executive functioning in particular. In addition, a longitudinal study with autistic children highlighted long-term links between early executive functions and later outcomes (Kenny, Cribb, & Pellicano, 2019). Better executive function skills in infancy were predictive of fewer autistic symptoms and higher adaptive behavior 12 years later.

In Study II, we found evidence for early differences in motor control in infants with familial history of ASD, but these differences were not related to later ASD symptomatology. Rather, we found that several kinematic variables were correlated with the Early Learning Composite Score on the MSEL, a developmental measure of cognitive development (Mullen, 1995). Specifically, a lower number of movement units and a longer distance traveled during the transport unit were associated with a higher MSEL score. Both of these kinematic variables are indicative of infants' ability to plan and execute motor actions. The findings of Study II are in line with an embodied cognition account, as early differences in motor control were associated with cognitive development. Thus, the results of Study II contribute to the assumption that infants' own motor actions shape cognitive development.

It is important to emphasize that there are several other non-embodied accounts that may explain cognitive development. For example, implicit learning and statistical learning are ways to detect regularities and extract patterns perceived in our environment (Perruchet & Pacton, 2006). The findings of Study III can be discussed in terms of statistical learning, since we examined how infants adapt to novel motion patterns that violated their initial expectations. Already at 10 months of age, infants were able to update their expectations in light of new visual information about an unexpected but regular motion pattern. Thus, there is evidence that infants are able to detect statistical relationships and use this new knowledge efficiently, which could point to-

ward a different mechanism for cognitive development (Kirkham, Slemmer, & Johnson, 2002; Saffran, Aslin, & Newport, 1996).

Interestingly, infants can learn implicitly by observation and without any instructions or feedback (Aslin, 2017). This suggests that learning may not only rely on infants' own movements, which opens up the need for discussions concerning non-embodied cognition and statistical learning, in particular. Along the same lines, Monroy, Meyer, Schröer, Gerson, and Hunnius (2019) examined statistical learning in relation to predictive motor activation in the brain. The results showed that knowledge from statistical learning obtained via observation was translated into action predictions generated in the infants' own motor system. In addition, infants' statistical learning ability when observing actions may not be as tightly linked to their own motor repertoire as assumed. There is likely to be an interplay of motor and non-motor strategies in the acquisition of new motor skills in infancy (Monroy, Gerson, & Hunnius, 2017), suggesting that embodied and non-embodied accounts are not mutually exclusive.

The predictive coding account (for a review, see Van de Cruys et al., 2014) could present a way to combine computational strategies, such as statistical learning accounts, with embodied accounts of development. On one hand, predictions are based on our perception of statistical regularities in our environment. On the other hand, predictions are also based on our interactions with the environment (Van de Cruys et al., 2014). We perceive with our bodies, and therefore, perception per se, can be regarded as embodied (J. J. Gibson, 1979; Wilson, 2002).

Ethical considerations related to infant sibling studies of autism spectrum disorder

Study IV surveyed parents about their experience participating in an infant sibling study. While infant sibling studies advance our understanding of developmental pathways in ASD, little is known about potential risks or disadvantages for participating families. Our findings, which were based on an anonymous questionnaire, indicated that parents were generally very positive about study participation from their own perspective, as well as the perceived child's perspective. Despite the mainly positive comments, some parents stated that the large number of questionnaires was perceived as a burden. Therefore, future studies should carefully reflect on the number of questionnaires included in the study. Study IV represents a first step in understanding parents' experiences while participating in an infant sibling

study. The results are generally positive both from the parents' perspective as well as the perceived child experience.

Understanding families' experiences while participating in research with their young children is important for ethical discussions about the benefits and risks of these studies. There are a number of ethical challenges that should be highlighted regarding infant sibling studies of ASD. The commitment and time required from the participating families is rather demanding. Often, infant sibling studies include a plethora of assessments that can be perceived as tiring and burdensome for participating families. Further, there is an ongoing debate about the use of "at-risk" labels in ASD research (see Kapp et al., 2013). It is important to consider that the vast majority of "at-risk" infants in fact develop typically. Therefore, applying a "high-risk" label to infants may be viewed as negatively loaded. In addition, "at-risk labels" may result in increased stigma, worries, or parental distress. In ASD studies, in particular, researchers may encounter families during vulnerable periods, which requires research personnel to act with necessary sensitivity in order to safeguard families' well-being. Finally, including infants in scientific research studies presents a general ethical issue because infants are not able to give informed consent, which is of course a central principle in research.

Although the results of Study IV are promising and positive, the findings should be interpreted with necessary caution and with the above-mentioned issues in mind. Future research is needed in order to further understand families' experiences and to determine how research can include the perspectives and needs of different stakeholders, such as parents of autistic children, autistic individuals, as well as professionals working with autistic individuals.

A large study by Fletcher-Watson et al. (2017) involving different stakeholder groups showed overall support for early ASD research. In particular, parents of autistic children stressed the need for earlier diagnosis. Autistic individuals, on the other hand, gave less importance to a quick diagnosis, but stressed research on environmental factors and understanding the unique development of autistic children (Fletcher-Watson et al., 2017). One autistic individual commented, "This research must be done in order to improve the lives of autistics to make them empowered and happy, and not in order to stigmatize them. To get a diagnosis is essential, but to offer a support adapted to each is equally important" (Fletcher-Watson et al., 2017, p. 70). Along the same lines, Fletcher-Watson et al. (2019) proposed a participatory approach to ASD research, including multiple stakeholder groups. Co-creating research could make a positive difference for autistic individuals and their families by incorporating new knowledge into clinical practice and community support.

Clinical implications

Increased knowledge about developmental trajectories in ASD will facilitate early detection, as well as adequate and timely treatment. Thus, Study II and III have clinical value for the future since the studies aim at contributing to our understanding of the development of early predictive abilities in infants with familial history of ASD. However, it is important to note that the findings of both Study II and III were not significantly related to ASD. Nevertheless, even negative findings can drive research forward by contributing to the common truths about ASD.

Study II found that certain measures of motor control were different in infants with and without a familial history of ASD. It is important to recognize that these differences were rather small, and therefore do not necessarily reflect a deficit or a delay. Importantly, early motor measures were not related to ASD symptomatology in toddlerhood, but rather to developmental level. Thus, the observed differences in motor control may reflect compromised developmental levels rather than atypicalities unique to ASD.

