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MOTOR PLANNING IN AUTISM AND IN TYPICAL DEVELOPMENT ACROSS EARLY SCHOOL AGE

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To all the kids who have taught me so much, without all of you there would have been nothing. Thank you for teaching me every day, you make life sparkle with joy and curiosity. Special thanks to all the kids and families who have participated in this thesis project, making it possible. It has been a privilege meeting all of you, thank you.

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Abstract

In our daily lives, we often engage in various manual activities with specific goals in mind. To adapt effectively to an ever-changing environment, it is important for us to anticipate future events while carrying out our actions. Motor planning plays a crucial role in most of our daily activities, underscoring the significance of comprehending its development and its connection to cognitive and perceptual development. In this endeavor, it is critical to also consider atypical development, including the role of motor planning in the prevalent motor problems experienced by children with autism. The primary goal of this thesis was to enhance our comprehension of motor planning development in early school-age children, including both those with typical development and those with autism. The main focus was to investigate the performance of sequential manual movements and detailed characteristics of motor planning from a developmental perspective. To achieve this goal, 3D motion capture technology was utilized. In Study I, variations in motor planning abilities among typically developing 6- and 10-year-old children were examined compared to adults. The findings demonstrated significant enhancements in movement organization between the ages of 6 and 10. However, it is important to note that, even at 10 years old, the children had not yet attained the same level of motor planning ability as adults. Additionally, at the age of 6, the children's sequential movements were more exploratory and relied strongly on feedback processes. It was also evident that they encountered difficulties in making real-time adjustments. By the age of 10, the children demonstrated movement speed and smoothness similar to that of adults, but differences in motor planning outcomes still persisted when compared to adults. Study II investigated differences in motor planning and movement execution between 6-year-old children with autism and typically developing children. In addition, it explored the associations between movement parameters and cognitive functions within the group of children with autism. The findings indicated that, compared to typically developing children, children with autism displayed difficulties in planning sequential movements and exhibited decreased performance consistency. Difficulties in movement execution were further evident towards the end of the movement, which was probably related to suboptimal planning. Among the children with autism, movement time and smoothness were linked to working memory ability, while proactivity in object adjustment (a specific planning aspect of the study task) was associated with general cognitive functioning and non-verbal fluid abilities. Study III was a longitudinal study that examined the development of motor planning in children with autism in comparison to typically developing children during early school age (ages 7, 8, and 9 years). Findings revealed that the children with autism displayed atypical motor planning development in sequential movements. Specifically, increased reliance on initial visual information, particularly at the age of 9, facilitated motor planning improvements in the typically developing children but not the children with autism. These findings support that early school age seems to be an important period when the reorganization of sequential movements develops into more adult-like behavior. These improvements appear to be associated with an increased reliance on initial visual information and changes in visuomotor integration in typical development. However, the children with autism demonstrated less efficient motor planning and atypical motor planning development during this period. This is primarily attributed to their reliance on initial visual information, which supports the notion that difficulties in visuomotor integration have an impact on motor planning development in children with autism. Overall, these findings underscore the importance of considering developmental aspects in both research and practice related to motor problems in children with autism.

Abbreviations

A1	Age-level 1 (age range 7–8 years)
A2	Age-level 2 (age range 8–9 years)
A3	Age-level 3 (age range 9–10 years)
ASD	Autism spectrum disorder (in this thesis “autism” and “ASD” are used interchangeably)
BRIEF	Behavioral Rating Inventory of Executive Function
EHQ	Edinburgh handedness questionnaire
ESC	End-state comfort
FSIQ	Full scale intelligence quotient
FRI	Fluid reasoning index
GEF	Global executive functioning
MABC-2	Movement assessment battery for children-2 checklist
MU	Movement unit
PPV	Part-peak velocity
PPV-RTG	Part-peak velocity in the reach-to-grasp phase
PV	Peak velocity
PV-RTG	Peak velocity in the reach-to-grasp phase
PV-Transport	Peak velocity in the transport phase
RA	Residual angle
RTG	Reach-to-grasp

TD	Typically developing
TTF	Transport-to-fit
WISC-V	Wechsler Intelligence Scale for Children, fifth edition
WMI	Working memory index
WPPSI-IV	Wechsler Preschool and Primary Scale of Intelligence, fourth edition

Sammanfattning på svenska

I vårt dagliga liv använder vi människor ofta våra händer för att utföra en mängd olika målinriktade rörelser. För att möta kraven från en ständigt föränderlig miljö är det viktigt för oss att förutse framtida händelser när vi utför våra handlingar. Motorisk planering spelar därför en avgörande roll för många dagliga aktiviteter, vilket understryker betydelsen av att förstå dess utveckling och dess koppling till kognitiv och perceptuell utveckling. I ansatsen av att öka kunskapen inom detta område är det viktigt att också beakta atypisk utveckling, vilket inkluderar att bättre förstå vilken roll motorisk planering spelar för de motoriska problem som många barn med autism uppvisar. Det övergripande målet med denna avhandling var att öka kunskapen om utveckling av motorisk planering hos barn i tidig skolålder, både hos barn som följer en typisk utveckling och hos barn med autism. Fokus har legat på att, med hjälp av rörelseregistreringsteknik, bidra med detaljerade beskrivningar av vad som karakteriserar motorisk planering vid manuella sekventiella rörelser i ett utvecklingsperspektiv. I Studie I undersöktes åldersrelaterad variation av motorisk planeringsförmåga hos typiskt utvecklade barn i 6 och 10 års åldern jämfört med vuxna. Resultaten visade att rörelsens organisation förbättrades markant mellan 6 och 10 års ålder, men att vuxennivåer fortfarande inte hade uppnåtts fullt ut hos 10-åringarna. 6-åringarnas sekventiella rörelser var mer utforskande och verkade förlita sig mindre på initial planering jämfört med de äldre barnen och de vuxna. Det verkade också vara svårare för 6-åringarna att justera och anpassa sina rörelser under utförandet av uppgiften. Hos 10-åringarna var både anpassningen av rörelsen under utförandet och den tid det tog att genomföra rörelsen jämförbar med de vuxnas rörelser. Skillnader gentemot vuxna sågs främst för mått som relaterade till motorisk planering. Studie II undersökte skillnader mellan 6-åriga barn med autism och typiskt utvecklade jämnåriga gällande motorisk planering och rörelseutförande vid manuella sekventiella rörelser. Dessutom undersöktes samband mellan rörelseparametrar och kognitiva funktioner inom gruppen av barn med autism. Resultaten indikerade att gruppen av barn med autism hade svårare att planera sekventiella rörelser och hade större variation i sina egna rörelsemönster jämfört med gruppen av barn med typisk utveckling. Svårigheter med rörelseutförande visades främst i slutet av rörelsen, troligen relaterat till mindre optimal planering. Bland barnen med autism relaterade den tid det tog att genomföra rörelsen och mängden justeringar av rörelsen under utförandet till arbetsminnesförmågor. Fortsatt var proaktivitet i objektjustering (en specifik planeringsaspekt av studiens uppgift) associerad med generell begåvning och icke-verbal logisk förmåga. Studie III var en longitudinell studie som undersökte utvecklingen av motorisk planering hos barn med autism i jämförelse med typiskt utvecklade barn under tidig skolålder (åldrarna 7, 8 och 9 år). Resultaten indikerade att barnen med autism hade atypisk utveckling av motorisk planering i samband med manuella sekventiella rörelser. Det verkade som att gruppen av barn med typisk utveckling ökade sitt nyttjande av initialt tillgänglig visuell information med stigande ålder, särskilt framträdande vid 9 års ålder, och att detta främjade motorisk planering. Detta verkade dock inte ske på liknande vis för gruppen av barn med autism. Dessa avhandlingsresultat stödjer att tidig skolålder verkar vara en viktig åldersperiod där omorganisering av sekventiella rörelser, mot mer vuxenliknande rörelser, sker. Dessa förbättringar verkar vara associerade med ett ökat nyttjande av initialt tillgänglig visuell information och förändringar i visuo-motorisk integration i typisk utveckling. Under tidig skolålder verkar däremot barnen med autism förlita sig mindre på initial planering och uppvisa en atypisk utveckling av motorisk planering jämfört med typiskt utvecklade jämnåriga. Detta relaterade främst till atypiskt nyttjande av initialt tillgänglig visuell information, vilket stödjer uppfattningen att svårigheter med visuo-motorisk integration påverkar motorisk planering hos barn med autism. Sammantaget betonar dessa avhandlingsresultat vikten av att beakta utvecklingsaspekter i både forskning och praktik relaterad till motoriska problem hos barn med autism.

List of papers

I. Domellöf, E., Bäckström, A., Johansson, A.-M., Rönnqvist, L., von Hofsten, C., & Rosander, K. (2020). Kinematic characteristics of second-order motor planning and performance in 6- and 10-year-old children and adults: Effects of age and task constraints. *Developmental Psychobiology*, *62*, 250–265. https://doi.org/10.1002/dev.21911

II. Bäckström, A., Johansson, A.-M., Rudolfsson, T., Rönnqvist, L., von Hofsten, C., Rosander, K., & Domellöf, E. (2021). Motor planning and movement execution during goal-directed sequential manual movements in 6-year-old children with autism spectrum disorder: A kinematic analysis. *Research in Developmental Disabilities*, *115*, 104014. https://doi.org/10.1016/j.ridd.2021.104014

III. Bäckström, A., Johansson, A.-M., Rudolfsson, T., Rönnqvist, L., von Hofsten, C., Rosander, K., & Domellöf, E. (Manuscript currently under peer review in *Autism*). Atypical development of sequential manual motor planning and visuomotor integration in children with autism at early school-age: A longitudinal kinematic study.

Description of individual contributions by Anna Bäckström to Study I-III, included in this thesis. Contributed to the conceptualization and methodology in Study I and had a major role in the conceptualization and methodology of Study II and III. Had a major role in project administration, research investigations and data pre-processing in Study I, II and III. Wrote parts of, reviewed and edited the manuscript in Study I. Had a major role in formal analysis and interpretation of results, visualization, and wrote the manuscripts in Study II and III. All work was conducted in collaboration with supervisors and co-authors, with increasing independence.

Preface

During my interview when applying for the position as a doctoral student, I was asked the question of why I thought this thesis topic was important for a psychologist. I do not remember what I answered then, but in this thesis, I go into the details of why I think motor development is highly relevant for a developmental psychologist. To summarize briefly: In childhood, there are close links between motor, perceptual and cognitive development (Diamond, 2000). Even before birth, the brain is involved in generating goal-directed movements (Zoia et al., 2007), illustrating the importance of the action-perception link in learning about oneself and the environment. Children process visual and other perceptual information from the environment to generate goal-directed actions, and generating actions allows them to acquire new perceptual information from the environment, thus providing experiences for learning. But what happens if the development in one or several of these areas is atypical? There is ample evidence that both motor development and perception are affected early on in autism (Lord et al., 2020). It has been suggested that even minor atypicality in one area can impact upon the development in other areas, leading to a kind of reciprocal domino effect that then generates divergent developmental trajectories (Falck-Ytter & Bussu, 2023; Iverson et al., 2023). Advances in understanding the features in one area, such as the detailed characteristics of motor planning development, may further inform other areas as well due to possible common governing neural mechanisms. In this thesis, I describe the characteristics of typical and atypical motor planning development in sequential manual movements during early school age. The included studies provide detailed information on various aspects of this characterization. Additionally, I synthesize these details into a more general overview, outlining the global patterns observed and explaining their significance in advancing our understanding of motor planning development in children with autism.

Background

Motor planning

As we go about our daily lives, we perform numerous goal-directed manual activities to achieve our objectives. Often, a single reach-and-grasp movement is insufficient; we frequently need to execute a complex sequence of sub-actions to accomplish our overall movement goals. For example, if I want to scribble with a nearby pen on a piece of paper, I must reach for the pen, grasp it, adjust the direction of the pen, and place the point on the correct spot on the paper where I want to start scribbling. To meet the demands of the environment, we need to proactively calculate future events when we execute our actions. If we did not foresee them, but just reacted to them when they happened, every action would be just a little bit too late (Jeannerod, 2006). Hence, since motor action needs to precede feedback signals about the movement, anticipation is required to generate a functional movement (von Hofsten, 2014). There are numerous examples in neuroscience of cerebral mechanisms that are used for the anticipation of motion and perception (Berthoz et al., 2008).

Goal-directed actions are often formed intentionally in a general or abstract manner, rather than focusing on the specific detailed steps involved. However, they need to be performed at a detailed, concrete level. The action goal, of scribbling with a pen, for example, needs to be transformed into motor commands specifying the movement trajectory when reaching for the pen, the force needed to grasp the pen and so on. Motor planning describes this, often implicit, process of planning and organizing one's motor behaviors to accomplish a specific motor objective. This process contains the prediction of an action goal outcome and the selection and organization of an appropriate movement program to achieve that goal. To form an appropriate action prediction, relevant sensory information needs to be attended to, decided upon and integrated with already formed motor representations (Wong et al., 2015). This action prediction is then used to organize the motor behaviors needed to accomplish the action. After the perceptual decisions that are necessary to define the goal of the action have been made, the remaining formation of the motor plan has been described as almost instantaneous in adults (Wong et al., 2015). In this sense, motor planning is often described as the initial anticipatory, feed-forward phase in a goal-directed movement (Wolpert & Ghahramani, 2000). In theories of motor control, it is proposed that the brain uses internal models to control movements. Internal models are representations of the relationship between motor actions and their consequences, and are formed by experience (Wolpert & Flanagan, 2001). Internal models use sensorimotor information to predict the outcomes of a motor command on our body and on the objects with which we interact. As the movement unfolds, the feed-forward prediction is evaluated and subsequently supported by feedback processes. The ongoing movement is monitored in its trajectory against the prediction and any potential incongruities based on actual sensory feedback induce online corrections. It is proposed that multiple feed-forward models generate simultaneous predictions of the feedback that the context should generate with different probability estimations (Wolpert & Flanagan, 2001). If the actual sensory feedback error is significant, the feed-forward model will be updated with an alternative context that produces a smaller mismatch. Prediction errors are not only used to monitor ongoing movement, they also contribute to updating the internal model from these experiences, thus facilitating learning.

A large proportion of everyday manual activities is constituted of sequential movements, i.e. movements containing two or more sub-steps. To generate a smooth sequential movement, the sub-steps of the total movement need to be taken into account in the anticipatory process. This may involve several phases, such as first-order motor planning, second-order motor planning and so forth (Rosenbaum et al., 2012). First-order motor planning consists of adjusting one's motor behaviors to achieve an imminent goal. An example could be to reach out and grasp a pen. Second-order motor planning means that motor behavior is adjusted, not only to achieve the imminent goal of the first movement sub-step but also the forthcoming goal of the following movement sub-step. An example here could be to reach out and grasp a pen with the intent of placing it in a pen stand. How the sequential chain of sub-steps of the movement are planned and integrated influence how efficiently the overall action goal can be executed.

Development of motor planning

Manual motor development has been extensively described in typically developing (TD) infants and toddlers. Research indicates that primitive goal-directed manual movements are present even before birth. Fetuses perform goal-directed hand movements towards the mouth (primitive thumb sucking) in a different manner than manual movements without a goal (Zoia et al., 2007). Progressively increased anticipatory mouth opening before the hand touches the face during prenatal development has also been reported (Reissland et al., 2014), strengthening the evidence that the development of motor planning starts in the womb. After birth, initial first-order motor planning has been observed in proactive hand adjustments during reaching in infants as young as 4–5 months (von Hofsten & Fazel-Zandy, 1984; von Hofsten & Rönnqvist, 1988). With experience and neurodevelopment, large improvements in reaching are then observed across the infancy period in terms of increased feed-forward reliance, straighter trajectories, faster pace and increased smoothness of the movement (Konczak et al., 1995; Rönnqvist & Domellöf, 2006; von Hofsten & Rönnqvist, 1988). In sequential movements, the emerging integration of sub-steps of the movement, i.e. second-order motor planning, has been reported in 10-month-old infants (Claxton et al., 2003) and 18–21-month-old toddlers (Chen et al., 2010). This was observed in the sense that the precision affordances of the final goal in a sequential action began to affect the features of the movement (i.e. movement kinematics) during the initial movement phase. More specifically, precision demands of the end-goal affected peak velocity (Claxton et al., 2003) and acceleration/deceleration proportions (Chen et al., 2010) of the hand during the reaching phase. In contrast, a study investigating children aged 4–11 years (Wilmut et al., 2013b) did not show the same kind of end-goal-related adjustments of movement kinematics in their youngest participants (4–5-year-old children). These kinds of second-order motor planning adjustments, i.e. adjustments of reach-to-grasp acceleration/deceleration proportions, were only evident in the older child groups, although not reaching adult levels. The final goal did, however, affect reach-to-grasp movement durations in the 4–5-year-old children (but not in the older age groups), with longer movement duration being observed for more difficult tasks. The authors propose that task differences could be related to inconsistencies between studies regarding the age at which second-order motor planning was evident (Wilmut et al., 2013b).

The development of second-order motor planning has further been investigated within end-state comfort (ESC) paradigms. The ESC effect describes the typical inclination of adults to take into account the future body states within a sequential action when grasping an object (Rosenbaum et al., 2012). This is done in order to generate a controllable and comfortable end state of the movement. A common example is that, when we grasp an overturned glass with the intent of pouring water into it, we typically do so with an awkward, upside-down grip. When we then turn the glass to pour a drink, the initially uncomfortable grasp aids in generating a more controlled end state of the movement. In typically developing children, a systematic review of studies has shown that the ESC effect emerges around the age of 3 years, with the most notable developmental increase around 5–8 years (Wunsch et al., 2013). Continuing development of second-order motor planning within this paradigm is described up to at least 10 years, showing increasing ESC stability with increasing age (Wunsch et al., 2013). Some between-study inconsistencies were reported in relation to when in age ESC emerges and when it reaches adult levels (Wunsch et al., 2013). Differences between studies have been related to task properties such as task complexity, precision demands of end-movement and the necessity of considering ESC in order to succeed at the task (Jongbloed-Pereboom et al., 2016; Krajenbrink et al., 2020; Wunsch et al., 2013).

The development of second-order motor planning has been examined not only in terms of how objects are grasped but also in terms of how they are adjusted in relation to the end-goal of their use. In preschool-aged children, the prospectivity of object adjustments has been investigated in fitting tasks. Younger preschool age (14–18 months) children do not seem to pre-orient objects during the process of fitting them into apertures (Örnkloo & von Hofsten, 2007; Street et al., 2011). Older preschool children (>24 months), however, do begin to show increasingly prospective object adjustments before fitting, and the required transportation and rotation of objects start to become integrated (Jung et al., 2015, 2018), although not at the level of adult performance (Ossmy et al., 2020).

Compared to research on infants and toddlers, detailed characterizations of the development of motor planning in children of early school age are scarce. Most previous studies have focused on motor organization in prehension movements (i.e. the act of reaching and grasping) (e.g. Kuhtz-Buschbeck et al., 1998; Martel et al., 2020; Olivier et al., 2007; Schneiberg et al., 2002; Simon-Martinez et al., 2018). The findings show that age-related improvements in prehension movements are continuously and consistently displayed during middle childhood. Younger children, around the age of 5–7 years, show relatively immature coordination and control of prehension and unstable linking between reaching and grasping movements. With increasing age, intra-individual movement variability decreases and children perform straighter and smoother prehension movements. Although age-related changes in movement characteristics have been reported to reach a plateau at 11–12 years (Kuhtz-Buschbeck et al., 1998; Simon-Martinez et al., 2018), children do not consistently perform at adult levels around this age

(Olivier et al., 2007; Schneiberg et al., 2002). It has been proposed that the improvements in movement organization during middle childhood are related to advances in motor planning. With regard to first-order planning, object size has been shown to affect grip size adjustments during visually guided prehension movements in 4–12-year-old children (Kuhtz-Buschbeck et al., 1998). However, although object size similarly affected grip size adjustments in 5-year-old children in another study, enlarged grip aperture in comparison to adults indicated that grip planning is not yet fully fine-tuned (Zoia et al., 2006). In addition, object weight has also been shown to affect prehension kinematics in middle childhood (Martel et al., 2020). Like adults, 7–10-year-old children performed faster reaches for heavier objects than for lighter ones. In contrast, 5–6-year-old children showed the opposite pattern of faster reaches for lighter objects than for heavier ones. The results further revealed that, by the end of displacement of the object, 5–6-year-old and 9–10-year-old children did not show any weight effect, reflecting a reduced need to continue utilizing correcting feedback processes. However, the 7–8-year-old children did show a weight effect throughout the displacement, indicating that further refinement of feed-forward and feedback processes is still ongoing during these ages.

Taken together, previous research describes a transition period occurring during early school age, around 7 to 11 years. The more feedback-based exploratory strategies observed in younger children (under 7 years) appear to evolve into more adult-like strategies (Jongbloed-Pereboom et al., 2016; Martel et al., 2020; Serrien & O'Regan, 2021; Thibaut & Toussaint, 2010; van Roon et al., 2008). Furthermore, a destabilization period is proposed to occur around ages 8 to 9 (Jongbloed-Pereboom et al., 2016; Martel et al., 2020; Serrien & O'Regan, 2021; Thibaut & Toussaint, 2010), preceding an increased reliance on both effective feed-forward and feedback strategies. Around this age, apart from the less efficient correcting feedback processes (Martel et al., 2020) previously described, a temporary reduction in ESC effects has been noted (Jongbloed-Pereboom et al., 2016; Thibaut & Toussaint, 2010). However, the detailed characterization of sequential movement planning during the early school years is limited.

Motor development is reciprocally linked to cognitive and perceptual development (Diamond, 2000). Changes in sensorimotor processes during development are related to changes in perceptual processing and sensory integration. There is evidence that some aspects of sensory integration are present almost from birth, although sensory integration is refined with neurodevelopment and experience during development

(Dionne-Dostie et al., 2015). Attention to and perceptual processing of the action goal are essential to form an efficient motor plan (Wong et al., 2015) and it has been shown that, during development, attention and perception for action are formed by action experience (Kontra et al., 2012). For example, empirical support includes findings that, with more reaching experience, attention and exploration increased for smaller, more graspable, objects in 4–6-month-old infants (Libertus et al., 2013). Increases in visual form perception have been shown to relate to previously increased opportunities for manual exploration in 8-month-old infants (Schröder et al., 2020). Early manual object manipulation abilities have further been related to later mathematical skills (Verdine et al., 2017). It has also been shown that the perception of other people's actions is shaped by experience. When young children start to be able to perform an action, they also start to be able to understand and predict the action goal of the same kind of action performed by someone else (Gredebäck & Falck-Ytter, 2015). Even though the ontogeny is debated, it has been proposed that these findings relate to parieto-frontal mirror neurons activating motor representations for an action goal in a corresponding way, independent of whether the action is performed or observed (Casartelli & Molteni, 2014). In the development of sensory integration, the period around early school age (about 8–10 years) has been highlighted as a period when sensory integration starts to become more adult-like (Gori et al., 2008; Nardini et al., 2010). Furthermore, it has been proposed that co-occurring changes in sensorimotor integration are related to the above-mentioned reorganization of motor planning towards more adult-like planning during early school age (Jongbloed-Pereboom et al., 2016; Martel et al., 2020; Serrien & O'Regan, 2021; Thibaut & Toussaint, 2010).

Autism

Autism spectrum disorder (ASD; in this thesis autism and ASD are used interchangeably) is a neurodevelopmental condition that begins early in life. It is characterized by socio-communicative difficulties and restricted, repetitive behaviors, which may include atypical sensory reactivity or interests. To receive a diagnosis, one must have persistent deficiencies in social communication and restricted behaviors affecting functioning and everyday life (American Psychiatric Association, 2013). The prevalence of autism worldwide is approximately 1%, but high-income countries show even higher prevalence estimates (Lord et al., 2020). The prevalence of autism diagnoses has increased over the last several decades, which is suggested to be in part due to changes in clinical diagnostic practices (Lundström et al., 2015). There are indications, however, that these changes do not affect autism diagnosed in children of preschool age to the same extent. The results from a birth cohort study of Swedish twins indicate no decrease in the number of symptoms present at diagnosis over time, unlike the pattern observed for children diagnosed at later age (Arvidsson et al., 2018).

In children diagnosed with autism, neurodevelopmental problems beyond the ones specified in the diagnostic criteria commonly occur (Lord et al., 2020). Comorbidity is so common that it has been proposed that this should be viewed as a norm rather than an exception (Happé & Frith, 2020). Among children with autism, challenges in intellectual, verbal and executive functions are frequently present (Lord et al., 2020). However, illustrating the neurodiversity of the condition, there are recent study results indicating that above-average cognitive ability is also relatively more common in children with autism (Billeiter & Froiland, 2023). The diagnostic criterion of atypical sensory reactivity further mirrors the frequently described differences in sensory perception among children with autism (Robertson & Baron-Cohen, 2017). Comparative strengths have been described in static tasks of detecting sensory details, while atypical processing of dynamic perceptual information has been proposed (Robertson & Baron-Cohen, 2017). These findings are in line with the descriptions of “weak central coherence” in autism. This cognitive style describes a bias for local rather than global processing, i.e. a focus on details, or parts, rather than on the whole (Happé & Frith, 2006). An alternative description, of temporal processing being slower or noisier, affecting global processing and multisensory processing, has also been proposed (Robertson & Baron-Cohen, 2017).

Today, autism is usually conceptualized as a heterogeneous condition with early genetic and environmental factors contributing to its development. Autism is highly heritable, with estimates ranging from approximately 40% to 90% (Lord et al., 2020). The inheritance pattern is complex, and deterministic models of autism have shown limited effectiveness. Rather, it has been proposed that complex bidirectional interactions between gene expression, brain activity and behavior lead to the atypical development of neural networks and a heterogeneous development of autism (Lord et al., 2020). Different explanations have been proposed for inclusion in these bidirectional interactions thought to form the basis of autistic development. According to so-called “sensory-first” accounts, which are relevant to this thesis, atypical early sensory processing is a core aspect of autistic development, generating dynamic effects on future development (Falck-Ytter & Bussu, 2023; Robertson &

Baron-Cohen, 2017). The sensory-first account highlights the differences in sensory processing that seem to be present in infants later diagnosed with autism. Early atypical processing of dynamical sensorimotor information can lead to problems in forming meaning and stable representations. This affects various forms of learning, since integrated sensorimotor information is a key medium for interactions with the world. Self-stratifying processes, for example where attention is directed, may also reduce exposure to and learning from interactions that are perceived as confusing or carrying little meaning. Hence, it is proposed that such atypical early sensory processing has an impact upon child development, and contributes to autism symptoms, by affecting experience-based learning and neural development.

Motor planning in autism

It is well established that motor problems, including manual motor skills, are prevalent in individuals with autism (American Psychiatric Association, 2013; Coll et al., 2020; Kangarani-Farahani et al., 2023; Wang et al., 2022). A recent systematic review found that around 50–88% of children with autism are estimated to have significant motor impairments (Kangarani-Farahani et al., 2023). Methods of assessment have been shown to have an impact on effect sizes in a recent meta-analysis (Wang et al., 2022), with more problems reported from standardized clinical assessments of motor function than kinematic assessments. This meta-analysis (Wang et al., 2022) also highlighted evidence for a relationship between motor problems and autism symptoms in children with autism. In the meta-analysis, more motor problems showed a moderate association with lower social skills. However, cognitive level was not found to be a significant moderator in the meta-analysis, questioning previous proposals that relationships between motor problems and autism symptoms are moderated by cognitive delay. Although not specific in relation to other neurodevelopmental disorders, a prospective study showed the presence of motor problems in infancy to be a predictor for later autism diagnosis (LeBarton & Landa, 2019). Although the link between autism and motor problems is well established, the underpinning factors for motor problems in autism are less clear. One domain of motor performance that has attracted increased attention in the consideration of specifiers to the motor problems exhibited in autism is motor planning.

It has been suggested that atypical motor planning plays an important role in understanding movement problems in autism (von Hofsten &

Rosander, 2012). Atypical motor planning has been demonstrated in children and adults with autism in both single goal-directed manual movements and sequential movements. However, the findings are inconsistent when it comes to describing what characterizes these disturbances in planned motor behavior, possibly related, in part, to a lack of consideration of developmental differences. In a reach-to-grasp paradigm, Campione and colleagues (2016) showed that the reach component of prehension was atypical in 4–5-year-old children with autism compared to typically developing children. More specifically, reach times in prehension were shown to be longer compared to typically developing children. Furthermore, in contrast to typically developing children, peak acceleration was not modulated by target size in the children with autism. No group differences were however detected regarding the grasp component (Campione et al., 2016). In another study using a reach-to-displace paradigm, 7–12-year-old children with autism exhibited decreased motor planning but preserved feedback control compared to typically developing children (Martel et al., 2023). This was shown by the finding that the children with autism did not modulate initial reach peak velocity or maximum grasping aperture in relation to the weight of the target. In contrast, another study (Yang et al., 2014) found adjustments of prehension towards target size in school-age children with autism (mean age 7 years, no age span reported). Nevertheless, the children with autism showed motor coordination problems in both reach and grasp components (Yang et al., 2014). There are indications that dynamic interactions between developmental level and task difficulty can help to explain this discrepancy in findings. In a study of goal-directed swipes on a smart tablet (Lu et al., 2022), children with autism under the age of 5 performed slower goal-directed swipes than typically developing children, but the opposite was found for children with autism over the age of 5 (i.e. faster goal-directed swipes than TD). Similarly to the effects of age, effects of developmental level on movement speed were shown by Mari and colleagues (2003). At age 7–12, children with autism and low cognitive function (Full-scale intelligence quotient, FSIQ, 70–79) were shown to have longer reach times with lower peak velocity than typically developing children (Mari et al., 2003). However, children with autism and higher cognitive function (FSIQ >80) showed the opposite pattern, with shorter reach times and higher peak velocity than typically developing peers (Mari et al., 2003). Furthermore, under a reach-to-grasp paradigm, Rodgers and colleagues (2019) demonstrated interactions between age and task complexity. They found that younger children (6–9 years) with autism did not adjust latencies or reach times in relation to task complexity (uni- or bimanual grasp) to the same extent as typically developing children. This generated shorter latencies and reach times for more complex tasks in the children with autism. Older children (9–16 years) with autism, however, did modulate latencies and reach times in relation to task complexity, but produced longer latencies and reach time in comparison to typically developing children on all tasks. These findings indicate that expressions of motor-planning problems vary with development, and are also affected by task complexity, underlining the need to apply a developmental perspective. However, motor-planning problems in autism have not only been shown in childhood but continue into adulthood (Glazebrook et al., 2006, 2009; Zheng et al., 2019).