The similarities and dissimilarities reported in Study II contribute to the understanding of motor control in infants with a familial history of ASD. Using fine-grained measures of motor control to detect subtle differences early in development may improve the accuracy of diagnostic assessments, and could prove to be valuable for future treatments or interventions. It is important to note that infants with a familial history of ASD are susceptible to a range of other developmental concerns, such as co-morbid conditions, motor problems, or developmental delay, all of which are factors with high clinical significance.

Study III suggested that visual motion prediction is intact in the early development of ASD. This finding is also interesting from a clinical point of view, since it is not only deficits that are found early in life, but also abilities in the typical range.

Limitations

There are a number of limitations to consider when interpreting the findings of the studies presented in this thesis, some of which are worth discussing here.

In Study I, we proposed that the development of executive functions emerges from prospective motor control, suggesting an embodied perspective. However, based on the cross-sectional data in this study, we cannot draw

any conclusions about the direction of this effect. Nevertheless, there is some evidence for the assumption that early motor measures are predictive of executive functioning based on longitudinal data from infancy to adulthood (Ridler et al., 2006).

Study II, III, and IV were based on the same infant sibling study of ASD (i.e., the EASE study). Thus, the findings should be interpreted with necessary caution as they reflect a specific group of individuals associated with a number of limitations. First, the majority of the participating families were native Swedish with an academic background. Second, common to the infant sibling design, families may behave differently with an infant sibling compared with an older autistic sibling. Third, families who chose to participate in an infant sibling study may differ from those who chose not to participate, resulting in an additional bias. Fourth, regardless of likelihood status or diagnostic outcome, participating infants showed similar developmental levels in the typical range, making it difficult to generalize the results to infants with lower developmental levels and IQ. In sum, findings from infant sibling studies do not necessarily reflect the population-wide heterogeneity in ASD.

Study II lacked diagnostic outcome data, as the infants had not reached the diagnostic assessment age of 36 months at the time of the analysis. Nevertheless, comparing infants with and without familial history has merit on its own. Observed effects may not be related to ASD diagnosis in particular, but can provide new knowledge about early behavioral measures involved in developmental trajectories of infants with a familial history of ASD.

A weakness of Study II is that the analysis suffered from substantial data loss due to undetected issues with the motion tracking application. However, even if this resulted in a loss of statistical power, these issues were related to a specific time period and not infant characteristic, and thus they were unlikely to explain observed effects.

Study III included diagnostic outcome of ASD; however, a small group of only 14 infants with later ASD were included in the final sample (valid data was retrieved from only 10 infants). While small sample sizes are unfortunate in terms of statistical power, this is a common issue in infant sibling studies with regards to the longitudinal design. By using Bayesian statistics (Study III), we tried to account for this issue in terms of estimating the likelihood of the data under the alternative, as well as the null hypothesis.

A limitation of Study IV is that the findings are based on a relatively short and positively framed questionnaire, which may have prevented parents from giving more in-depth information on study participation, and therefore limiting the ability to generalize these findings.

Future directions

Based on the findings of the studies in this thesis, there are multiple avenues of research that could be investigated.

Study I was based on data of concurrent time points. Therefore, future research on the relationship between early motor measures and executive functioning should be assessed in a longitudinal design. Longitudinal data and multiple assessments could illuminate the direction of the observed effect and its stability over time. In addition, assessing the relationship between prospective motor control and executive functioning is interesting in atypical development as well. Atypicalities in executive functioning are common in ASD (Demetriou et al., 2018; Hill, 2004); however, the link to motor control is not well understood. Thus, extending Study I to infants with familial history of ASD, in order to examine an embodied approach of executive function development in atypical development, would be a logical next step.

Study II, III, and IV are part of an ongoing infant sibling study. Further research opportunities could open up by combining measures of the different assessment days, including social as well as non-social behavioral measures. With regard to predictive abilities, it would be fruitful to add a social component. For example, one could use eye tracking to assess the prediction of turn-taking behavior in a social interaction. This approach would allow researchers to understand if and how predictive abilities differ in terms of social versus non-social contexts.

Another approach would be to link behavioral and brain imaging data. First, future studies could assess whether motor differences in ASD as observed in Study II are related to specific brain regions early in life. Second, future studies could increase our understanding of the neural underpinnings of prediction. Within the predictive coding framework, it has been proposed that an imbalance in how the brain handles prediction errors may underlie atypicalities in ASD (Den Ouden, Kok, & De Lange, 2012; Friston, 2010). Therefore, future studies could investigate brain regions, as well as the role of neuromodulators, such as acetylcholine and norepinephrine, in prediction.

Furthermore, it is valuable to follow up with the infant sibling cohort until school age in order to re-assess diagnosis and ASD symptomatology, as well as other potential co-occurring conditions, such as ADHD, language impairment or intellectual disability.

Regarding Study IV, future research about experiences during infant sibling studies should be directed toward conducting in-depth interviews with participating families. It would be favorable to not only assess parents' perspec-

tives, but also to directly query the children about their experiences once they reach an appropriate age. In addition, continuously considering all stakeholders in ASD research, including families, autistic individuals, and practitioners in healthcare and education, would generate a greater understanding of the needs in ASD research, and help bridge the gap between lab, clinic, and the everyday life of individuals.

Final conclusions

The significance of the studies comprising this thesis relate to both unexplored areas in typical development, as well as novel findings in atypical development, with a focus on ASD in particular. The studies investigated different aspects of prediction using advanced technology to explain the fine-grained nature of early behavioral measures, as well as ethical aspects related to conducting this type of research on infants at risk for neurodevelopmental conditions. The thesis points to the important role of prediction and motor control for later cognitive development, but fails to find a specific link to later ASD.

Summary in Swedish

Redan tidigt i livet börjar ett barn förstå och försöka förutse vad som kommer hända härnäst. Förmågan att förutse kallas prediktion och innebär exempelvis att predicera hur en boll kommer röra sig i tid och rum för att kunna fånga den, eller att i sociala sammanhang prediktera vem som kommer prata härnäst under ett samtal. Förmågan att predicera vad som händer i ens omgivning och att planera utifrån det, har stor betydelse för ett barns utveckling och inlärning. Det finns viss forskning som tyder på att personer med autismspektrumtillstånd (AST) kan ha svårigheter med prediktion. Den här avhandlingen undersöker olika mått relaterade till prediktion (motorisk kontroll och visuell expektans) hos spädbarn och hur de hänger samman med AST.