Sequential movements and second-order motor planning in children with autism have been investigated under ESC paradigms and in studies investigating the chaining of movements, i.e. how sub-actions are linked together. Within one ESC paradigm, Ansuini and colleagues (2018) investigated how the height of the placement of the end-goal affected initial grasp height in 7–12-year-old children with autism. In comparison to typically developing children, they did not find any differences in the employment of ESC. They did, however, find an overall effect of average or above-average cognitive level, with above-average level showing increased initial grasp modulation independent of group. These results are similar to those reported by van Swieten and colleagues (2010), where performance on an ESC task did not generate group differences between 9–14-year-old children with autism and typically developing children. A study including 5–11-year-old children with autism did however find reduced ESC effects in comparison to age-matched typically developing children (Scharoun & Bryden, 2016). A study by Hughes (1996) also revealed problems with ESC in school-age children with autism. She investigated ESC in school-age children with autism and children with learning disabilities divided into two groups of relatively low (mean age autism: 14 years; mean age learning disability: 10 years; no age range reported) and high nonverbal cognitive function (mean age autism: 13 years; mean age learning disability: 12 years; no age range reported). She also included two groups of typically developing preschool children (mean age 3 and 4 years, no age range reported). She found that the children with autism displayed less ESC compared to the children with learning disabilities, which was most clearly expressed when comparing the two child-groups with low cognitive function. In addition, there was no significant difference between the children with autism and the younger typically developing children. Lower ESC performance has also been demonstrated in studies including adults with autism (Beelen et al., 2018; Gonzalez et al., 2013). Hence, the expression of ESC in individuals with autism varies between studies, and it seems as though developmental level and task difficulty interactions hold an explanatory value for sequential movements as well. Considering the findings from studies investigating the chaining of movement sequences in more detail might provide further information about second-order planning in autism. In a transport-to-drop task performed by children under the age of 5, Forti and colleagues (2011) showed that, even though no group differences emerged during the initial stages of transporting a ball to its target, the children with autism reached the end of transportation less prepared, with higher velocities and less adjustment of wrist inclination in relation to the goal. They further found that lower cognitive level was associated with longer movement duration, lower peak velocity and less wrist adjustment. These findings were further strengthened by similar results, related to differences in the second transporting part of the movement, in a later study with 2–4-year-old children with autism (Crippa et al., 2015). While there appear to be no group differences in initial movement modulation among younger preschool age children, group differences in initial prehension modulation seem to appear at older ages. Cavallo and colleagues (2018) let school age children with and without autism (mean age 9 years, no range reported) perform a sequential movement of grasping a bottle and subsequently placing it into a box, passing it over to an examiner or pouring water. Using pattern classification analyses, it was found that initial prehension modification towards the action goal was less pronounced in the children with autism, in terms of lower classification accuracy than in the typically developing children. No relationships were found, however, between classification accuracy (i.e. chaining problems) and symptom severity, executive functioning or cognitive level. Chaining of sequential movements was also investigated in 5–9-year-old children with autism, but employing a different paradigm that measured initial mouth muscle activation (Cattaneo et al., 2007). The children were asked to grasp food or paper and subsequently bring the food to their mouth and eat it, or place the paper in a container located on their shoulder. Impaired chaining of action in children with autism was revealed in that, while the typically developing children had activated their mouth muscles in anticipation during prehension in the food condition, the children with autism did not activate their mouth muscles until after grasping the food. However, this finding failed to be replicated in a subsequent study by Pascolo and Cattarinussi (2012). Fabbri-Destro and colleagues (2009) also proposed that children with autism exhibit chaining difficulties. They asked school-age children with and without autism (mean age 10 and 7 years, respectively, no range reported) to perform a sequential movement of grasping an object and placing it in a small or large container. Less chaining of sub-actions towards the overall global action goal was indicated by measurable time differences between prehension movements depending on end-goal for the typically developing children, but such differences were lacking in the children with autism. The need to understand different aspects of the development of autism across different ages has recently been emphasized (Lord et al., 2020). Despite this topic receiving increased attention in general, there are few studies investigating motor planning difficulties in children with autism that take a developmental perspective. Hence, how the motor planning processes proposed in typical development unfold as children with autism develop is largely unknown.

In keeping with the reciprocal links between motor, perceptual and cognitive functioning through development, atypical motor planning has also been related to perceptual and cognitive functions known to be affected in autism. Visuomotor integration is one area that has received particular attention. Converging evidence suggests atypical sensory integration in autism (Robertson & Baron-Cohen, 2017). Related to sensorimotor processes, visuomotor integration has been proposed to be more challenging in autism (Elliott et al., 2020; Lidstone & Mostofsky, 2021). Delayed development of sensorimotor integration has also been suggested in a recent study involving 10–20-year-old individuals with autism (Shafer et al., 2021). Furthermore, a reduced reliance on visual information has been shown to be related to adjustment of movement plans in a study including 3–7-year-old children with autism (Dowd et al., 2012). Instead, a bias for greater reliance on proprioceptive rather than visual feedback has been suggested, which is indicative of problems with visuomotor integration (Glazebrook et al., 2009; Lidstone & Mostofsky, 2021). In addition, it has been proposed that the previously described atypical processing of global sensory information causes problems in extracting stable representations (Happé & Frith, 2006). Problems in generating stable representations can often be indicated by elevated variability of sensory responses within an individual, which is frequently present in autism (Robertson & Baron-Cohen, 2017). These problems also concern the acquisition of stable motor representations, indicated in repeated study findings of elevated intra-individual movement variability (Foster et al., 2020; Glazebrook et al., 2006, 2009; Hayes et al., 2018; Papadopoulos et al., 2012). Problems in acquiring stable motor representations have further been linked to atypical sensory integration, in particular the greater reliance on proprioceptive feedback that has been shown to affect motor learning (Lidstone & Mostofsky, 2021). Research has also highlighted the contribution of atypical movements to social cognition in autism. This has been explained by referring to parieto-frontal mirror neurons and the link between motor representations being used in the interpretation of the action intentions of others (Cook, 2016).

While motor planning problems in autism have been related to lower general cognitive function and executive problems, the characterization of these problems is not consistent between studies. Despite the established link between cognitive and motor development (Diamond, 2000), a systematic review on the relationship between motor and cognitive skills in typically developing children shows that the specifics of how these skills relate during development is not clear, even in typically developing children (van der Fels et al., 2015). The strongest relationships between assessments of motor and cognitive abilities in typical development have been shown for what can be interpreted as more complex motor skills, and with more robust associations for prepubertal children (van der Fels et al., 2015). In addition, children with autism may also show atypical relations between cognitive and motor skills during development in comparison to typically developing peers. If so, this may be linked to difficulties in shifting from more effortful control to more habitual motor performance, reflecting problems generating stable internal motor representations (Mostofsky & Ewen, 2011). This problem was also put forward in a qualitative study involving adults with autism (Gowen et al., 2023). The informants stated that most actions needed to be thought through, and that everyday motor behaviors required effort and concentration. It has been proposed that the relationship between executive and motor deficits in autism is related to dysfunctional frontal brain networks governing both motor and non-motor processes (Leisman et al., 2023). In repetitive motor tasks, movement sequences seem to be stored in working memory prior to conversion into a motor plan (Ohbayashi et al., 2003). A recent study, examining sustained force production, proposed that challenges with sensorimotor function are related to problems with motor memory, that is, with the retrieval or storage of internal motor representations, in individuals with autism (Neely et al., 2019). Furthermore, a study involving 14–33-year-old individuals with autism indicated that, as in typical development, executive function most strongly influences motor planning in autism for tasks requiring initially more complex perceptual decisions (Sachse et al., 2013). As with typically developing children, there are also indications that aspects of perceptual and executive functions, such as visuospatial cognition, working memory and inhibition, are altered by action experience (Hellendoorn et al., 2015; Hilton et al., 2014; Tse et al., 2021).

Thus, rather than merely investigating motor problems in autism as a comorbidity, research is increasingly focusing on examining motor issues as an integrated aspect of core symptoms. Atypical visuomotor integration appears to be related to motor planning in autism, and there seems to be a connection between motor and executive dysfunction. However, much remains unknown about the relationships between motor planning, perception and higher cognition in autism. It has been suggested that changes in sensorimotor integration are important for developmental advances in motor planning during early school-age years. Nonetheless, there is very limited knowledge about how visuomotor integration relates to the development of motor planning in autism.

Aims of the thesis

The overarching aim of this thesis is to advance knowledge about motor planning development in children of early school age following a typical developmental path and in developing children with autism. A particular focus was placed on sequential manual movements and the detailed characteristics of second-order motor planning and motor planning development during early school age. Motor planning is fundamental to many activities in daily life, making it important to understand its typical development. Additionally, increasing knowledge in this area is essential to enable a better understanding of the prevalent motor problems experienced by children with autism.

Study I

In Study I, age-related differences in motor planning and performance were investigated in 6- and 10-year-old typically developing children compared to adults by applying a cross-sectional design. Kinematic expressions of motor planning during the performance of a sequential manual task with varying goal complexity were investigated. The specific focus was on investigating the different sub-parts of the sequential movement in order to provide detailed characteristics of age-related differences in motor planning and performance.

Study II

In Study II, kinematic differences in motor planning and movement execution between 6-year-old children with autism and children with typical development were investigated. A sequential manual task was used, in which both goal complexity and initial visibility of the goal were varied. The relationship between kinematic measures and cognitive abilities in the group of children with autism was further examined. Specific emphasis was placed on investigating the different sub-parts of the sequential movement in children of a similar age. This was done in order to provide detailed characteristics of possible alterations in motor planning and performance between children with autism and those with typical development, expecting less proficient motor planning in the group of children with autism.

Study III

Study III is a longitudinal study in which the development of motor planning was investigated at three time-points over a two-year period in early school-age children with autism and with typical development. A sequential manual task was employed, but with varying goal complexity, precision affordances of the goal and initial goal visibility. The focus was specifically on investigating potential differences in motor planning development between children with autism and those with typical development, as well as any potential relationships with (a)typical visuomotor integration.

Methods

Participants

Study I

Eight 6-year-old children (four boys; mean age 6.7 years; age range 6.2–7.5 years), eight 10-year-old children (five boys; mean age 10.3 years; age range 9.9–10.4 years) and eight adults (four men; mean age 34.9 years; age range 26.5–42.2 years) participated in Study I. The children in Study I were recruited through advertisements at an elementary school in proximity to the university grounds and by convenience sampling. Recruitment of the participating adults was conducted at the university. One adult and one 6-year-old child were left-handed.

Study II

Twelve children with autism (six boys; mean age 6.7 years; age range 6.0–7.2 years) and 12 children with typical development (five boys; mean age 6.7 years; age range 6.0–7.4 years) of preschool class age participated in Study II. The recruitment of children with autism in Study II was conducted in collaboration with the regional habilitation center (Habilitation Centre, Region Västerbotten). Individual autism diagnoses were identified through hospital records and children in the selected age range without an established co-occurring intellectual disability diagnosis were invited to participate in the study. The children with typical development were recruited through advertisements at elementary schools in close proximity to the university grounds and by convenience sampling. To participate, each child needed to be in the selected age range and could not have an established neurodevelopmental disorder diagnosis. More information about the cognitive and motor characteristics of the included children is presented in Table 1.

Table 1

Descriptive characteristics of the children in Study II.

	ASD (n=12)			TD (n=12)		
	M	SD	Range	*M*	SD	Range
FSIQ	81.5*[a]	20.5	54–110[c]	101.7	4.9	93–110[c]
FRI	94.9[a]	21.2	67–126[d]	98.3	8.1	88–112[d]
WMI	88.9[b]	17.5	65–115[e]	101.3	10.1	88–117[e]
GEF	67.5*[b]	33.4	13–99[f]	22.3	26.4	2–96[f]
Inhibit	63.3[b]	36.5	12–99	33.58	24.1	12–97
Shift	81.7*[b]	23.4	38–99	30.7	24.2	12–78
Emotional control	70.1*[b]	32.9	17–98	31.3	21.7	7–83
Initiate	72.8*[b]	31.7	10–99	38.1	27.7	10–90
Working memory	72.1*[b]	26.9	24–99	30.6	29.5	6–98
Plan/organize	53.9*[b]	28.8	23–99	28.7	26.1	10–84
Organization of materials	59.4[b]	27.6	19–92	35.1	24.6	4–96
Monitor	55.1*[b]	28.2	15–96	21.1	26.6	7–96
MABC-2	20.1*[b]	11.0	6–39[g]	7.9	6.8	0–26[g]
EHQ	.83	.29	.14–1	.92	.18	.54–1

Note: ASD = Autism spectrum disorder; TD = Typically developing; n = Number; *M* = Mean; SD = Standard deviation; FSIQ = Full scale Intelligence Quotient; FRI = Fluid reasoning index; WMI = Working memory index (FSIQ, FRI, WMI assessed by WISC-V or WPPSI- IV); GEF = %-rank of global executive composite score assessed by the BRIEF (caregiver ratings); MABC-2 = total score on Movement assessment battery for children-2 checklist (caregiver ratings); EHQ = absolute values of laterality index assessed by Edinburgh handedness questionnaire (caregiver ratings); [a] = n=11; [b] = n=10; [c] = Performance 1SD/2SD below average, n ASD = 1/4, n TD = 0/0; [d] = Performance 1SD/2SD below average, n ASD = 2/1, n TD = 0/0; [e] = Performance 1SD/2SD below average, n ASD = 3/1, n TD = 0/0; [f] = Ratings 1SD/2SD above average, n ASD = 3/2, n TD = 1/0; [g] = Ratings indicating borderline/high likelihood of movement difficulties, n ASD = 1/4, n TD = 0/1; * = Significant group difference, Mann-Whitney U Test ($p<.05$).

Study III

The development of motor planning was investigated at three time-points, starting when the children were in, or had just finished, first grade (age-level 1, A1). Follow-up testing occurred at one-year intervals (A2, A3). Fourteen children with autism (nine boys; mean age 7.9 years; age range 7.3–8.8 years) and 17 children with typical development (eight boys; mean age 7.7 years; age range 6.11–8.8 years) participated in the Study initially (at A1). Two boys with autism declined to continue their participation after the first testing occasion. More information about the cognitive and motor characteristics of the initially included children is presented in Table 2. Apart from re-recruiting the children who had participated in Study II, recruitment of additional participants for Study III copied the procedure followed in Study II. Of the included children, eight of the children with autism and 12 of the children with typical development had participated in Study II at an earlier age.

Table 2

Descriptive characteristics of the children in Study III at first assessment (A1).

	ASD (n=14)			TD (n=17)		
	Mean	SD	Range	Mean	SD	Range
FSIQ	82.4	15.0	54–110[b]	106.1	9.4	93–126[b]
FRI	92.9	15.3	72–126[c]	101.9	9.6	88–118[c]
WMI	82.9	16.0	65–115[d]	102.5	10.5	88–122[d]
GEF	81.8[a]	26.0	21–99[e]	25.5	22.0	1–71[e]
Inhibit	75.7[a]	25.7	27–97	36.2	25.4	10–89
Shift	87.6[a]	17.3	41–99	29.3	15.6	12–60
Emotional control	71.4[a]	30.4	23–99	34.4	27.3	5–83
Initiate	80.6[a]	23.2	22–99	43.5	27.4	9–89
Working memory	84.3[a]	17.9	49–99	32.7	22.0	6–63
Plan/organize	76.3[a]	25.0	30–99	30.5	22.3	10–79
Organization of materials	78.0[a]	25.9	25–99	38.2	28.7	4–88
Monitor	81.2[a]	31.3	13–99	21.8	15.9	7–47
MABC-2	23.5[a]	13.5	2–46[f]	4.4	4.4	0–14[f]
EHQ	.72	.25	.25–1	.93	.12	.56–1

Note: ASD = Autism spectrum disorder; TD = Typically developing; n = Number; *M* = Mean; SD = Standard deviation; FSIQ = Full scale Intelligence Quotient; FRI = Fluid reasoning index; WMI = Working memory index (FSIQ, FRI, WMI assessed by WISC-V); GEF = %-rank of global executive composite score assessed by the BRIEF (caregiver ratings); MABC-2 = total score on Movement assessment battery for children-2 checklist (caregiver ratings); EHQ = absolute values of laterality index assessed by Edinburgh handedness questionnaire (caregiver ratings); [a] n=12; [b] = Performance 1SD/2SD below average, n ASD = 3/3, n TD = 0/0; [c] = Performance 1SD/2SD below average, n ASD = 3/0, n TD = 0/0; [d] = Performance 1SD/2SD below average, n ASD = 3/4, n TD = 0/0; [e] = Ratings 1SD/2SD above average, n ASD =8/1, n TD = 0/0; [f] = Ratings indicating borderline/high likelihood of movement difficulties, n ASD = 0/9, n TD = 2/0; Significant group difference were evident for all measures, Mann-Whitney U Test ($p<.05$).

Procedures

Study I

In Study I, age-related differences in motor planning and movement execution were studied using a cross-sectional design. Performance on a goal-directed sequential manual task was compared between 6-year-old children, 10-year-old children and adults. The task consisted of grasping a cylindrical (diameter = 25 mm) or semi-circular (straight side = 25mm) peg, transporting it to and fitting it into a corresponding goal-holder (Figure 1). For the cylindrical peg, the start-holder and goal-holder matched, with identical round shapes. The semi-circular goal-holder was presented in four different orientations (0°, 90°, 180° and -90°) relative to the starting orientation of the peg.

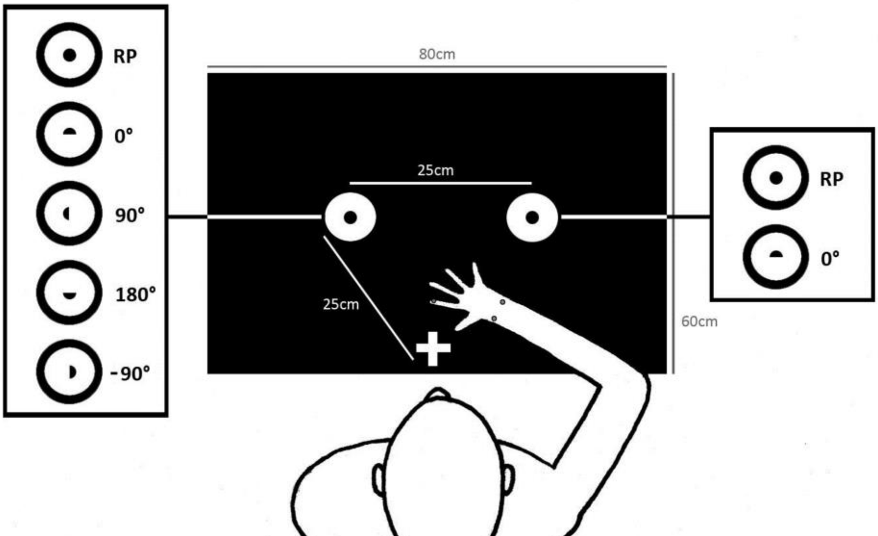

Figure 1. *Illustration of the experimental setup from a bird's-eye view, including marker placement and the different start and goal conditions. The peg is positioned in the start-holder to the right (for a right-handed participant), ready to be grasped, transported and fitted into the goal-holder (to the left). Abbreviation: RP, round peg. (Figure from Domellöf et al. (2020) reprinted under the Creative Commons CC-BY license)*

Thus, the semi-circular peg needed to be rotated prior to placing it into the goal-holder in the 90°, 180° and -90° orientations. The goal-holder was initially occluded by a black screen and revealed at the onset of measurement. Prior to the experiment, the four different goal-orientations of the semi-circular peg and the cylindrical peg were tested by the participants. The participants then performed two blocks of all five task variations using both right and left hand. The task order within each block was randomized. In Study I, results derived from preferred hand performance were analyzed. When a block was finished, any unsuccessful trials were repeated.

Study II

In Study II, differences in motor planning and movement execution between children with autism and children with typical development were investigated. Relationships between motor planning and execution outcomes and cognitive abilities were further investigated in the group of children with autism. Performance on a goal-directed sequential manual task was compared between 6-year-old children with and without autism. The semi-circular task, described in Study I, was used, but this time not only the orientation but also the initial visibility of the goal was manipulated (Figure 2). In the visual condition, the goal-holder was fully visible before the measurement started. In the occluded condition, the goal-holder was occluded with a black cloth prior to the start of measurement. Hence, the goal orientation was first revealed at measurement onset by the synchronized mechanical removal of the cloth. The visual condition allowed visual processing of the end-goal before the measurement started while the occluded condition limited visual processing of the end-goal until after measurement onset. Prior to the experiment, the different orientations of the task were practiced in the visual condition. The preferred hand was used when the children performed the task. The experiment consisted of three blocks of all four included orientations in both the visual and occluded conditions. The order within each block was randomized and at the end of the block, any unsuccessful trials were repeated.

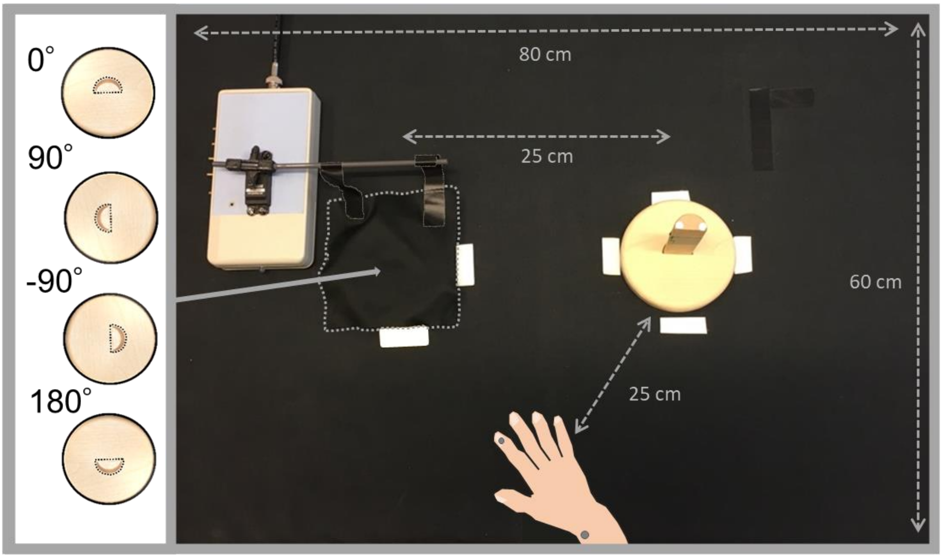

Figure 2. *Illustration of the experimental setup including marker placement for a right-handed child in the occluded condition. The peg is positioned in the start-holder to the right, ready to be grasped, transported and fitted into the goal-slot (occluded under the cloth to the left) as one of the four different goal-slot orientations (illustrated in the panel to the left) becomes visible. (Figure from Bäckström et al. (2021) reprinted under the Creative Commons CC-BY license, slightly altered for clarity)*

Study III

In Study III, the development of motor planning in early school-age children with autism and with typical development was investigated using a longitudinal design. The development of preferred-hand performance on a goal-directed sequential manual task was studied and compared between children with and without autism. The semi-circular task, described in Study II, was used, with an alteration where the -90° orientation was replaced with a flat disc that placed little demand on end-goal fitting precision (Figure 3). The disc version of the task consisted of grasping the semi-circular peg, transporting it to and placing it on the flat disc (which was the goal-holder turned upside down). Initial visibility of the goal was also manipulated following the visual and occluded condition procedure, as in Study II. Prior to the experiment, all orientations of the task were practiced in the visual condition and placing the peg on the flat disc was practiced once more in the occluded condition. The experiment consisted of four blocks of all four included orientations in both the visual and occluded conditions. The order within each block was randomized and at the end of each block, any unsuccessful trials were repeated.

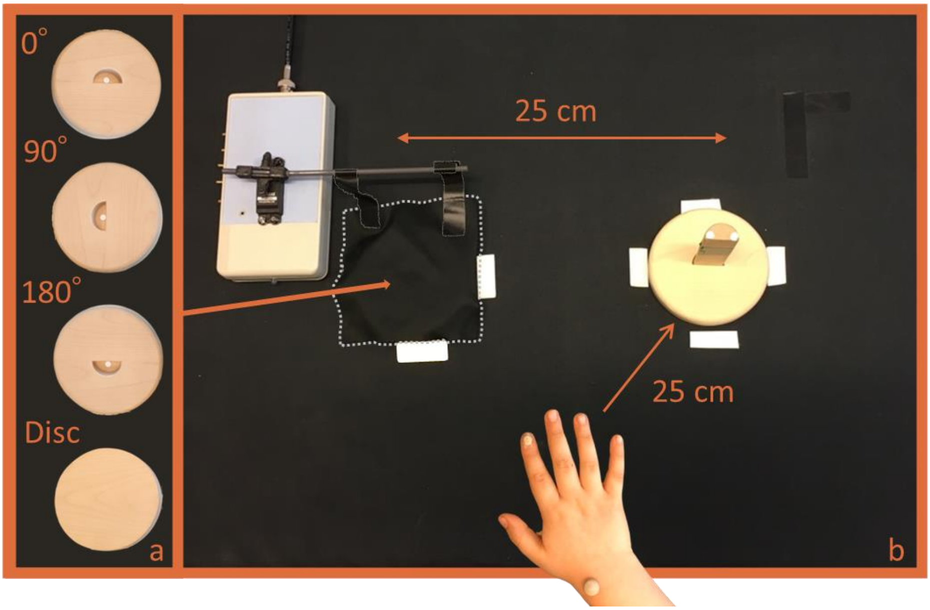

Figure 3. *Panel a) shows the four different presentations of the goal, and panel b) illustrates the setup of the occluded condition for a right-handed child, including marker placement. The semi-circular peg is positioned in the start-holder to the right and the goal-holder is occluded under the cloth to the left, about to become visible. (Figure from Bäckström et al., currently under peer review for Autism)*

Measures

Kinematic movement analysis

Motion tracking by marker-based 3D optoelectronic recordings provides detailed and highly accurate measures of movement kinematics (Chiari et al., 2005). Correctly used, marker-based optoelectronic recording techniques provide one of the most precise and accurate spatial and temporal quantifications of motion available (van Schaik & Dominici, 2020). The motion-capture cameras used in this thesis measure the position of passive reflective spherical markers by emitting infrared light and recording the returning light from each marker. The reflective markers are lightweight and can be attached to body parts or objects simply by using double-sided adhesive tape, making measurement accessible and non-invasive. The 3D coordinates of a marker are estimated by combining 2D information from at least two cameras. Further processing of 3D information, such as interpolation of missing data and filtering, is often used to reduce signal noise and random errors (Chiari et al., 2005; van Schaik & Dominici, 2020). However, there are limitations to motion tracking which are dependent upon several factors. It is important to have a well-thought-through camera setting in relation to the task to minimize marker occlusion and avoid missing data, since at least two cameras need to always be measuring the markers. The distance between the markers and the camera also affects precision, with the calibration of the system being most precise for smaller volumes, and thus appropriate for upper-limb movements. The outcome measure of movement elements is also naturally affected by aspects such as marker position, definition of movement elements etc., thus it is important to describe these in order to facilitate between-study comparisons.

Motion tracking is a widely used technique in developmental studies for investigating motor development and motor planning, in both typical and atypical development (van Schaik & Dominici, 2020). It is also a technique that is used to collect implicit measures of change in cognition by utilizing the intertwined nature of motor and cognitive development (van Schaik & Dominici, 2020). Therefore, it is a suitable assessment method for the aims of all the studies included within this thesis.

To assess motor planning and movement execution in the studies included in this thesis, optoelectronic recordings (Oqus, Qualisys Inc.) were made during performance of the goal-directed sequential manual tasks. To record manual movements, a 6-camera (Studies I and II) or 5-camera (Study III) setup with 120 Hz (Studies I and II) or 100 Hz (Study III) sampling frequence was used. In addition, 2D videos were recorded to facilitate data pre-processing. Passive reflective markers were attached to the side of the wrist (radial styloid) (12 mm) and index finger (7 mm) on the preferred hand of the participant. On top of the peg with 20 mm centroid distance, two circular markers (5 mm) were attached, one on each side. Collected 2D motion information was combined into 3D data using the Qualisys software (Qualisys Track Manager). All 3D data was smoothed using a 12 Hz (Study I) or 6 Hz (Studies II and III) Butterworth filter and kinematic outcomes were extracted by use of in-house written MATLAB (The Mathworks Inc.) scripts.

Sub-phases of the sequential movement
The goal-directed sequential movements were divided into sub-phases prior to outcome extraction. The sub-phases identified were:

- Latency, the time between trial start and movement onset
- Reach-to-grasp (RTG), reaching towards the peg
- Grasp, the grasping of the peg
- Transport, the transportation of the peg to the goal-holder
- Fitting/placing, the fitting or placing of the peg after arriving at the goal-holder location

The division in Study I consisted of four movement phases: Latency; RTG; Grasp; and Transport-to-fit (TTF), with TTF consisting of two parts, Rota I (identifying the transport part of the movement) and Rota II (identifying the fitting part of the movement). The division in Studies II and III consisted of five movement phases: Latency; RTG; Grasp; Transport; and Fitting(/placing) (Figure 4).

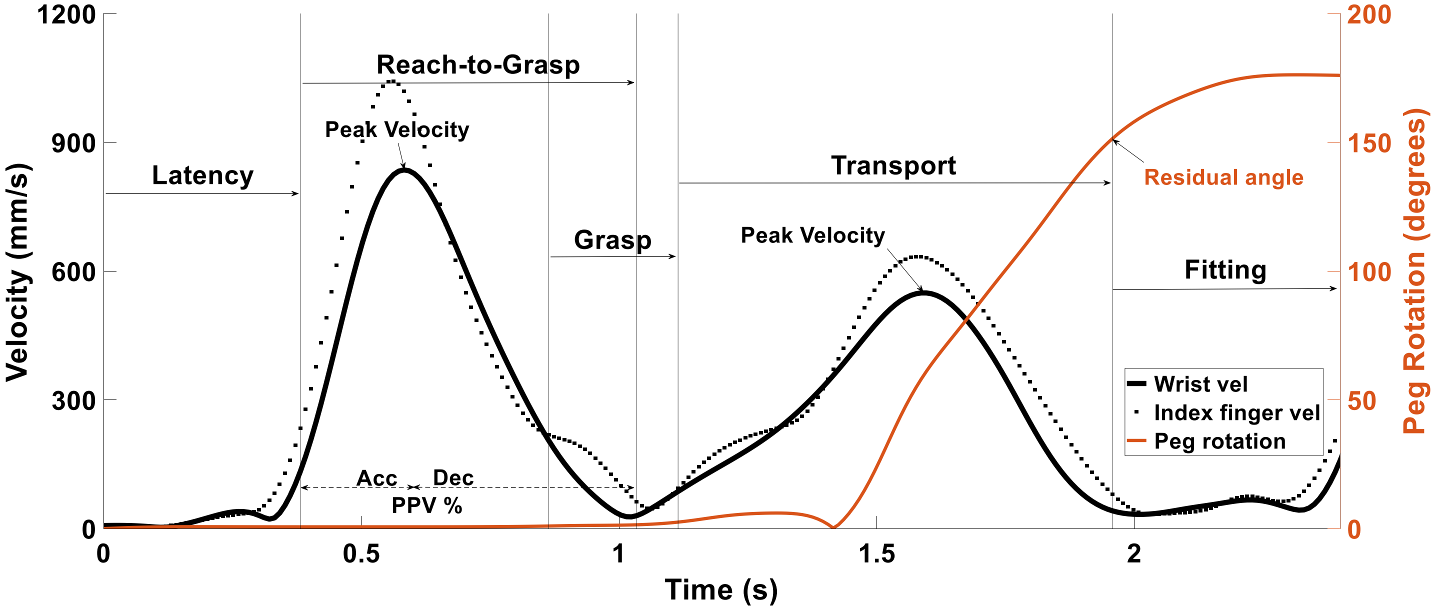

Figure 4. *Illustration of the sequential movement sub-phases and a selection of the kinematic outcome variables, made by a 7-year-old TD child in the 180° goal orientation (visible condition). Left-hand y-axis shows wrist and index finger velocity, and right-hand y-axis shows peg rotation angle. (Figure from Bäckström et al., currently under peer review for Autism)*

Kinematic outcome measures

Latency

Analysis of latency was used as a measure of motor planning in all three studies included in this thesis. It is assumed that initial motor planning occurs before movement onset. The subsequent online modifications in the unfolding of the movement can then give information about the reliance on the initial plan and its efficiency. In typical development of sequential manual movements, decreasing latencies have been shown with increasing age in 5–12-year-old children (Krajenbrink et al., 2020). The decreasing time needed to form the feed-forward model has been interpreted as a sign of increasing motor planning proficiency. Increases in sequential movement end-goal complexity have further been shown to result in prolonged latencies (Krajenbrink et al., 2020). Prolonged latency times, related to forming the motor plan, may be indicative of motor planning difficulties, and are common in autism (Sacrey et al., 2014), at least in older children and adults. It is, however, difficult to separate perceptual decisions related to defining the motor goal from movement-related decisions about how to perform the movement, and the motor planning process begins at this junction (Wong et al., 2015). In Studies II and III, the visual/occluded condition was introduced as a way of trying to disentangle these processes and investigate visuomotor integration in motor planning.