Studie I undersökte sammanhanget mellan motorisk kontroll och exekutiva funktioner hos 8-månader gamla barn. Resultaten visade att förmågan att gripa ett objekt på ett effektivt sätt är relaterad till både arbetsminne och inhibition. Resultaten stämmer överens med hypotesen om att exekutiva funktioner har sin grund i motorisk kontroll.

Studie II undersökte motorisk kontroll hos småsyskon till barn med AST och hur motorisk förmåga relateras till senare autistiska symptom och kognitiv förmåga. Resultaten visade att vissa aspekter av motorisk kontroll är annorlunda hos småsyskon till autistiska barn vid 10 månaders ålder. Motorisk förmåga var dock inte relaterad till autistiska symptom vid 24 månader, utan till kognitiv förmåga.

Studie III undersökte förmågan att ta in ny, oväntad visuell information och barnets förväntningar på hur ett objekt rör sig i tid och rum. Resultaten visade att spädbarn som senare fick en AST-diagnos inte skiljde sig från barn med typisk utveckling.

Studie IV undersökte själva upplevelsen att vara med i forskningsstudier om småsyskon till barn med AST. De flesta föräldrar var positiva när det gäller deras egna upplevelser under studiens gång, men också kring barnets upplevelse under besökstillfällena.

Sammantaget visar studierna i denna avhandling att forskningsstudier kan bedrivas på ett deltagarvänligt sätt och att studierna bidrar till förståelse om prediktion för typisk och atypisk utveckling. Motorisk kontroll är en central komponent i kognitiva processer, dock fanns det inga tydliga tecken på att motorisk förmåga är specifikt kopplat till AST.

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References

Achermann, S., Bölte, S., & Falck-Ytter, T. (2020). Parents' experiences from participating in an infant sibling study of autism spectrum disorder. *Research in Autism Spectrum Disorders, 69*, 101454. doi:10.1016/j.rasd.2019.101454

Achermann, S., Nyström, P., Bölte, S., & Falck-Ytter, T. (2020). Motor Atypicalities in Infancy are Associated with General Developmental Level at Two Years, but Not Autistic Symptoms. *Autism (forthcoming)*. doi:10.1177/1362361320918745

Adolph, K. E. (1997). Learning in the development of infant locomotion. *Monographs of the Society for Research in Child Development, 62*(3), I-VI, 1-158.

Agyei, S. B., van der Weel, F. R., & van der Meer, A. L. (2016). Development of Visual Motion Perception for Prospective Control: Brain and Behavioral Studies in Infants. *Frontiers in Psychology, 7*, 100. doi:10.3389/fpsyg.2016.00100

American Psychiatric Association. (2013). *Diagnostic and Statistical Manual of mental disorders (5th Ed.)*. Washington, DC: American Psychiatric Association.

Anzulewicz, A., Sobota, K., & Delafield-Butt, J. T. (2016). Toward the Autism Motor Signature: Gesture patterns during smart tablet gameplay identify children with autism. *Scientific Reports, 6*, 31107-31107. doi:10.1038/srep31107

Aslin, R. N. (2017). Statistical learning: a powerful mechanism that operates by mere exposure. *WIREs Cognitive Science, 8*(1-2), e1373. doi:10.1002/wcs.1373

Baio, J., Wiggins, L., Christensen, D. L., Maenner, M. J., Daniels, J., Warren, Z., . . . Dowling, N. F. (2018). Prevalence of Autism Spectrum Disorder Among Children Aged 8 Years - Autism and Developmental Disabilities Monitoring Network, 11 Sites, United States, 2014. *MMWR Surveillance Summaries, 67*(6), 1-23. doi:10.15585/mmwr.ss6706a1

Bar-Haim, Y., & Bart, O. (2006). Motor Function and Social Participation in Kindergarten Children. *Social Development, 15*(2), 296-310. doi:10.1046/j.1467-9507.2006.00342.x

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin, 121*(1), 65-94. doi:10.1037/0033-2909.121.1.65

Barkley, R. A. (2012). *Executive Functions: What They Are, How They Work, and Why They Evolved*. New York: Guilford.

Barrett, L. F., Mesquita, B., & Gendron, M. (2011). Context in Emotion Perception. *Current Directions in Psychological Science, 20*(5), 286-290. doi:10.1177/0963721411422522

Bedford, R., Pickles, A., Gliga, T., Elsabbagh, M., Charman, T., Johnson, M. H., & BASIS Team. (2014). Additive effects of social and non-social attention during infancy relate to later autism spectrum disorder. *Developmental Science, 17*(4), 612-620.

Best, J. R., Miller, P. H., & Naglieri, J. A. (2011). Relations between Executive Function and Academic Achievement from Ages 5 to 17 in a Large, Representative National Sample. *Learning and individual differences, 21*(4), 327-336. doi:10.1016/j.lindif.2011.01.007

Bhat, A. N., Galloway, J. C., & Landa, R. J. (2012). Relation between early motor delay and later communication delay in infants at risk for autism. *Infant Behavior & Development, 35*(4), 838-846. doi:10.1016/j.infbeh.2012.07.019

Blair, C., & Razza, R. P. (2007). Relating Effortful Control, Executive Function, and False Belief Understanding to Emerging Math and Literacy Ability in Kindergarten. *Child Development, 78*(2), 647-663. doi:10.1111/j.1467-8624.2007.01019.x

Blasi, A., Lloyd-Fox, S., Sethna, V., Brammer, M. J., Mercure, E., Murray, L., . . . Johnson, M. H. (2015). Atypical processing of voice sounds in infants at risk for autism spectrum disorder. *Cortex, 71*, 122-133. doi:10.1016/j.cortex.2015.06.015

Bosl, W. J., Tager-Flusberg, H., & Nelson, C. A. (2018). EEG Analytics for Early Detection of Autism Spectrum Disorder: A data-driven approach. *Scientific Reports, 8*(1), 6828. doi:10.1038/s41598-018-24318-x

Broady, T. R., Stoyles, G. J., & Morse, C. (2017). Understanding carers' lived experience of stigma: the voice of families with a child on the autism spectrum. *Health & Social Care in the Community, 25*(1), 224-233. doi:10.1111/hsc.12297

Bull, R., & Scerif, G. (2001). Executive Functioning as a Predictor of Children's Mathematics Ability: Inhibition, Switching, and Working Memory. *Developmental Neuropsychology, 19*(3), 273-293. doi:10.1207/S15326942DN1903_3

Bushnell, E. W., & Boudreau, J. P. (1993). Motor development and the mind: the potential role of motor abilities as a determinant of aspects of perceptual development. *Child Development, 64*(4), 1005-1021.

Campos, J. J., Anderson, D. I., Barbu-Roth, M. A., Hubbard, E. M., Hertenstein, M. J., & Witherington, D. (2000). Travel Broadens the Mind. *Infancy, 1*(2), 149-219. doi:10.1207/S15327078in0102_1

Cannon, E. N., Woodward, A. L., Gredebäck, G., von Hofsten, C., & Turek, C. (2012). Action production influences 12-month-old infants' attention to others' actions. *Developmental Science, 15*(1), 35-42. doi:10.1111/j.1467-7687.2011.01095.x

Chen, D. T., Miller, F. G., & Rosenstein, D. L. (2003). Ethical aspects of research into the etiology of autism. *Mental Retardation and Developmental Disabilities Research Reviews, 9*(1), 48-53. doi:10.1002/mrdd.10059

Chen, Y. P., Keen, R., Rosander, K., & von Hofsten, C. (2010). Movement planning reflects skill level and age changes in toddlers. *Child Dev, 81*(6), 1846-1858. doi:10.1111/j.1467-8624.2010.01514.x

Claxton, L. J., Keen, R., & McCarty, M. E. (2003). Evidence of motor planning in infant reaching behavior. *Psychological Science, 14*(4), 354-356. doi:10.1111/1467-9280.24421

Constantino, J. N., Zhang, Y., Frazier, T., Abbacchi, A. M., & Law, P. (2010). Sibling recurrence and the genetic epidemiology of autism. *American Journal of Psychiatry, 167*(11), 1349-1356. doi:10.1176/appi.ajp.2010.09101470

Corbetta, D., Thurman, S. L., Wiener, R. F., Guan, Y., & Williams, J. L. (2014). Mapping the feel of the arm with the sight of the object: on the embodied origins of infant reaching. *Frontiers in Psychology, 5*, 576. doi:10.3389/fpsyg.2014.00576

Cummins, A., Piek, J. P., & Dyck, M. J. (2005). Motor coordination, empathy, and social behaviour in school-aged children. *Developmental Medicine & Child Neurology, 47*(7), 437-442. doi:10.1017/s001216220500085x

Demetriou, E. A., Lampit, A., Quintana, D. S., Naismith, S. L., Song, Y. J. C., Pye, J. E., . . . Guastella, A. J. (2018). Autism spectrum disorders: a meta-analysis of executive function. *Molecular Psychiatry, 23*(5), 1198-1204. doi:10.1038/mp.2017.75

Den Ouden, H., Kok, P., & De Lange, F. (2012). How Prediction Errors Shape Perception, Attention, and Motivation. *Frontiers in Psychology, 3*(548). doi:10.3389/fpsyg.2012.00548

Diamond, A. (2000). Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. *Child Development, 71*(1), 44-56. doi:10.1111/1467-8624.00117

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135-168. doi:10.1146/annurev-psych-113011-143750

Dowd, A. M., McGinley, J. L., Taffe, J. R., & Rinehart, N. J. (2012). Do planning and visual integration difficulties underpin motor dysfunction in autism? A kinematic study of young children with autism. *Journal of Autism and Developmental Disorders, 42*(8), 1539-1548. doi:10.1007/s10803-011-1385-8

Eigsti, I. M. (2013). A review of embodiment in autism spectrum disorders. *Frontiers in Psychology, 4*, 224. doi:10.3389/fpsyg.2013.00224

Einspieler, C., Sigafoos, J., Bartl-Pokorny, K. D., Landa, R., Marschik, P. B., & Bölte, S. (2014). Highlighting the first 5 months of life: General movements in infants later diagnosed with autism spectrum disorder or Rett syndrome. *Research in Autism Spectrum Disorders, 8*(3), 286-291. doi:10.1016/j.rasd.2013.12.013

Ekberg, T. L., Falck-Ytter, T., Bölte, S., & Gredebäck, G. (2016). Reduced Prospective Motor Control in 10-Month-Olds at Risk for Autism Spectrum Disorder. *Clinical Psychological Science, 4*(1), 129-135. doi:10.1177/2167702615576697

Elsabbagh, M., & Johnson, M. H. (2010). Getting answers from babies about autism. *Trends in Cognitive Sciences, 14*(2), 81-87. doi:10.1016/j.tics.2009.12.005

Elsabbagh, M., Mercure, E., Hudry, K., Chandler, S., Pasco, G., Charman, T., . . . BASIS Team. (2012). Infant Neural Sensitivity to Dynamic Eye Gaze Is

Associated with Later Emerging Autism. *Current Biology, 22*(4), 338-342. doi:10.1016/j.cub.2011.12.056

Falck-Ytter, T. (2010). Young children with autism spectrum disorder use predictive eye movements in action observation. *Biology letters, 6*(3), 375-378. doi:10.1098/rsbl.2009.0897

Falck-Ytter, T., Gredebäck, G., & von Hofsten, C. (2006). Infants predict other people's action goals. *Nature Neuroscience, 9*(7), 878-879. doi:10.1038/nn1729

Flanagan, J. E., Landa, R., Bhat, A., & Bauman, M. (2012). Head lag in infants at risk for autism: a preliminary study. *American Journal of Occupational Therapy, 66*(5), 577-585. doi:10.5014/ajot.2012.004192

Fletcher-Watson, S., Adams, J., Brook, K., Charman, T., Crane, L., Cusack, J., . . . Pellicano, E. (2019). Making the future together: Shaping autism research through meaningful participation. *Autism : the international journal of research and practice, 23*(4), 943-953. doi:10.1177/1362361318786721

Fletcher-Watson, S., Apicella, F., Auyeung, B., Beranova, S., Bonnet-Brilhault, F., Canal-Bedia, R., . . . Yirmiya, N. (2017). Attitudes of the autism community to early autism research. *Autism, 21*(1), 61-74. doi:10.1177/1362361315626577

Focaroli, V., Taffoni, F., Parsons, S. M., Keller, F., & Iverson, J. M. (2016). Performance of Motor Sequences in Children at Heightened vs. Low Risk for ASD: A Longitudinal Study from 18 to 36 Months of Age. *Frontiers in Psychology, 7*, 724. doi:10.3389/fpsyg.2016.00724