PPV

Part-peak velocity (PPV) was applied as a measure of motor planning in all the studies included in this thesis. PPV describes the acceleration/deceleration proportions of the movement phase. In Studies II and III, it was defined as the percentage of acceleration time (of total phase duration) during which wrist velocity is increasing, leading up to the point of peak velocity. In sequential movements, PPV in the reach-to-grasp movement (PPV-RTG) has been used to indicate second-order motor planning and the chaining of sequential movements. In general, lower PPV-RTG indicates less reliance on feed-forward planning in prehension. It has been shown that PPV-RTG is affected by the task difficulty of the end-goal in both children and adults (Chen et al., 2010; Marteniuk et al., 1987; Wilmut et al., 2013b). Relative deceleration has also been shown to be generally shorter in adults compared to 8–11-year-old typically developing children (Wilmut et al., 2013a), with the relatively longer deceleration indicating more reliance on online monitoring and feedback adjustments. Peak velocity placement in absolute terms (milliseconds) was further investigated as an alternative measure in Study I.

Peak Velocity

An analysis of peak velocity (PV) during the reach-to-grasp (PV-RTG) (Studies I, II and III) and transport (PV-Transport) (Studies II and III) phases was applied as a measure of motor planning. PV-RTG has also been used to measure second-order motor planning and the chaining of sequential movements. It has been shown that PV-RTG is influenced by the movement objective in both children and adults (Armbrüster & Spijkers, 2006; Claxton et al., 2003), with PV being reduced to adjust to more difficult tasks. In comparisons between younger children with autism and typical development, it is mainly the latter part of the sequential movement (transport) that seems to show atypically planned PV adjustments towards task difficulty (Crippa et al., 2015; Forti et al., 2011). This is probably due to low use of second-order motor planning in general at this age. Average velocity in RTG and TTF was further investigated as an alternative measure in Study I.

Rotation of the peg

An analysis of the angle of the peg at the end of transport was applied as a measure of motor planning in all the studies included in this thesis. In Study I, the remaining angle of the semi-circular peg at the end of Rota I was calculated for all orientations. In Studies II and III the relative residual angle (RA; the percentage difference between peg orientation and goal-slot orientation) of the peg at the end of the transport phase was calculated for the orientations requiring peg rotations. Proactivity in orientating an object towards goal-slot orientation have been shown to increase with age in preschool children performing fitting tasks (Jung et al., 2015, 2018). Moving from a more step-wise approach, the increasingly proactive orientation of objects during object transportation movements towards the end of preschool age indicate increasing motor planning abilities; however, these have not yet reached adult levels (Ossmy et al., 2020).

Movement units

An analysis of segmentation of the movement trajectory was applied in Studies I and II. Each segmentation was calculated using the movement unit (MU) algorithm defined by von Hofsten (1991). An MU contains a phase of acceleration and a phase of deceleration, where accumulated velocity increases or decreases of a minimum of 20mm/s occurs and acceleration/deceleration exceeds 5mm/s^2 (von Hofsten, 1991). Movement segmentation is a sensitive measure related to movement organization and motor system development (Rönnqvist & Domellöf, 2006; von Hofsten, 1991). Smoothness in prehension has been shown to continue to increase between the ages of 4–12 (Kuhtz-Buschbeck et al., 1998), reflecting a decreasing need for and better control of online adjustments.

Duration

An analysis of movement duration was applied in all the studies included in this thesis. It has been shown that initial movement duration in sequential movements is influenced by second-order motor planning in preschool-age children (Wilmut et al., 2013b), with more difficult movements generating longer initial durations. Shorter movement duration has further been shown to reflect increasing general movement proficiency across early school age (Kuhtz-Buschbeck et al., 1998).

3D distance

An analysis of movement trajectory distance was applied in Study I. Shorter, straighter, movement trajectories have been shown to develop with increasing age across the early school years (Kuhtz-Buschbeck et al., 1998; Simon-Martinez et al., 2018), reflecting maturational processes and increasing general movement efficiency.

Handedness

For the 6-year-old children in Study I, and for all children in Studies II and III, hand preference was measured by caregiver ratings on a version of the Edinburgh handedness questionnaire (EHQ) (Oldfield, 1971), modified to be age appropriate. These ratings generate a handedness index ranging from -1 (left-hand preference) to +1 (right-hand preference) where scores between -.3 and .3 indicate no established hand preference. For the 10-year-old children and adults in Study I, determination of hand preference was based on the hand that was preferred for writing.

Cognitive functioning

Intellectual functioning was assessed in Study II using the Swedish version of the Wechsler Intelligence Scale for Children, fifth edition (WISC-V) (Wechsler, 2014), except for three of the children with autism for whom the Swedish version of the Wechsler Preschool and Primary Scale of Intelligence, fourth edition (WPPSI-IV) (Wechsler, 2012) was used. In Study III, intellectual functioning, used as a sample descriptive variable, was assessed using the Swedish version of WISC-V (Wechsler, 2014). The WISC-V and WPPSI-IV generate a measure of full-scale intelligence quotient (FSIQ) and five sub-scale measures reflecting intellectual functioning within different cognitive areas. In Studies II and III, the measure of FSIQ and two of the sub-scale measures, the non-verbal fluid reasoning index (FRI) and the working memory index (WMI), were used.

To describe the general executive functioning of the children included in Studies II and III, executive difficulties were assessed by caregiver ratings on the Behavioral Rating Inventory of Executive Function (BRIEF) (Gioia et al., 2000). The BRIEF generates a measure of Global executive functioning (GEF), which was used as a sample descriptive variable in Studies II and III. The GEF is derived from 8 subscales (inhibit, shift, emotional control, initiate, working memory, plan/organize, organization of material, monitor), presented as further sample descriptive variables within this thesis in Tables 1 and 2.

General movement ability

In Studies II and III, general movement abilities were assessed by caregiver ratings on the Movement Assessment Battery for Children- 2 checklist (MABC-2) (Henderson et al., 2007), and used as sample descriptive variables.

Statistical methods

Study I

Each selected kinematic outcome measure was analyzed using a mixed design analysis of variance in STATISTICA software. Age group and task effects were analyzed using a 3 × 5 design including age groups (6-year-olds, 10-year-olds, adults) × task orientations (RP, 0°, 90°, 180°, −90°). For the two parts of the transport-to-fit phase (Rota I, identifying the peg-transportation phase and Rota II, identifying the peg-fitting phase), group and task effects were analyzed using a mixed analysis of variance with Rota I and II as repeated measure and age groups and task orientations as between-group factors. Furthermore, in each age group, Pearson’s product-moment and partial correlations were used to investigate correlations between phase parameters.

Study II

Each selected kinematic outcome measure was analyzed using linear mixed effects models in SPSS (version 26). Each model included clustering of the trials for each participant and a random effect intercept for each participant. Group, goal-slot orientation and visual condition were used as fixed main effects, and interactions between group × orientation and group × condition were specified. SDs from the calculated means of included kinematic outcomes (latency, PPV-RTG, PV-RTG, PPV-Transport, PV-Transport, RA, total MU from the whole sequential movement, and duration of the whole sequential movement) were used to test group differences in intra-individual variability using Mann-Whitney U Tests. The associations between the calculated means of the included kinematic outcomes and the WISC/WPPSI measures of FSIQ, FRI and WMI were further assessed using Spearman's correlation in the group of children with autism only.

Study III

Each selected kinematic outcome measure was analyzed using linear mixed effects models in SPSS (version 28). For each participant, outcomes were averaged for each orientation, and the two conditions (visual and occluded) were analyzed separately. Participant ID and orientation were specified as subjects in each model and age-level as repeated measures, and a random effect intercept for each participant was further included in each model. Fixed main effects included age-level, group and orientation, and specified interactions were age-level × group and group × orientation. The developmental pattern of the orientation effects on PPV-RTG and PV were further investigated to study adjustments made in relation to task difficulty. Here, fixed main effects included age-level, group and orientation, and a three-way age-level × group × orientation interaction was specified. Developmental changes in the use of initial visual information, which were proposed to reflect changes in visuomotor integration, were further investigated. We calculated the mean difference between conditions (visual and occluded) for each participant for all kinematic outcome measures in order to investigate the benefits of early available visual information (visual condition) for motor planning. The linear mixed effects models used to analyze these outcomes included participant ID specified as subjects and age-level as repeated measures. Each model also included a random effect intercept for participants. The fixed main effects were age-level and group, with specified interactions for age-level × group.

Experimental studies in atypical populations

Preparation for participation

New environments and transitions are challenging for many children with autism. Hence, a variety of measures were taken for the children to facilitate their participation in the unusual setting and methods used in the studies within this thesis project. To support familiarization with the setting and to help the children understand what they were going to do if they chose to participate, a child-oriented website was used as a supplement to the written information in Studies II and III. This website included a series of photos showing the environment, the researchers, the technical equipment and an image-based schedule showing the routine for the investigation, together with descriptive text. Short videos were also included describing the task. Before the children participated, all caregivers were given a link to this website together with follow-up verbal information answering any questions about the investigation routine. The caregivers were encouraged to use the website to help prepare their children for participation by viewing the photos and videos together. During the assessment, many caregivers of children with autism reported that this preparation process significantly facilitated their child's participation. Several caregivers of children following a typical developmental path also said that the website had aided them when explaining the study to their children.

Experimental setup

It was expected that a number of the children included in Studies II and III would be demand-sensitive and have difficulties with sensory aspects of the environment and verbal comprehension. To optimize for participation, these factors were considered in the experimental setup. In addition to the website described above, further familiarization with the passive markers was enabled prior to assessment if needed by letting the children and caregivers handle them together. The design of the sequential task was intended to function with limited verbal instructions. It was further designed to be quite an easy task that the children would master without too much difficulty. A block design was applied to facilitate data coverage in the case of early termination of the study protocol. Even though great care was taken in the planning of the procedure and task design, many of the challenges in performing experimental studies with young children remained. One of the greatest challenges for experimental studies is that children do not always act in expected ways. Such incidents are described in the included papers as "unsuccessful trials" or "excluded trials." Although these unexpected behaviors may have influenced the results presented in these papers and therefore had to be excluded, they are not excluded from my learning. In fact, many of these behaviors raised new questions that I hope will be pursued in the future.

Ethical considerations

All participants and the legal guardians of the included children were informed verbally about the content and purposes of the studies. Written information about the study was also given to all adult participants and to the legal guardians of the included children. Informed consent was given by all participants and legal guardians. All studies within this thesis were approved by the Umeå Regional Ethical Board registration (nr 2016/365-31) and carried out in accordance with the Declaration of Helsinki.

Approximately 1 ½ years after the longitudinal data collection for Study III had begun, the Covid-19 pandemic hit Sweden, which affected the study. Swedish universities transferred almost all activities to a remote working online format, although, it was possible to apply for an exception from the remote working policy if deemed necessary. Since the population included in the sample was not identified as a risk group by the Public Health Agency of Sweden, and since young children in Sweden continued regular on-site schooling (i.e., having daily contact with people outside their family), it was deemed ethically acceptable to apply for an exception to continue the data collection. This application was approved by the University. The continuing data collection was conducted in accordance with the guidelines of the Public Health Agency of Sweden and the local University regulations.

Results and brief discussion of findings

Study I

Study I investigated age-related differences in motor planning and performance between 6- and 10-year-old typically developing children and adults. We investigated kinematic expressions of motor planning and performance within the movement sub-phases of a sequential manual task with varying levels of goal complexity. Generally, we expected to find consistent age-related differences in kinematic outcomes.

As expected, significant age-related differences were found in each of the sub-phases of the sequential movement (Table 3). The 6-year-old children demonstrated less efficient movement organization compared to both the 10-year-old children and adults. This was shown in both motor planning and more performance-related kinematic outcomes. For the 10-year-old children, it was mainly outcomes related to motor planning that differed from the adults, while less difference with adults was shown on performance aspects more closely related to movement control.

Table 3
Means and standard errors for kinematic outcomes as a function of age group, together with main effects of age and task.

	Age group				
Kinematic parameters	Adult	10-year	6-year	Main effect of age	Main effect of task
Latency phase					
Wrist latency (ms)	**296±25.7**[a]	**128±30.3**[b]	187±25.2	$F = 9.3$, $p < .001$, $\eta^2p = .08$	$F = 1.1$, $p = .39$, n.s.
Reach-to-grasp phase					
Reach duration (ms)	846±30.4	733±34.1	**905±30.4**[c]	$F = 6.5$, $p < .005$, $\eta^2p = .05$	$F = 1.5$, $p = .18$, n.s.
Wrist MUs (n)	1.3±0.1	1.7±0.1	**2.4±0.1**[c]	$F = 15.7$, $p < .001$, $\eta^2p = .12$	$F = 1.3$, $p = .25$, n.s.
Index MUs (n)	3.1±0.2	3.2±0.2	3.4±0.2	$F = 0.7$, $p = .51$, n.s.	$F = 0.8$, $p = .48$, n.s.
Wrist peak velocity (mm/s)	**654±20.9**[a]	942±20.7	852±20.9	$F = 51.6$, $p < .001$, $\eta^2p = .32$	$F = 0.9$, $p = .42$, n.s.

Wrist peak velocity placement (ms)	**388±10.9** [a]	328±11.4	345±10.9	$F = 7.2$, $p < .001$, $\eta^2p = .06$	$F = 0.8$, $p = .48$, n.s.
Index peak velocity (mm/s)	**1128±38.2**[a]	1366±40.2	1363±38.5	$F = 11.9$, $p < .001$, $\eta^2p = .10$	$F = 0.5$, $p = .76$, n.s.
Index peak velocity placement (ms)	**361±11.3** [a]	277±11.5	290±11.4	$F = 18.8$, $p < .001$, $\eta^2p = .12$	$F = 1.1$, $p = .35$, n.s.
Time diff Index-Wrist peak vel place (ms)	**-27±5.6** [a]	-51±5.8	-55±5.7	$F = 6.9$, $p < .001$, $\eta^2p = .06$	$F = 0.7$, $p = .59$, n.s.
Wrist acceleration/deceleration phase (%)	46/54	45/55	**41/59** [c]	$F = 8.5$, $p < .001$, $\eta^2p = .07$	$F = 1.9$, $p = .10$, n.s.
Index acceleration/deceleration phase (%)	**43/57** [a]	**38/62** [b]	**35/65** [c]	$F = 22.5$, $p < .001$, $\eta^2p = .17$	$F = 0.8$, $p = .48$, n.s.
Wrist average velocity (mm/s)	**299±9.3** [a]	**411±9.7** [b]	360±9.3	$F = 33.6$, $p < .001$, $\eta^2p = .23$	$F = 0.5$, $p = .71$, n.s.
Index average velocity (mm/s)	**423±15.8** [a]	541±16.4	525±15.8	$F = 15.7$, $p < .001$, $\eta^2p = .14$	$F = 1.4$, $p = .23$, n.s.
Wrist 3D distance (mm)	**260±4.5** [a]	305±5.5	307±4.5	$F = 36.6$, $p < .001$, $\eta^2p = .25$	$F = 3.4$, $p = .02$, n.s.
Index 3D distance (mm)	**366±5.2** [a]	**403±5.3** [b]	**438±5.3** [c]	$F = 46.5$, $p < .001$, $\eta^2p = .29$	$F = 1.2$, $p = .29$, n.s.
Grasp phase					
Grasp duration	77±22.5	64±24.3	**254±22.6** [c]	$F = 18.9$, $p < .001$, $\eta^2p = .15$	$F = 1.5$, $p = .19$, n.s.
Transport-to-fit phase					
Transport-to-fit duration (ms)	1461±91	1618±92	**2280±93** [c]	$F = 22.4$, $p < .001$, $\eta^2p = .17$	$F = 9.8$, $p < .001$, $\eta^2p = .15$
Time transporting peg to goal (ms)	752±31	691±31	776±32	$F = 1.9$, $p = .14$, n.s.	$F = 2.7$, $p = .04$, n.s.
Peg rotation duration (ms)	574±48	659±49	774±49	$F = 4.2$, $p = .05$, n.s.	$F = 12.2$, $p < .001$, $\eta^2p = .14$
Wrist transport-to-fit MUs (n)	6.5±0.7	7.5±0.8	**13.3±0.8** [c]	$F = 22.1$, $p < .001$, $\eta^2p = .16$	$F = 5.5$, $p < .001$, $\eta^2p = .09$
Index transport-to-fit MUs (n)	7.8±0.7	9.7±0.8	**15.4±0.8** [c]	$F = 21.5$, $p < .001$, $\eta^2p = .16$	$F = 9.8$, $p < .001$, $\eta^2p = .15$
Wrist average velocity (mm/s)	**181±6.5** [d]	212±6.5	193±6.5	$F = 5.8$, $p < .005$, $\eta^2p = .05$	$F = 11.3$, $p < .001$, $\eta^2p = .17$