Forti, S., Valli, A., Perego, P., Nobile, M., Crippa, A., & Molteni, M. (2011). Motor planning and control in autism. A kinematic analysis of preschool children. *Research in Autism Spectrum Disorders, 5*(2), 834-842. doi:10.1016/j.rasd.2010.09.013

Fournier, K. A., Hass, C. J., Naik, S. K., Lodha, N., & Cauraugh, J. H. (2010). Motor coordination in autism spectrum disorders: a synthesis and meta-analysis. *Journal of Autism and Developmental Disorders, 40*(10), 1227-1240. doi:10.1007/s10803-010-0981-3

Friedman, N. P., Miyake, A., Robinson, J. L., & Hewitt, J. K. (2011). Developmental trajectories in toddlers' self-restraint predict individual differences in executive functions 14 years later: a behavioral genetic analysis. *Developmental Psychology, 47*(5), 1410-1430. doi:10.1037/a0023750

Friston, K. (2010). The free-energy principle: a unified brain theory? *Nature Reviews Neuroscience, 11*(2), 127-138. doi:10.1038/nrn2787

Garon, N., Bryson, S. E., & Smith, I. M. (2008). Executive function in preschoolers: a review using an integrative framework. *Psychological Bulletin, 134*(1), 31-60. doi:10.1037/0033-2909.134.1.31

Garon, N., Smith, I. M., & Bryson, S. E. (2014). A novel executive function battery for preschoolers: Sensitivity to age differences. *Child Neuropsychology, 20*(6), 713-736. doi:10.1080/09297049.2013.857650

Gerson, S. A., & Woodward, A. L. (2014). Learning From Their Own Actions: The Unique Effect of Producing Actions on Infants' Action Understanding. *Child Development, 85*(1), 264-277. doi:10.1111/cdev.12115

Gibson, E. J. (1988). Exploratory-Behavior in the Development of Perceiving, Acting, and the Acquiring of Knowledge .9. *Annual Review of Psychology, 39*, 1-41. doi:10.1146/annurev.ps.39.020188.000245

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

Gottwald, J. M., Achermann, S., Marciszko, C., Lindskog, M., & Gredebäck, G. (2016). An Embodied Account of Early Executive-Function Development. *Psychological Science, 27*(12), 1600-1610. doi:10.1177/0956797616667447

Gottwald, J. M., De Bortoli Vizioli, A., Lindskog, M., Nyström, P., Ekberg, T. L., von Hofsten, C., & Gredebäck, G. (2017). Infants prospectively control reaching based on the difficulty of future actions: To what extent can infants' multiple-step actions be explained by Fitts' law? *Developmental Psychology, 53*(1), 4-12. doi:10.1037/dev0000212

Gottwald, J. M., & Gredebäck, G. (2015). Infants' prospective control during object manipulation in an uncertain environment. *Experimental Brain Research, 233*(8), 2383-2390. doi:10.1007/s00221-015-4308-7

Gowen, E., & Hamilton, A. (2013). Motor abilities in autism: a review using a computational context. *Journal of Autism and Developmental Disorders, 43*(2), 323-344. doi:10.1007/s10803-012-1574-0

Grafton, S. T., & Hamilton, A. F. d. C. (2007). Evidence for a distributed hierarchy of action representation in the brain. *Human movement science, 26*(4), 590-616. doi:10.1016/j.humov.2007.05.009

Gray, D. E. (1993). Perceptions of Stigma - the Parents of Autistic-Children. *Sociology of Health & Illness, 15*(1), 102-120. doi:DOI 10.1111/1467-9566.ep11343802

Gray, D. E. (2002). 'Everybody just freezes. Everybody is just embarrassed': felt and enacted stigma among parents of children with high functioning autism. *Sociology of Health & Illness, 24*(6), 734-749. doi:Doi 10.1111/1467-9566.00316

Gredebäck, G., von Hofsten, C., & Boudreau, J. P. (2002). Infants' visual tracking of continuous circular motion under conditions of occlusion and non-occlusion. *Infant Behavior & Development, 25*(2), 161-182. doi:10.1016/S0163-6383(02)00119-4

Green, D., Charman, T., Pickles, A., Chandler, S., Loucas, T., Simonoff, E., & Baird, G. (2009). Impairment in movement skills of children with autistic spectrum disorders. *Developmental Medicine and Child Neurology, 51*(4), 311-316. doi:10.1111/j.1469-8749.2008.03242.x

Grönqvist, H., Strand Brodd, K., & von Hofsten, C. (2011). Reaching strategies of very preterm infants at 8 months corrected age. *Experimental Brain Research, 209*(2), 225-233. doi:10.1007/s00221-011-2538-x

Hamilton, A. F. d. C., & Grafton, S. T. (2007). The motor hierarchy: from kinematics to goals and intentions. *Sensorimotor Foundations of Higher Cognition*, 381.

Hazlett, H. C., Gu, H., Munsell, B. C., Kim, S. H., Styner, M., Wolff, J. J., . . . Statistical, A. (2017). Early brain development in infants at high risk for autism spectrum disorder. *Nature, 542*(7641), 348-351. doi:10.1038/nature21369

Hendry, A., Jones, E. J. H., & Charman, T. (2016). Executive function in the first three years of life: Precursors, predictors and patterns. *Developmental Review, 42*, 1-33. doi:10.1016/j.dr.2016.06.005

Hill, E. L. (2004). Executive dysfunction in autism. *Trends in Cognitive Sciences, 8*(1), 26-32.

Holmboe, K., Bonneville-Roussy, A., Csibra, G., & Johnson, M. H. (2018). Longitudinal development of attention and inhibitory control during the first year of life. *Developmental Science, 21*(6), e12690. doi:10.1111/desc.12690

Houwen, S., van der Veer, G., Visser, J., & Cantell, M. (2017). The relationship between motor performance and parent-rated executive functioning in 3- to 5-year-old children: What is the role of confounding variables? *Human movement science, 53*, 24-36. doi:10.1016/j.humov.2016.12.009

Hudry, K., Chandler, S., Bedford, R., Pasco, G., Gliga, T., Elsabbagh, M., . . . Charman, T. (2014). Early Language Profiles in Infants at High-Risk for Autism Spectrum Disorders. *Journal of Autism and Developmental Disorders, 44*(1), 154-167. doi:10.1007/s10803-013-1861-4

Iverson, J. M. (2010). Developing language in a developing body: the relationship between motor development and language development. *Journal of Child Language, 37*(2), 229-261. doi:10.1017/S0305000909990432

Iverson, J. M. (2018). Early Motor and Communicative Development in Infants With an Older Sibling With Autism Spectrum Disorder. *Journal of Speech, Language, and Hearing Research, 61*(11), 2673-2684. doi:10.1044/2018_JSLHR-L-RSAUT-18-0035

Iverson, J. M., Northrup, J. B., Leezenbaum, N. B., Parlade, M. V., Koterba, E. A., & West, K. L. (2018). Early Gesture and Vocabulary Development in Infant Siblings of Children with Autism Spectrum Disorder. *Journal of Autism and Developmental Disorders, 48*(1), 55-71. doi:10.1007/s10803-017-3297-8

Iverson, J. M., Shic, F., Wall, C. A., Chawarska, K., Curtin, S., Estes, A., . . . Young, G. S. (2019). Early motor abilities in infants at heightened versus low risk for ASD: A Baby Siblings Research Consortium (BSRC) study. *Journal of Abnormal Psychology, 128*(1), 69-80. doi:10.1037/abn0000390

Iverson, J. M., & Wozniak, R. H. (2007). Variation in vocal-motor development in infant siblings of children with autism. *Journal of Autism and Developmental Disorders, 37*(1), 158-170. doi:10.1007/s10803-006-0339-z

Jeannerod, M. (1988). *The neural and behavioural organization of goal- directed movements*. New York, NY: Clarendon Press.

Jonsson, B., & von Hofsten, C. (2003). Infants' ability to track and reach for temporarily occluded objects. *Developmental Science, 6*(1), 86-99. doi:10.1111/1467-7687.00258

Kahrs, B. A., Jung, W. P., & Lockman, J. J. (2013). Motor Origins of Tool Use. *Child Development, 84*(3), 810-816. doi:10.1111/cdev.12000

Kaiser, M. L., Schoemaker, M. M., Albaret, J. M., & Geuze, R. H. (2015). What is the evidence of impaired motor skills and motor control among children with attention deficit hyperactivity disorder (ADHD)? Systematic review of the literature. *Research in Developmental Disabilities, 36*, 338-357. doi:10.1016/j.ridd.2014.09.023

Kapp, S. K., Gillespie-Lynch, K., Sherman, L. E., & Hutman, T. (2013). Deficit, Difference, or Both? Autism and Neurodiversity. *Developmental Psychology, 49*(1), 59-71. doi:10.1037/a0028353

Kenny, L., Cribb, S. J., & Pellicano, E. (2019). Childhood Executive Function Predicts Later Autistic Features and Adaptive Behavior in Young Autistic People: a 12-Year Prospective Study. *Journal of Abnormal Child Psychology, 47*(6), 1089-1099. doi:10.1007/s10802-018-0493-8

Kirkham, N. Z., Slemmer, J. A., & Johnson, S. P. (2002). Visual statistical learning in infancy: evidence for a domain general learning mechanism. *Cognition, 83*(2), B35-42. doi:10.1016/s0010-0277(02)00004-5

Kochukhova, O., & Gredebäck, G. (2007). Learning about occlusion: initial assumptions and rapid adjustments. *Cognition, 105*(1), 26-46. doi:10.1016/j.cognition.2006.08.005

Lai, M.-C., Lombardo, M. V., & Baron-Cohen, S. (2014). Autism. *The Lancet, 383*(9920), 896-910. doi:10.1016/S0140-6736(13)61539-1

Landa, R., & Garrett-Mayer, E. (2006). Development in infants with autism spectrum disorders: a prospective study. *Journal of Child Psychology and Psychiatry, 47*(6), 629-638. doi:10.1111/j.1469-7610.2006.01531.x

Lawson, R. P., Mathys, C., & Rees, G. (2017). Adults with autism overestimate the volatility of the sensory environment. *Nature Neuroscience, 20*(9), 1293-1299. doi:10.1038/nn.4615

Lawson, R. P., Rees, G., & Friston, K. J. (2014). An aberrant precision account of autism. *Frontiers in Human Neuroscience, 8*, 302. doi:10.3389/fnhum.2014.00302

Ledouit, S., Casanova, R., Zaal, F. T. J. M., & Bootsma, R. J. (2013). Prospective control in catching: the persistent Angle-of-approach effect in lateral interception. *PLoS One, 8*(11), e80827-e80827. doi:10.1371/journal.pone.0080827

Libertus, K., Joh, A. S., & Needham, A. W. (2016). Motor training at 3 months affects object exploration 12 months later. *Developmental Science, 19*(6), 1058-1066. doi:10.1111/desc.12370

Licari, M. K., Alvares, G. A., Varcin, K., Evans, K. L., Cleary, D., Reid, S. L., . . . Whitehouse, A. J. O. (2019). Prevalence of Motor Difficulties in Autism Spectrum Disorder: Analysis of a Population-Based Cohort. *Autism Research*. doi:10.1002/aur.2230

Lord, C., Rutter, M., DiLavore, P. C., Risi, S., Gotham, K., Bishop, S. L., . . . Guthrie, W. (2012). *Autism Diagnostic Observation Schedule: ADOS-2*. Los Angeles, CA.

Ludlow, A., Skelly, C., & Rohleder, P. (2012). Challenges faced by parents of children diagnosed with autism spectrum disorder. *Journal of Health Psychology, 17*(5), 702-711. doi:10.1177/1359105311422955

Manning, C., Kilner, J., Neil, L., Karaminis, T., & Pellicano, E. (2017). Children on the autism spectrum update their behaviour in response to a volatile environment. *Developmental Science, 20*(5), e12435. doi:10.1111/desc.12435

Mari, M., Castiello, U., Marks, D., Marraffa, C., & Prior, M. (2003). The reach-to-grasp movement in children with autism spectrum disorder. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 358*(1430), 393-403. doi:10.1098/rstb.2002.1205

Marteniuk, R. G., MacKenzie, C. L., Jeannerod, M., Athenes, S., & Dugas, C. (1987). Constraints on human arm movement trajectories. *Canadian Journal of Psychology, 41*(3), 365-378.