Index average velocity (mm/s)	251±9.0	273±9.4	239±9.1	F = 3.1, p = .05, n.s.	F = 9.4, p < .001, η^2p = .14
Wrist 3D distance (mm)	**258±7.2**[a]	**315±5.9**[b]	**369±7.2**[c]	F = 58.1, p < .001, η^2p = .34	F = 7.7, p < .001, η^2p = .12
Index 3D distance (mm)	**359±6.4**[a]	**409±5.4**[b]	**437±6.4**[c]	F = 39.3, p < .001, η^2p = .26	F = 12.8, p < .001, η^2p = .18

Note: Significant (p < .005) age-group differences (in bold) are indicated as (a) difference between adults and both child groups, (b) difference between 10-year-old group and both adult and 6-year-old group, (c) difference between 6-year-old group and both adult and 10-year-old group, and (d) difference between adults and 10-year-old group. Abbreviations: MUs = movement units; n = number; n.s. = not significant (Table from Domellöf et al. (2020), reprinted under the Creative Commons CC-BY license, slightly altered for clarity)

The children showed shorter latencies than adults, with the shortest latency in the 10-year-old group. During the reach-to-grasp (RTG) phase, the children exhibited longer movement trajectories with higher velocities than adults, with the 10-year-old group generating the highest velocities. The 6-year-old children further showed greater reliance on feedback aspects of prehension with earlier PPV-RTG, more MUs and longer RTG and grasp durations than either the 10-year-old children or the adults. In the transport-to-fit (TTF) phase, a main effect of age (F = 17.91, p < .001, η^2p = 0.17) was found regarding the residual angle of peg rotation remaining at the end of transportation (Rota I) (Figure 5).

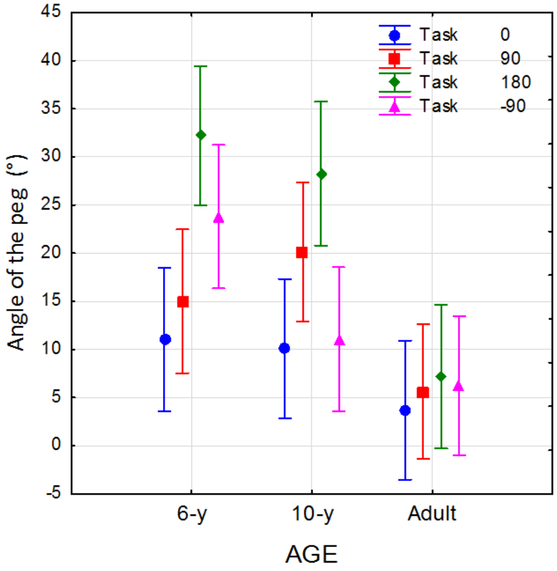

Figure 5. *The mean angle of the horizontal line of the peg relative to the frontoparallel axis at goal arrival for the different task conditions as a function of age. Vertical bars denote 0.95 confidence intervals. (Figure from Domellöf et al. (2020), reprinted under the Creative Commons CC-BY license, slightly altered for clarity)*

The children showed less proactive peg rotation than the adults (M = 5.6°), but no significant difference was shown between the 6-year-old (M = 20.7°) and 10-year-old (M = 17.3°) child groups. Furthermore, the 10-year-old children displayed longer movement distance and higher TTF wrist mean velocities than the adults. In addition, the 6-year-old children displayed longer movement trajectories, longer durations and more MUs than both the 10-year-old children and the adults.

The 6-year-old children also exhibited a more coupled sequential movement than either the 10-year-old children or the adults, with RTG and TTF kinematics correlating for a wide range of outcomes (Table 4). This indicates that general aspects of movement organization govern the sequential movement more in 6-year-old children than in 10-year-old children or adults. For the older children and adults, coupling of RTG and TTF kinematics was mainly shown for velocity and duration. The fewer correlations among 10-year-old children and adults indicate that they adjust their movements more towards the specific sub-phase.

These findings provide an insight into how second-order motor planning differs between 6-year-old and 10-year-old children and in relation to adult engagement in action planning. These results show that there are considerable gains in movement organization of sequential movements between 6 and 10 years of age. At the younger age, sequential movements were more exploratory, relying more on feedback processes, and challenges with adjustments related to performance were evident. By 10 years of age, there were no clear challenges with performance adjustments and differences from adults mainly related to motor planning outcomes. These findings support previous (Kuhtz-Buschbeck et al., 1998; Olivier et al., 2007; Simon-Martinez et al., 2018) and more recent (Martel et al., 2020) research indicating that development across early school age is important in the transition towards more adult-like movement organization. A different speed–accuracy trade-off in children and adults is suggested by the straighter movements and lower velocities seen in adults. These velocity differences between children and adults shows a reversed pattern compared to findings from single manual movements (Olivier et al., 2007). Typically, adults seem to perform movements towards uncertain goals at a slower speed to promote task performance (Wong & Haith, 2017) and the initially occluded goal may introduce some ambiguity about the specific end-goal.

Table 4

Correlations between kinematic variables derived from the RTG phase and the TTF phase.

6-year-olds	TTF duration	TTF wrist MU	TTF wrist mean velocity	TTF wrist distance
Latency	0.174	0.160	-0.315	-0.182
RTG duration	**0.526**	**0.570**	**-0.572**	0.024
RTG wrist MU	**0.456**	**0.532**	**-0.462**	0.013
RTG wrist peak velocity	-0.220	-0.204	**0.436**	0.172
RTG wrist peak placement	**0.375**	**0.371**	**-0.479**	0.044
RTG deceleration	**0.331**	0.322	**-0.374**	0.003
RTG wrist mean velocity	**-0.483**	**-0.440**	**0.687**	0.061
RTG wrist distance	0.263	0.320	-0.171	0.240
Grasp duration	**0.602**	**0.568**	**-0.555**	0.106
10-year-olds				
Latency	0.047	-0.053	-0.172	-0.201
RTG duration	0.238	0.064	**-0.458**	-0.109
RTG wrist MU	0.048	-0.018	-0.135	0.002
RTG wrist peak velocity	-0.312	-0.187	**0.531**	0.103
RTG wrist peak placement	0.175	-0.024	-0.324	-0.110
RTG deceleration	0.079	0.150	-0.127	0.061
RTG wrist mean velocity	-0.204	-0.033	**0.459**	0.118
RTG wrist distance	0.118	0.072	-0.133	-0.014
Grasp duration	0.026	-0.120	-0.075	0.013
Adults				
Latency	0.171	-0.027	-0.157	0.043
RTG duration	**0.407**	0.244	**-0.371**	0.068
RTG wrist MU	0.207	0.276	-0.238	0.012
RTG wrist peak velocity	-0.075	0.019	0.308	0.279
RTG wrist peak placement	0.323	0.227	-0.309	0.012
RTG deceleration	0.165	0.079	-0.111	0.094
RTG wrist mean velocity	-0.279	-0.106	**0.484**	0.254
RTG wrist distance	0.294	0.226	0.003	**0.397**
Grasp duration	0.054	0.004	-0.140	-0.077

Note: Bold values are significant at $p < .005$. Abbreviations: MU = movement units; RTG = reach-to-grasp; TTF = transport-to-fit. (Table from Domellöf et al. (2020) reprinted under the Creative Commons CC-BY license, slightly altered for clarity)

The differences between children and adults are probably due to increased attention towards the second-order end-goal in adults. The greater adult engagement in motor planning could also be indicated by the longer time dedicated to initial visual processing of the goal (longer latency) and the more proactive peg rotation. Although significant changes in movement organization occur between the ages of 6 and 10, the results show that, by age 10, adult levels of motor planning have still not been reached.

Study II

Study II investigated kinematic differences in motor planning and movement execution between 6-year-old children with autism and with typical development. Less proficient motor planning (including longer latencies, decreased chaining of sequential movement and less proactive peg rotation) was expected in the group of children with autism. We further examined the relationship between kinematic measures and cognitive capabilities in the group of children with autism.

Partly in line with our hypothesis, the children with autism did show lower motor planning proficiency. A significant main effect of group on RA (residual angle of the peg at the end of transport) (F = 19.19, $p < .001$) showed that the children with autism exhibited less proactive peg rotation. Furthermore, a significant group x orientation interaction (F = 3.07, $p = .028$) on peak velocity in the transport phase showed that adjustments of peak velocity towards goal-slot orientation were only significantly exhibited in the group of typically developing children ($p < .001$). The typically developing children showed higher peak velocities in the 0° and 90° compared with the -90° and 180° goal-slot orientations. No significant peak velocity difference between goal-slot orientations was observed in the group of children with autism. This result indicates that the children with autism exhibited decreased chaining of sequential movement. In contrast to our hypothesis, no group difference in latency was found. The absence of latency group differences in younger children might relate to generally immature inhibition, together with less initial attention towards the second-order end-goal among younger children in general. This interpretation is further supported by the weak condition effect (F = 4.65, $p = .032$), showing that whether the goal was visible prior to measurement onset or first revealed at measurement onset had only a weak impact on the time dedicated to initial visual processing of the end-goal (latency). The children with autism primarily displayed difficulties related to movement execution at the end of the movement, during the fitting phase. However, more movement corrections were made by the group of children with autism in prehension, which is seen in a significant main effect of group on MU in RTG (F = 7.43, $p = .012$). This result probably reflects a more awkward grip preparation in the group of children with autism. Compared to the typically developing children, the group of children with autism only showed longer movement duration (F = 22.39, $p < .001$) during the fitting phase and corresponding increases in MU (F = 19.47, $p < .001$), reflecting less optimal fitting of the peg, which is probably related to atypical motor planning.

The group of children with autism also exhibited greater intra-individual variability than the typically developing group on many measures, which affected general performance efficiency. The children with autism showed greater shifts between efficient and inefficient movements. Compared to the typically developing children, the group of children with autism had higher intra-individual variability on latency (U = 35, $p = .035$, r = .43), PPV in the RTG phase (U = 29, $p = .014$, r = .50), RA (U = 35, $p = .035$, r = .43), total movement duration (of the whole sequential movement) (U = 25, $p = .007$, r = .55) and total movement MUs (of the whole sequential movement) (U = 27, $p = .010$, r = .52).

Within the autism group, significant correlations were evident between RA and FRI ($r_s = -.63$, $p = .038$) as well as RA and FSIQ ($r_s = -.64$, $p = .034$). However, this association alone did not produce the significant group difference. This negative relationship shows that pro-activity in object adjustments (lower RA) correlates with higher non-verbal and full-scale intelligence measures. This is in line with previous research (Ansuini et al., 2018), which has shown that the object manipulation aspects of motor planning relate to full-scale intelligence measures in children both with and without autism. Significant correlations were also found between total movement duration and WMI ($r_s = -.78$, $p = .008$) as well as between total MUs and WMI ($r_s = -.71$, $p = .023$). This relationship shows that less efficient execution of movement sequences (higher MUs and longer duration) correlates with lower working memory ability.

These results show that, in comparison to the typically developing children, the children with autism displayed difficulties in the planning and execution of sequential movements. This was mainly shown in the fact that the children with autism exhibited less planned peg rotation and less chaining of the sequential movement during the transport phase. Previous observations support our finding that it is mainly during later parts of sequential movements that atypical planning is exhibited in younger children with autism (Crippa et al., 2015; Forti et al., 2011). This is probably because children at these ages exhibit a low use of second-order motor planning in general. Movement execution differences were also mostly observed at the end of the movement, during the fitting phase. Longer durations and more movement adjustments were seen in the group of children with autism, probably related to less optimal planning towards the end-goal of fitting the peg. Increased intra-individual movement variability, indicating difficulties with motor planning, including the formation and/or retrieval of motor representations, has previously been observed in individuals with autism (Foster et al., 2020; Glazebrook et al., 2006, 2009; Hayes et al., 2018; Papadopoulos et al., 2012). The current findings of lower performance stability among the children with autism compared to the typically developing children give further support to these suggestions. This, together with the findings of correlations between movement execution outcomes and working memory ability in the group of children with autism, strengthens previous suggestions that motor memory deficits relate to sensorimotor problems in autism (Neely et al., 2019). The results highlight the importance of investigating difficulties with motor planning and performance in developing children with autism and provide support for previous suggestions that aspects of motor planning contribute to motor problems in autism.

Study III

Study III was a longitudinal study that investigated the development of motor planning at three time-points over a two-year period in early school-age children with autism and with typical development. We expected that the group of children with autism would exhibit less proficient motor planning and performance, with the most pronounced group differences at older ages. We did, however, expect both child groups to demonstrate increasing motor planning and performance efficacy with age. We further expected the autism group to display less age-related improvement in chaining sequential movements and less benefit from early available visual information in motor planning compared to the typically developing group.

The results showed increased efficiency with age on all measures in both child groups, with the exception of outcomes for RA. In the visual condition, the reduced RA with age ($F = 4.56$, $p = .014$) was mainly driven by changes in the typically developing group, and neither of the groups exhibited reduced RA with age in the occluded condition. The development of motor planning did, however, appear atypical among the children with autism on several measures, but almost exclusively in the visual condition. At the oldest age-level (~9 years), significant effects of group emerge in the visual condition. This was shown by the results of PPV-RTG and RA. A significant age-level × group interaction for PPV-RTG (F = 7.78, *p* < .001) revealed lower PPV-RTG in the autism group than the typically developing group at A3 (*p* = .038). This lower PPV-RTG indicated increased dependence on feedback mechanisms in prehension. Group differences on RA (F = 6.41, *p* = .017) were further shown to be mainly driven by evidence of higher RA in the autism group compared to the typically developing group at A3 (*p* = .003). The higher RA indicated decreased predictive rotation of the peg and less coordination between peg transportation and rotation. These divergent developmental trajectories support previous findings that, over the school years, there are increasing difference in manual motor performance between children with autism and typically developing children (Rodgers et al., 2019; Travers et al., 2017). A significant group × orientation interaction for PV-Transport (F = 2.81, *p* = .044) was also present, showing higher PV-Transport in the autism group than the typically developing group at 180° orientation (*p* = .013). This finding indicates atypical PV adjustments towards the most difficult task in the autism group compared to the typically developing group. This result is in line with previous results showing that early school-age children with autism produce faster movements than their typically developing peers (Mari et al., 2003; Rodgers et al., 2019). In contrast to the visual condition, the only group difference emerging in the occluded condition was for grip duration, where a significant age-level × group interaction (F = 5.75, *p* = .004) showed longer grip duration in the autism group compared to the typically developing group at A3 (*p* = .009).

In contrast to motor planning measures, no clear differences were seen between conditions related to performance proficiency. Significant effects of group on fitting duration were shown in both the visual (F = 11.06, *p* = .002) and the occluded (F = 12.93, *p* < .001) condition, with longer durations in the autism group compared to the typically developing group. However, the visual condition did seem somewhat less challenging for the autism group when observing the developmental patterns of fitting duration. In the occluded condition, group differences were observed at all age-levels (A1 *p* = .013; A2 *p* < .001; A3 *p* = .028). In the visual condition, no group difference was observed at the first age-level (~7 years), indicating that the visual information about the goal provided prior to measurement onset initially aided more equal fitting durations between the groups. However, possibly underlined by gains in motor planning for the typically developing children, a group difference was observed at the second age-level (~8 years) (*p* < .001), and this was still present at last age-level (~9 years) (*p* = .003).