Mercer, L., Creighton, S., Holden, J. J., & Lewis, M. E. (2006). Parental perspectives on the causes of an autism spectrum disorder in their children. *Journal of Genetic Counseling, 15*(1), 41-50. doi:10.1007/s10897-005-9002-7

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: a latent variable analysis. *Cognitive Psychology, 41*(1), 49-100. doi:10.1006/cogp.1999.0734

Mohring, W., & Frick, A. (2013). Touching up mental rotation: effects of manual experience on 6-month-old infants' mental object rotation. *Child Development, 84*(5), 1554-1565. doi:10.1111/cdev.12065

Monroy, C. D., Gerson, S. A., & Hunnius, S. (2017). Infants' Motor Proficiency and Statistical Learning for Actions. *Frontiers in Psychology, 8*(2174). doi:10.3389/fpsyg.2017.02174

Monroy, C. D., Meyer, M., Schröer, L., Gerson, S. A., & Hunnius, S. (2019). The infant motor system predicts actions based on visual statistical learning. *NeuroImage, 185*, 947-954. doi:10.1016/j.neuroimage.2017.12.016

Mullen, E. M. (1995). *Mullen Scales of Early Learning (AGS ed.)*. Circle Pines, MN: National Academy Press.

Murray, G. K., Veijola, J., Moilanen, K., Miettunen, J., Glahn, D. C., Cannon, T. D., . . . Isohanni, M. (2006). Infant motor development is associated with adult cognitive categorisation in a longitudinal birth cohort study. *Journal of Child Psychology and Psychiatry, 47*(1), 25-29. doi:10.1111/j.1469-7610.2005.01450.x

Nyström, P., Bölte, S., Falck-Ytter, T., & EASE Team. (2017). Responding to Other People's Direct Gaze: Alterations in Gaze Behavior in Infants at Risk for Autism Occur on Very Short Timescales. *Journal of Autism and Developmental Disorders, 47*(11), 3498-3509. doi:10.1007/s10803-017-3253-7

Nyström, P., Falck-Ytter, T., & Gredebäck, G. (2015). The TimeStudio Project: An open source scientific workflow system for the behavioral and brain sciences. *Behavior Research Methods*. doi:10.3758/s13428-015-0616-x

Ozonoff, S., Young, G. S., Carter, A., Messinger, D., Yirmiya, N., Zwaigenbaum, L., . . . Stone, W. L. (2011). Recurrence risk for autism spectrum disorders: a Baby Siblings Research Consortium study. *Pediatrics, 128*(3), e488-495. doi:10.1542/peds.2010-2825

Park, W. J., Schauder, K., Kwon, O.-S., Bennetto, L., & Tadin, D. (2018). Atypical visual motion prediction in autism spectrum disorder. *Journal of Vision, 18*(10), 547-547. doi:10.1167/18.10.547

Pellicano, E., & Burr, D. (2012). When the world becomes 'too real': a Bayesian explanation of autistic perception. *Trends in Cognitive Sciences, 16*(10), 504-510. doi:10.1016/j.tics.2012.08.009

Perruchet, P., & Pacton, S. (2006). Implicit learning and statistical learning: one phenomenon, two approaches. *Trends in Cognitive Sciences, 10*(5), 233-238. doi:10.1016/j.tics.2006.03.006

Piek, J. P., Bradbury, G. S., Elsley, S. C., & Tate, L. (2008). Motor Coordination and Social–Emotional Behaviour in Preschool-aged Children. *International Journal of Disability, Development and Education, 55*(2), 143-151. doi:10.1080/10349120802033592

Piek, J. P., Dawson, L., Smith, L. M., & Gasson, N. (2008). The role of early fine and gross motor development on later motor and cognitive ability. *Human movement science, 27*(5), 668-681. doi:10.1016/j.humov.2007.11.002

Ridler, K., Veijola, J. M., Tanskanen, P., Miettunen, J., Chitnis, X., Suckling, J., . . . Bullmore, E. T. (2006). Fronto-cerebellar systems are associated with infant motor and adult executive functions in healthy adults but not in schizophrenia. *Proceedings of the National Academy of Sciences of the United States of America, 103*(42), 15651-15656. doi:10.1073/pnas.0602639103

Rinehart, N. J., Bellgrove, M. A., Tonge, B. J., Brereton, A. V., Howells-Rankin, D., & Bradshaw, J. L. (2006). An examination of movement kinematics in young people with high-functioning autism and Asperger's disorder: further evidence for a motor planning deficit. *Journal of Autism and Developmental Disorders, 36*(6), 757-767. doi:10.1007/s10803-006-0118-x

Rosander, K., & von Hofsten, C. (2002). Development of gaze tracking of small and large objects. *Experimental Brain Research, 146*(2), 257-264. doi:10.1007/s00221-002-1161-2

Rosander, K., & von Hofsten, C. (2004). Infants' emerging ability to represent occluded object motion. *Cognition, 91*(1), 1-22.

Rosander, K., & von Hofsten, C. (2011). Predictive gaze shifts elicited during observed and performed actions in 10-month-old infants and adults. *Neuropsychologia, 49*(10), 2911-2917. doi:https://doi.org/10.1016/j.neuropsychologia.2011.06.018

Rutter, M., LeCouteur, A., & Lord, C. (2003). *Autism Diagnostic Interview Revised (ADI-R)*. Los Angeles, USA.

Sacrey, L. A. R., Zwaigenbaum, L., Bryson, S., Brian, J., & Smith, I. M. (2018). The reach-to-grasp movement in infants later diagnosed with autism spectrum disorder: a high-risk sibling cohort study. *Journal of Neurodevelopmental Disorders, 10*(1), 41. doi:10.1186/s11689-018-9259-4

Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical learning by 8-month-old infants. *Science, 274*(5294), 1926-1928. doi:10.1126/science.274.5294.1926

Sandin, S., Lichtenstein, P., Kuja-Halkola, R., Larsson, H., Hultman, C. M., & Reichenberg, A. (2014). The familial risk of autism. *JAMA, 311*(17), 1770-1777. doi:10.1001/jama.2014.4144

Sheinkopf, S. J., Iverson, J. M., Rinaldi, M. L., & Lester, B. M. (2012). Atypical cry acoustics in 6-month-old infants at risk for autism spectrum disorder. *Autism Res, 5*(5), 331-339. doi:10.1002/aur.1244