Atypical development of chaining in sequential movement was further shown in the autism group. The typically developing children adjusted peak velocity more towards orientation difficulty (i.e. lower peaks for more difficult orientations) than the autism group (see Figure 6). However, this atypicality was only clearly expressed in the visual condition.

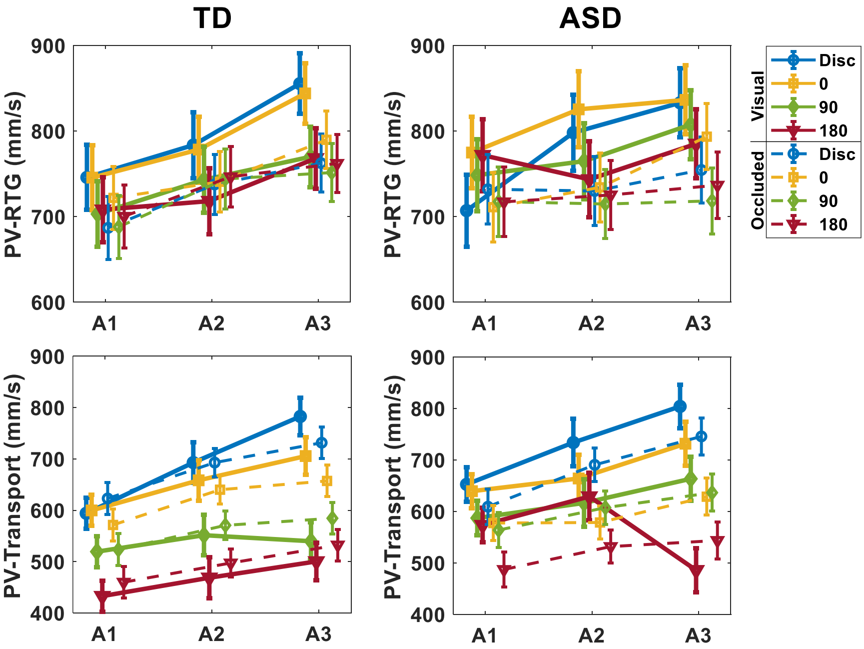

Figure 6. *The graphs illustrate estimated mean values ± SE from the interaction between age-level and orientation over time for each group in both the visual (solid line) and occluded (dotted line) condition. Both groups show lower peak velocities for more difficult orientations, more clearly differentiated in the TD than the ASD group, particularly in the visual condition. (Figure from Bäckström et al., currently under peer review for Autism)*

In the visual condition, although not reflected in a significant three-way interaction (F = .95, p = .518), orientation effects for PV-RTG were only observed in the typically developing group at A3 (p = .003). Neither group showed a significant orientation effect for PV-RTG in the occluded condition. For PV-Transport, adjustments towards orientation difficulty were seen in the visual condition for both groups, although at a later age in the autism group than the typically developing group, as indicated by the significant three-way interaction (F = .3.08, p < .001). In the typically developing group, adjustments towards orientation difficulty were already evident at A1 (p < .001), continuing at A2 (p < .001) and A3 (p < .001), and becoming more clearly differentiated as the children grew older. However, in the autism group, clear adjustments towards orientation difficulty only appeared at A3 (p < .001). In the occluded condition, orientation effects were found on PV-Transport in both groups and were evident at all age-levels (TD: p_{A1} < .001; p_{A2} < .001; p_{A3} < .001) (ASD: p_{A1} = 016; p_{A2} < .001; p_{A3} < .001). These findings are in line with previous suggestions of chaining difficulties and atypical global processing of sequential movements among children with autism (Cavallo et al., 2018; Crippa et al., 2015; Fabbri-Destro et al., 2009; Forti et al., 2011). As the results reveal, the typically developing children seemed to be assisted by having visual information of the goal prior to measurement onset in the process of chaining sequential movements, particularly when older. However, this increased reliance on initial visual information was not seen among the children with autism. These findings suggest problems with visuomotor integration in the children with autism which affects motor planning development.

We further investigated whether the benefits of having visual information about the specific end-goal prior to measurement onset differed between the child groups or changed with age. Neither group seemed to show increasing latency difference between conditions with age, and there were no effects of group. An additional analysis of developmental patterns of difference between conditions not included in the manuscript showed a significant condition effect for latency (F = 38.21, p < .001) with longer latency in occluded than the visual condition. This effect was driven by observed condition differences at A2 and A3 in both groups (TD: p_{A1} = .142; p_{A2} = .019; p_{A3} = .003) (ASD: p_{A1} = .325; p_{A2} = .006; p_{A3} = .020); however, this did not generate a significant three-way interaction. These findings indicate that the children did not seem to explicitly increase the time they spent visually inspecting the end-goal prior to movement onset as they got older. As the typically developing children grew older, they did however seem to be implicitly assisted in their motor planning by having visual information of the end-goal provided prior to measurement onset. This increased reliance upon initial visual information did not seem to appear with age in the children with autism. At A3, the difference between conditions was greater in the typically developing group than in the autism group for PPV-RTG and RA. A significant age-level × group interaction (F = 5.90, $p = .007$) was shown for PPV-RTG difference between conditions (higher PPV-RTG in the visual than the occluded condition). The typically developing group showed evidence of a condition difference increase between A2 and A3 ($p < .001$) and a larger condition difference at A3 ($p = .026$) than the autism group. A significant age-level × group interaction (F = 3.99, $p = .030$) was also shown for RA difference between conditions (lower RA in the visual than the occluded condition). The typically developing group displayed a larger condition difference at A3 ($p = .030$) than the autism group. These results indicate atypical visuomotor developmental trajectories in the autism group. At the oldest age (~9 years), the autism group seemed to gain less benefit from early available visual information for their motor planning processes than the typically developing group. A significant group effect was further shown for PV difference between conditions (higher peak velocities in the visual than the occluded condition) during both the RTG (F = 5.06, $p = .033$) and transport (F = 7.90, $p = .009$) phase. The autism group displayed larger condition differences than the typically developing group. The children with autism increased peak velocities in the visual condition compared to the occluded condition more than their typically developing peers did. This result reflects the previous observation that atypically increased PV in the autism group only occurred in the visual condition. Significant effects of group were also shown for grip duration difference between conditions (shorter grip duration in the visual than the occluded condition) (F = 4.61, $p = .041$). The autism group showed larger differences between conditions than the typically developing group. The grip duration was increased in the occluded compared to the visual condition to a greater extent than for the typically developing children, probably reflecting increased updating of the ongoing movement in the occluded condition. Together, these differences support previous findings of difficulties in considering all the available visual information during movement modulation (Dowd et al., 2012), which is linked to suggested problems with visuomotor integration in autism (Dowd et al., 2012; Glazebrook et al., 2009; Lidstone & Mostofsky, 2021). These problems seem to further underpin the above-described atypical motor planning development.

Taken together, these results show that, in comparison to the typically developing children, the children with autism displayed atypical motor planning development during sequential manual movements. Increased initial reliance on visual information promoted motor planning gains in the typically developing group but not in the autism group. This indicates that divergent global sensory processing and visuomotor integration are associated with the atypical development of motor planning in autism.

General discussion

The general aim of this thesis was to investigate motor planning and movement organization for sequential manual movements in typically developing children and children with autism. A specific focus was directed towards the detailed characteristics of both typical and atypical motor planning and its development during early school-age years. The three studies included here provide information about different aspects of this overarching aim. A brief discussion of the findings related to each study was provided in the previous section. In this section, I connect these findings and consider their common contribution to the understanding of both typical and atypical motor planning development. Additionally, I discuss their connection with prior empirical findings and theoretical suggestions. I also describe the limitations of the current work, provide a general conclusion, and conclude with some suggestions for future research directions.

Typical development

Knowledge about how sequential movement organization develops during early school-age years is still limited. To add to this knowledge, my thesis includes studies involving both longitudinal and cross-sectional investigations of typical development during early school age and in reference to adults. The studies included here provide information about the initial motor planning that takes place prior to the onset of movement and about the reliance on and efficiency of this initial plan in the unfolding of that movement. This detailed investigation of sequential movement performance provides a deeper understanding of how the development of sequential motor planning unfolds during early school-age years.

Attention and perceptual processing of the motor goal prior to the onset of movement are motor planning processes included in the latency measure. In Studies I and III, latency was shown to decrease across early school-age years, indicating that motor planning processes become quicker and less demanding during this period. There are indications, however, that speed is prioritized over accuracy by early school-age children when performing these kinds of sequential tasks that allow for online correction. In Study I, in comparison to 6- and 10-year-old children, adults take more time initiating movement (longer latency), generate slower initial movements (lower velocity) and proactively rotate their peg prior to arriving at the goal. This indicates that adults adjust their speed to meet the demands of the task, resulting in a balance between speed and accuracy in their motor planning process, while children seem rather to prioritize speed. These suggestions are in line with findings from developmental studies on sensory integration. It has been proposed that developing and adult visual systems might involve different optimization processes related to sensory detection and sensory integration (Nardini et al., 2010). In an experiment by Nardini and colleagues (2010), 6-year-old children and adults were presented with different numbers of visual cues to determine the surface slant of a visual projection. The results indicated that adults integrate the available information to reduce perceptual uncertainty, and increase their accuracy when presented with more cues. The children did not increase their accuracy when presented with more cues but reduced their reaction time, seemingly following the single cue that was most rapidly available. Hence, the authors suggest that, while the adult sensory system might be optimized towards the reduction of sensory uncertainty, the developing system might be optimized towards speed and the detection of sensory conflict. Study III gives further indications that only rudimentary knowledge about the task goal of grasping and placing a peg seems to be sufficient for children of early school age when planning and initiating their movement. The difference in latency between when the goal was visible versus when it was occluded prior to measurement onset did not seem to significantly increase over time. Furthermore, not enough time was dedicated during the latency phase to overcome condition effects during the unfolding of the movement. These suggestions are in line with findings of lower response inhibition during sequential movements in young teenagers versus adults (Domellöf & Säfström, 2020). As described, perceptual decision-making is the most time-consuming part of motor planning (Wong et al., 2015). Given that information processing is slower in young children (Kail, 1991), their more exploratory motor-planning strategy might be the most adaptive one for these children since it renders a movement that is rapid enough to keep up with the demands of the environment. The costs of tailoring prehension towards the end-goal may be weighed against the gains for the efficiency of the onward performance (Wilmut et al., 2013b). In Studies II and III, at 6 and 7–8 years old, no gains in motor planning were seen between when the goal was visible versus when it was occluded prior to measurement onset. This indicates that, in this setting, the extra time available to attend to and process perceptual information was of no use to the younger children in improving their internal model predictions. At 9 years of age, however, the visibility of the goal prior to measurement onset improved motor planning efficiency, probably linked to increased visuomotor integration in action planning, in keeping with previous suggestions from cross-sectional studies (Jongbloed-Pereboom et al., 2016; Martel et al., 2020; Serrien & O'Regan, 2021; Thibaut & Toussaint, 2010). The relative benefit of tailoring the initial movement towards the end-goal in sequential movements can probably also be influenced by how effectively feedback processes (i.e. online corrections) can be used. In a previous study, Krajenbrink and colleagues (2020) used a task in which second-order grip planning was needed at the initial grasping for successful completion. In this study, high rates of second-order planning of the grip movement were shown to already exist at preschool age. The authors argue that these findings support the argument that younger children can use second-order motor planning if tasks require the tailoring of the initial movement for successful accomplishment (Krajenbrink et al., 2020). Furthermore, in their study, latency times were affected by task demands. Simple action selection seems to have little impact on latency (Wong et al., 2015). This result hence indicates that this kind of task (requiring second-order motor planning for successful completion) includes more complex motor planning, calling for additional cognitive planning at preschool age. The tailoring of the initial movement towards the end-goal (i.e. second-order planning) comes with a high cost (prolonged latency), but even so, it seems adaptive to use this strategy since the gains are high (successful task performance relies upon this initial tailoring). Furthermore, as seen in Studies I and III, in line with previous research (Simon-Martinez et al., 2018), the efficiency of arm/hand movements improves across early school years, with increased movement smoothness and shorter durations. Since adult-like movement smoothness and durations were seen at 10 years in Study I, there are probably few benefits related to generating an even faster movement. As Study III shows, at 9 years of age the feed-forward model predictions do, however, begin to improve given the extended time to process the end-goal in the visual condition. This is probably because it enables a more complete end-goal prediction. The gains achieved in efficiency of movement performance might make it easier to shift towards a more flexible prioritization between speed and accuracy. Together with the reduced effort needed for second-order motor planning at older ages due to experience and neurodevelopment, this might change the cost/benefit relationship. The lower cost related to initial second-order motor planning and the increased benefit of a more precise perception of the end-goal may facilitate the shift from more exploratory to more adult-like planned sequential motor behavior. These developmental gains might be reciprocally related. Experiences of gains such as increased visuomotor integration in action planning might increase the amount of attention and perceptual processing directed towards visual information about the end-goal. With time, these processes may direct the reorganization of sequential movements towards adult-like behaviors in children with typical development.

Autism

What happens during atypical development? In Studies II and III, we investigated differences in motor planning and movement execution between children with autism and those developing typically. Study III focused on the development of motor planning and visuomotor integration in children with autism. Additionally, Study II explored the relationship between action performance and cognitive abilities in the group of children with autism.

Previous findings regarding motor planning atypicality in children with autism have shown between-study inconsistencies in their outcomes. However, few studies have taken a developmental perspective. Nonetheless, the available findings seem to indicate that the characteristics of motor planning differences between children with autism and those with typical development are dynamically affected by both task complexity and age (Lu et al., 2022; Rodgers et al., 2019).

Studies II and III demonstrated that the children with autism exhibited less efficient motor planning than their typically developing peers. In Study II, this was seen in less proactive peg rotation at 6 years of age and no difference in transport phase peak velocity between goals with different levels of difficulty. The typically developing children did, however, show transport phase peak velocity adjustments related to goal difficulty. Furthermore, larger intra-individual movement variability was shown in the children with autism than in the typically developing children in Study II. In Study III, differences in motor planning between the groups were related to visibility of the end-goal. The children with autism displayed increased dependence on feedback mechanisms in prehension (lower PPV-RTG) and less proactive peg rotation compared to typically developing children at ~9 years of age in the visual condition only. Chaining difficulties were also shown among the children with autism, who adjusted peak velocity less in relation to goal difficulty than the children with typical development. This was specifically prominent in the visual condition. In Study II, movement execution difficulties primarily appeared at the end of the movement, during the fitting phase, when the children with autism showed longer fitting durations and increased need for corrective sub-movements. In Study III, the children with autism had longer fitting durations in both conditions. This was observable at all ages (~7, ~8 and ~9 years) in the occluded condition. In the visual condition, no observed difference was seen between the youngest child groups (~7 years) in fitting duration but later on, at ~8 and ~9 years, the longer fitting duration in the autism group became observable.

In contrast to previous findings from a systematic review (Sacrey et al., 2014), neither Study II nor III found any difference in latency between groups. The absence of group differences in latency in Studies II and III might be related to less initial attention and processing being directed towards the second-order end-goal by younger children in general and possibly even more so by younger children with autism. The difference with previous common findings of longer latencies in autism (Sacrey et al., 2014) might be related to the age of the children included in Studies II and III. Rodgers and colleagues (2019) investigated latency times in younger (6–9.5 years) and older (9.5–16 years) children with autism and typically developing peers. They showed that only the older children with autism exhibited increased latency times compared to their typically developing peers. It might be that the longer latency often seen in autism serves as a compensatory function, developing at older ages. In line with this suggestion, adults with autism have described that most everyday actions need to be thought through (Gowen et al., 2023). This developmental change could be related to increasing second-order motor planning ability. With age, these children may learn that increased processing of perceptual information (increased latency duration) can aid them in improving motor performance.

Lower proactivity of peg rotation among the children with autism compared to the typically developing children was observed at 6 years in Study II and then again first at 9 years in Study III. While these somewhat contradictory findings of group differences being present at 6 years (Study II) and absent at 7 and 8 years (Study III) might be related to differences in method and participants, it could also be an effect of developmental processes. The period around 8 years of age has been highlighted as a stage of destabilization in typical motor planning development (Jongbloed-Pereboom et al., 2016; Martel et al., 2020; Serrien & O'Regan, 2021; Thibaut & Toussaint, 2010), preceding re-organization towards more adult-like behaviors. It might be that the lack of group differences at 7 and 8 years of age relates to such destabilization processes affecting general performance in the typically developing group but not in the autism group. The fact that reorganization of peg rotation towards more adult-like behaviors, with increasing proactivity between 7 and 9 years, is only seen in the typically developing group under the visual condition gives further support to this interpretation.

The atypical motor planning development in children with autism, shown in Study III, appears to be related to the availability of visual information. In contrast to the typically developing children, no increased reliance on initial visual information in motor planning emerges across early school age in the children with autism. This is in line with previous findings of less reliance upon visual information for adjusting movement plans among children with autism (Dowd et al., 2012). The findings of Study III hence strengthen the indication that children with autism have problems with visuomotor integration and that these affect motor planning development. Although reliance on proprioception has not been investigated in the present work, the lower reliance on visual information further aligns with descriptions of a bias in autism towards reliance on proprioceptive rather than visual feedback to form internal motor representations (Glazebrook et al., 2009; Lidstone & Mostofsky, 2021).

Among the children with autism, problems with the chaining of movements and atypical global processing of sequential movements is seen in both Studies II and III, in line with previous studies (Cavallo et al., 2018; Crippa et al., 2015; Fabbri-Destro et al., 2009; Forti et al., 2011). Increased reliance on initial visual information in typical development seems to relate to improved global processing of sequential movements, as shown in Study III. In contrast, earlier available visual information does not seem to facilitate chaining in the autism group. Weak connectivity of neural networks has been related to the preference for local versus global sensory processing in autism (Happé & Frith, 2006; Leisman et al., 2023). Enhanced connectivity in typical development (Tsujimoto, 2008; Uytun, 2018) and the possibly divergent development of connectivity within neural networks in autism might lead to low-level perceptual atypicality in autism becoming increasingly evident. This may then generate differences in the planning of sequential movements at early school age. Over this age period, the typically developing children seem to optimize performance in the occluded condition by generating an initial plan that, as shown by reach-to-grasp peak velocity, was similar to the plan generated for the more difficult goal orientations in the visible condition (see Figure 6). Furthermore, the velocity in the visible condition was only increased for the easier goal orientations. In contrast, among the children with autism, the visual condition generated increased initial peak velocities in general in comparison to the occluded condition. This indicates that the children with autism generated a general plan in the visual condition towards an easier target, showing no adjustments concerning end-goal difficulty. Rather than being a facilitating factor, it thus seems that the early availability of visual information distracted global processing in the group of children with autism. In the autism group, the initially occluded end-goal may have generated increased attention towards the end-goal during transport. The bias towards local over global processing in children with autism has been shown in a previous study to diminish if they are instructed to attend to global information (Plaisted et al., 1999). Related to these results, the visible and occluded conditions may generate different processing biases due to differences in how attention is directed by task constraints. Hence, the global processing (chaining) of sequential manual movements might not be generally deficient. Rather, processing biases might be related to how visual information is attended to and integrated, supporting the suggestion of atypical visuomotor integration.

Stability of representations

Impairments in both visuomotor integration and global processing have been related to problems with learning and to the generation of stable representations (Happé & Frith, 2006; Lidstone & Mostofsky, 2021). In addition to motor planning difficulties, further indications of challenges in the generation and/or retrieval of motor representations are shown in the increased within-individual variability among the children with autism in Study II. The lower performance consistency in this group of children aligns with previous findings of increased within-individual variability of sensory responses in autism (Robertson & Baron-Cohen, 2017). Impairments in the formation of internal motor representations may contribute to the impaired formation of representations of others (Cook, 2016; Lidstone & Mostofsky, 2021). It has further been proposed that neural networks encoding internal models, which support prediction and error-based learning, are used to predict not only motor but also social action sequences (van Overwalle et al., 2020). The motor-base for understanding the action intentions of others and possible common governing neural mechanisms exemplifies that advances in the understanding of motor performance in autism might enable the targeting not only of motor skills but also of social functioning.

Relationship between cognitive and motor development in autism

Children with autism are a very heterogeneous group and many face cognitive challenges beyond the ones defined by diagnostic criteria (Lord et al., 2020). Although cognitive and motor development are clearly linked (Diamond, 2000), the characteristics of these relationships are less clear (van der Fels et al., 2015). To investigate the relationship between the assessment of motor and cognitive development in the group of children with autism, associations between kinematic measures and cognitive capabilities were investigated in Study II. Study II shows that FSIQ and FRI were related to proactivity in object adjustments (RA) at 6 years old in the group of children with autism. This is in line with previous findings, where proactivity in object manipulation has been related to FSIQ in 7–12-year-old children both with and without autism (Ansuini et al., 2018). Visuospatial skills, the ability to mentally represent and manipulate objects in the environment, are a part of the FSIQ construct that show strong correlations with the FRI sub-scale (Wechsler, 2012, 2014). FSIQ did not relate to movement duration or smoothness in the 6-year-old children with autism in Study II. This contrasts with previously shown relations between movement speed and FSIQ in preschool aged (<5 years old) children with autism (Forti et al., 2011). These study differences might indicate that relationships between motor and cognitive skills are mediated by developmental level. Relationships between measures of cognitive and motor functions are generally more robust before puberty (van der Fels et al., 2015). This further supports the suggestion that developmental level seems to influence relationships between motor and cognitive skills. At preschool ages, children with autism seem to generate slower manual movements in general compared to typically developing peers (Campione et al., 2016; Forti et al., 2011; Lu et al., 2022). This group difference relates to what seems to be an important developmental task at this age, to produce faster movements. However, at early school age, in line with previous findings (Lu et al., 2022; Mari et al., 2003; Rinehart et al., 2006), Study II shows that it is not slower manual movements in general that differentiated children with autism from children without autism. It might be that slower movement speed is less related to developmental delays at early school age than during preschool years. That is, the typical increase in movement speed might have been mastered by school age even if a delayed development was present during preschool years. The developmental step to be mastered at school age might be more closely related to the change towards more flexibly planned movement. However, in Study II, movement duration and smoothness did relate to working memory capacity in the 6-year-old children with autism. It has been proposed that, during repeated movements, the motor program is stored and updated in working memory (Ohbayashi et al., 2003). This result thus aligns with previous suggestions about motor memory deficits relating to motor problems in autism (Neely et al., 2019).

Methodological considerations

Kinematic registration is both sensitive and reliable for detecting subtle changes in motor performance. The detailed measurements facilitate the identification of movement aspects that are not visible to the naked eye. However, a recent meta-analysis indicated that kinematic analysis may yield lower effect sizes for group differences than clinical assessments (Wang et al., 2022). The kinematic analysis of motor problems in autism is typically conducted using well-defined and straightforward tasks. In contrast, studies utilizing clinical assessments of motor functions often involve larger samples and assessment batteries that include a wide range of tasks, both simple and complex. Since motor performance in autism seems to be more strongly affected during more complex tasks (Rodgers et al., 2019; Yang et al., 2014), it is likely that it is the kinds of tasks and outcomes used, rather than the technique itself, that is affecting the magnitude of effect sizes. Kinematic measurements can provide a detailed and dynamic picture of motor behavior. By offering precise, quantitative data on distinct movements, this approach opens up possibilities for researching specific aspects of motor behavior that are difficult to detect using common standardized assessment measures (Wilson et al., 2018). This approach may facilitate explorations of the interaction between motor and cognitive development in autism; and/or investigations of how the role of sensory processing in motor impairments (variability and consistency over age) co-occur with the severity of core symptoms within the diagnostic criteria for autism. This may improve our ability to understand whether there are common underlying neurodevelopmental disruptions in autism related to the suggested association between the severity of motor impairments and autism symptoms (Wang et al., 2022). It is, however, important to take methodological differences between investigations into consideration when reviewing studies on motor problems in autism to ensure that the everyday motor problems within this population are not underestimated.

Although the numbers of participants in the studies included in this thesis are similar to those in most kinematic studies of motor planning in children with autism (e.g. Campione et al., 2016; Dowd et al., 2012; Fabbri-Destro et al., 2009; Forti et al., 2011; Martel et al., 2023), some may argue that the samples are limited. However, the motion capture technique does provide highly reliable measurements, and the outcomes were derived from several trials, generating more stable outcomes, thus enabling the gathering of reliable data even in a relatively small sample. There are also indications of sufficient statistical power to detect relevant group differences in that we had significant results aligning with our hypothesis. Nevertheless, in some instances, a larger sample would probably have generated less variability in the outcomes, allowing for clearer detection of significant effects. Notably, a clear strength related to the sample is that Studies II and III did recruit a narrower age range of included children than most studies on the topic, reducing age-related variability. This narrow age range is important when investigating development in children because aspects of motor planning may be age specific. In the planning for Study III, steps were taken to include a larger sample than in Studies I and II, to allow for attrition and the more complex analysis planned for the longitudinal design. However, the success of this strategy was limited due to the Covid-19 pandemic. Since longitudinal kinematic data on motor planning development in children across these ages is sparse, or even lacking, we found the longitudinal approach to be very important. Replication in larger independent samples is nonetheless warranted because the sample size is relatively limited.

The overarching aim of this thesis was to provide a detailed description of the developmental patterns of sequential manual motor planning in children following a typical development trajectory and in developing children with autism across early school age. The investigation of different aspects of the unfolding of sequential movement performance provides a rich description of sequential manual motor planning development. The many outcome measures, together with the somewhat limited sample size, do however increase the risk of both type I and type II statistical errors. In relation to this risk, we have been transparent in reporting the results by providing descriptive statistics, all p-values and all non-significant results. The hypothesis specification and the subsequent results for each kinematic outcome have different amounts of previous evidence to build upon and to be interpreted against. This makes some of the findings more robust and some more indicative. Because consensus is lacking as to which motor planning measures are the most appropriate to use at which age, future studies should take advantage of the opportunity to specify their outcome selection(s) in relation to the included sample in pre-registered study protocols. In addition, it is important to incorporate developmental aspects when planning studies in order to guide the production of a coherent understanding of motor planning in developing children with autism. To this end, this thesis contributes by providing detailed developmental information for future studies to draw from and corroborate.

Many children with autism have motor problems affecting postural control and balance (Lim et al., 2017). Poor postural control and body sway can affect motor planning and the execution of hand movements.

This could lead to inconsistent or jerky hand movements as the child attempts to adjust for changes in body position related to body sway and balance issues. This might also reduce the effectiveness of feed-forward systems since it becomes harder to predict the relationship between an action and its outcome. As with manual motor planning, it has been proposed that balance issues in autism could be related to problems with sensorimotor integration (Lim et al., 2017). Given these potential influences, kinematic measures of hand movements in children with autism might not purely reflect problems with hand control but could also be confounded by difficulties with postural control.

The generalizability of the findings of this thesis is affected by several factors. First and foremost, as this thesis work has shown, interactions between age and task generate dynamic effects. This has an impact on the possibility to generalize findings to other ages and types of task. For example, the inclusion of children with a wide age range could mask differences or similarities between groups related to specific developmental periods, and between-study discrepancies may be related to developmental processes. The results from the visual and occluded conditions in Study III highlight the possibility that minor task differences may impact differently at different ages. Furthermore, this thesis has investigated motor planning in sequential manual movements during which online adjustments of the movement plan were possible. The results would probably have been different in a task that did not allow for online adjustments (for more details on this topic, see the Discussion section).

The neurodiversity observed in the group of children with autism in the studies within this thesis mirrors the heterogeneity commonly found among children with autism (Lord et al., 2020). One exception to this concerns the exclusion of children with autism and an early established diagnosis of intellectual disability. All the children had been diagnosed with autism at a relatively young age. This might limit the relevance of the thesis findings for children with autism diagnosed at a later age, because different sample characteristics have been observed depending on age at diagnosis (Arvidsson et al., 2018). In Studies II and III, several measures were presented to describe the study sample with the intention of making between-study comparisons easier. However, although Study II provides some insights, there is still very limited knowledge regarding how the relationship between motor planning and higher cognition is characterized among developing children with autism. Possible cognitive-motor relations may nonetheless affect the generalizability of the results presented here. Continued research is necessary to improve our understanding of these relationships, both in typical development and in developing children with autism.

Conclusions

The findings presented in this thesis indicate that the development of motor planning and the performance of sequential manual movements continues throughout early school age. This period appears to be significant for the reorganization of sequential movements, transitioning towards a more adult-like form in typical development. Consistent with previous cross-sectional studies, this thesis provides longitudinal evidence that changes in visuomotor integration are related to improved motor planning during early school age. Regarding development in children with autism, the results of the studies included in this thesis suggest that this group of children exhibit less efficient motor planning and atypical motor planning development compared to their typically developing peers. These motor planning difficulties, along with the increased variability within individuals with autism, indicate challenges with motor representations in this population. Furthermore, the atypical motor planning development is related to the availability of visual information, supporting the notion that visuomotor integration difficulties affect motor planning development in children with autism.

Future directions

Autism is a neurodevelopmental disorder, and it is essential to enhance our understanding of its development. A deeper comprehension of the mechanisms underlying developmental challenges is crucial for generating interventions that can mitigate adverse effects. What should we address directly, and what should we find ways to accommodate? Considering how behaviors evolve over time—both for the children themselves and for those in their surrounding environment—can help in identifying alternative methods to promote learning. The results presented in this thesis support the assertion that early school age is an important stage during which the reorganization of sequential manual movements moves towards more adult-like forms and that changes in visuomotor integration seem to be related to improved motor planning. To further investigate the role of visuomotor integration in motor planning development, a synchronized examination of gaze and detailed movement registration appears to be a promising methodology (Abney et al., 2024; Lavoie et al., 2018; Ossmy et al., 2020). This is particularly true when studying developing children with autism since gaze behavior during the execution of movements has been reported as atypical in autism (Crippa et al., 2013; Glazebrook et al., 2009).

In addition, knowledge about typical development might inform interventions directed at children following an atypical development pathway. For example, second-order planning may be observed at an earlier age if the task requires it for success. Since internal models are updated by prediction errors, it might be a good idea to train tasks with clear and direct error feedback. Can training in these kinds of tasks aid motor planning development in autism? In this area, it is important to consider how different sensory modalities of feedback seem to affect motor learning in autism. And how do cognitive problems affect possible gains in this kind of training? To this end, it is important to further corroborate and expand knowledge about the development of motor planning and mechanisms that hinder the development of motor planning in autism. Several interesting issues related to the link between cognitive and motor development remain unanswered in both autism and typical development.

Another important area of research is to provide more empirical evidence to test theories about the relationships between planning deficits in autism and common neural mechanisms. The proposal that common neural networks support both motor and non-motor predictions of action sequences is very interesting (van Overwalle et al., 2020). Advances in knowledge in this area bring the possibility of elucidating underlying mechanisms to both atypical social functioning and restrictive behaviors, which are often linked to problems with predicting what will happen in new and changing environments.

Additionally, it is important to determine whether findings on motor planning problems and mechanisms hindering motor planning are specific to autism. Motor impairments are increasingly recognized as an integral aspect of autism; however, whether they should be considered a core symptom, included as a “specifier” or addressed with an additional diagnosis of developmental coordination disorder remains a subject of debate among researchers and clinicians (Miller et al., 2024). We have yet to discover whether specific aspects of motor problems, which could help to differentiate autism from other developmental disorders, can be directly related to autism. There is, however, substantial evidence of a high degree of motor problems within the population of children with autism, and these issues remain significantly underrecognized in clinical practice (Miller et al., 2024). The overlooked motor problems in autism call for action. Knowledge about motor problems, including information about the high intra-individual variability and problems with generalizing efficient movement strategies, need to be considered in interactions with developing children with autism in order to ensure relevant support. The high prevalence of motor problems within this population further motivates increased knowledge transfer about motor issues in autism to organizations serving children with autism.

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