Sinha, P., Kjelgaard, M. M., Gandhi, T. K., Tsourides, K., Cardinaux, A. L., Pantazis, D., . . . Held, R. M. (2014). Autism as a disorder of prediction. *Proceedings of the National Academy of Sciences, 111*(42), 15220-15225. doi:10.1073/pnas.1416797111

Smith, L. B., Thelen, E., Titzer, R., & McLin, D. (1999). Knowing in the context of acting: the task dynamics of the A-not-B error. *Psychological Review, 106*(2), 235-260. doi:10.1037/0033-295x.106.2.235

Smyth, M. M., & Anderson, H. I. (2001). Football participation in the primary school playground: The role of coordination impairments. *British Journal of Developmental Psychology, 19*(3), 369-379. doi:10.1348/026151001166155

Soska, K. C., Adolph, K. E., & Johnson, S. P. (2010). Systems in development: motor skill acquisition facilitates three-dimensional object completion. *Developmental Psychology, 46*(1), 129-138. doi:10.1037/a0014618

Sparrow, S. S., Balla, D. A., & Cicchetti, D. V. (1984). *Vineland adaptive behavior scales*. American Guidance Service: Circle Pines, MN.

Stephens, R. L., Watson, L. R., Crais, E. R., & Reznick, J. S. (2018). Infant quantitative risk for autism spectrum disorder predicts executive function in early childhood. *Autism research : official journal of the International Society for Autism Research, 11*(11), 1532-1541. doi:10.1002/aur.2024

Taffoni, F., Focaroli, V., Keller, F., & Iverson, J. M. (2019). Motor performance in a shape sorter task: A longitudinal study from 14 to 36 months of age in children with an older sibling ASD. *PLoS One, 14*(5), e0217416. doi:10.1371/journal.pone.0217416

Tewolde, F. G., Bishop, D. V. M., & Manning, C. (2018). Visual Motion Prediction and Verbal False Memory Performance in Autistic Children. *Autism Research, 11*(3), 509-518. doi:10.1002/aur.1915

Thelen, E., Corbetta, D., Kamm, K., Spencer, J. P., Schneider, K., & Zernicke, R. F. (1993). The transition to reaching: mapping intention and intrinsic dynamics. *Child Development, 64*(4), 1058-1098.

Thorup, E., Nyström, P., Gredebäck, G., Bölte, S., Falck-Ytter, T., & EASE Team. (2016). Altered gaze following during live interaction in infants at risk for autism: an eye tracking study. *Molecular Autism, 7*, 12. doi:10.1186/s13229-016-0069-9

Thorup, E., Nyström, P., Gredebäck, G., Bölte, S., Falck-Ytter, T., & EASE Team. (2018). Reduced Alternating Gaze During Social Interaction in Infancy is Associated with Elevated Symptoms of Autism in Toddlerhood. *Journal of Abnormal Child Psychology, 46*(7), 1547-1561. doi:10.1007/s10802-017-0388-0

Van de Cruys, S., Evers, K., Van der Hallen, R., Van Eylen, L., Boets, B., de-Wit, L., & Wagemans, J. (2014). Precise minds in uncertain worlds: predictive coding in autism. *Psychological Review, 121*(4), 649-675. doi:10.1037/a0037665

van der Meer, A. L., van der Weel, F. R., & Lee, D. N. (1994). Prospective control in catching by infants. *Perception, 23*(3), 287-302. doi:10.1068/p230287

von Hofsten, C. (1991). Structuring of early reaching movements: a longitudinal study. *Journal of Motor Behavior, 23*(4), 280-292. doi:10.1080/00222895.1991.9942039

von Hofsten, C. (1993). Prospective Control - a Basic Aspect of Action Development. *Human Development, 36*(5), 253-270. doi:10.1159/000278212

von Hofsten, C. (2004). An action perspective on motor development. *Trends in Cognitive Sciences, 8*(6), 266-272. doi:10.1016/j.tics.2004.04.002

von Hofsten, C. (2007). Action in development. *Developmental Science, 10*(1), 54-60. doi:10.1111/j.1467-7687.2007.00564.x

Von Hofsten, C. (2009). Action, the foundation for cognitive development. *Scandinavian Journal of Psychology, 50*(6), 617-623. doi:10.1111/j.1467-9450.2009.00780.x

von Hofsten, C., & Lindhagen, K. (1979). Observations on the Development of Reaching for Moving-Objects. *Journal of Experimental Child Psychology, 28*(1), 158-173.

von Hofsten, C., & Rosander, K. (1996). The development of gaze control and predictive tracking in young infants. *Vision Research, 36*(1), 81-96. doi:10.1016/0042-6989(95)00054-4

von Hofsten, C., Uhlig, H., Adell, M., & Kochukhova, O. (2009). How children with autism look at events. *Research in Autism Spectrum Disorders, 3*(2), 556 - 569. doi:https://doi.org/10.1016/j.rasd.2008.12.003

von Hofsten, C., Vishton, P., Spelke, E. S., Feng, Q., & Rosander, K. (1998). Predictive action in infancy: tracking and reaching for moving objects. *Cognition, 67*(3), 255-285.

Walsh, P., Elsabbagh, M., Bolton, P., & Singh, I. (2011). In search of biomarkers for autism: scientific, social and ethical challenges. *Nature Reviews Neuroscience, 12*(10), 603-612. doi:10.1038/nrn3113

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review, 9*(4), 625-636. doi:10.3758/bf03196322

Yudell, M., Tabor, H. K., Dawson, G., Rossi, J., Newschaffer, C., Working Group in Autism Risk, C., & Ethics. (2013). Priorities for autism spectrum disorder risk communication and ethics. *Autism, 17*(6), 701-722. doi:10.1177/1362361312453511

Zoia, S., Blason, L., D'Ottavio, G., Bulgheroni, M., Pezzetta, E., Scabar, A., & Castiello, U. (2007). Evidence of early development of action planning in the human foetus: a kinematic study. *Experimental Brain Research, 176*(2), 217-226. doi:10.1007/s00221-006-0607-3

Zwaigenbaum, L., Thurm, A., Stone, W., Baranek, G., Bryson, S., Iverson, J., . . . Sigman, M. (2007). Studying the emergence of autism spectrum disorders in high-risk infants: methodological and practical issues. *Journal of Autism and Developmental Disorders, 37*(3), 466-480. doi:10.1007/s10803-006-0179-x

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