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# Motor planning and movement execution during goal-directed sequential manual movements in 6-year-old children with autism spectrum disorder: A kinematic analysis☆

Anna Bäckström [a,*], Anna-Maria Johansson [a], Thomas Rudolfsson [a,b], Louise Rönnqvist [a], Claes von Hofsten [c], Kerstin Rosander [c], Erik Domellöf [a]

[a] Department of Psychology, Umeå University, Umeå, Sweden
[b] Centre for Musculoskeletal Research, Department of Occupational Health Science and Psychology, University of Gävle, Gävle, Sweden
[c] Department of Psychology, Uppsala University, Uppsala, Sweden

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ABSTRACT

*Background:* Atypical motor functioning is prevalent in children with autism spectrum disorder (ASD). Knowledge of the underlying kinematic properties of these problems is sparse.
*Aims:* To investigate characteristics of manual motor planning and performance difficulties/diversity in children with ASD by detailed kinematic measurements. Further, associations between movement parameters and cognitive functions were explored.
*Methods and procedures:* Six-year-old children with ASD (N = 12) and typically developing (TD) peers (N = 12) performed a sequential manual task comprising grasping and fitting a semi-circular peg into a goal-slot. The goal-slot orientation was manipulated to impose different motor planning constraints. Movements were recorded by an optoelectronic system.
*Outcomes and results:* The ASD-group displayed less efficient motor planning than the TD-group, evident in the reach-to-grasp and transport kinematics and less proactive adjustments of the peg to the goal-slot orientations. The intra-individual variation of movement kinematics was higher in the ASD-group compared to the TD-group. Further, in the ASD-group, movement performance associated negatively with cognitive functions.
*Conclusions and implications:* Planning and execution of sequential manual movements proved challenging for children with ASD, likely contributing to problems in everyday actions. Detailed kinematic investigations contribute to the generation of specific knowledge about the nature of atypical motor performance/diversity in ASD. This is of potential clinical relevance.

## What this paper adds

Kinematic movement registration was used as an important tool to understand the underlying characteristics of frequently reported movement problems in children with ASD. Focus was specifically on motor planning and performance difficulties in sequential goal-directed manual movements. Six-year-old children with ASD were compared to typically developing (TD) children. Goal-directed

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* Corresponding author at: Department of Psychology, Umeå University, SE- 901 87, Umeå, Sweden.
*E-mail address:* anna.backstrom@umu.se (A. Bäckström).

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manual movements involving sequences of subgoals are common in everyday life, but rarely studied using detailed measurement technique. We recorded such movements during a sequential manual task comprising of grasping and fitting a semi-circular peg into a goal-slot. Different constraints on motor planning was imposed by manipulating the required final orientation of the peg. Different sub-phases of the movements (latency, reach-to-grasp, grasp, transport, and fit) were identified, allowing a thorough analysis of the spatio-temporal features comprising possible atypical movement performance. The TD-group mainly rotated the peg during transport while the ASD-group was more prone to rotate it after arriving at the goal, indicating motor planning difficulties. Children with ASD also displayed a less proficient movement organization during the reach-to-grasp and when transporting the peg. Furthermore, children with ASD showed more variable performance, shifting between inefficient and efficient movements. This study indicates that children with ASD show less functional anticipatory strategies, likely attributed to a limited ability to plan movement sequences. This may help to explain problems in performing everyday actions. The results offer an important insight into the nature of atypical motor performance/diversity in children with ASD, with implications for raising the awareness of movement difficulties in ASD and informing professionals and families.

## 1. Introduction

Autism spectrum disorder (ASD) is a condition characterized by socio-communicative difficulties and repetitive/restricted behavior that affect everyday life and contribute to functional limitations in school, work and/or social relations (American Psychiatric Association, 2013). In addition to the core symptoms, a growing body of research suggests that impaired motor skills are common (Gowen & Hamilton, 2013), including atypical fine motor functioning (Sacrey, Germani, Bryson, & Zwaigenbaum, 2014). Despite the increased research interest directed towards atypical motor behavior in children with ASD, detailed measurement techniques in the investigation of arm and hand movements are not generally used. The generation of highly detailed movement data enables a more precise description of what seems to characterize the movement problems associated with the condition. This type of specific knowledge is of importance for the development of relevant interventions. The main objective of the present study was to describe and analyze the kinematic characteristics of manual movement planning and performance in children with ASD. These functions have been suggested to contribute to the atypical motor behaviors observed in this condition (von Hofsten & Rosander, 2012).

The generation of rapid and efficient movements is very important to meet the demands of daily life. Everyday goal-directed manual activities are constituted by complex action sequences where sub-movements are planned and executed to optimize a sequential chain of actions leading towards a forthcoming action goal. A mechanism underpinning efficient movement performance is motor planning, a process including the prediction of action goal outcomes and the associated organization of motor behaviors to accomplish a specific action goal.

In early motor development, emerging anticipatory grasp-adjustments can be observed among young infants (von Hofsten & Rönnqvist, 1988) indicating first-order motor planning ability (i.e., adjustment of manual behavior towards an imminent action goal like reaching and grasping an object; Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012). Emerging second-order motor planning (i.e. modification of manual behavior in relation to the forthcoming action goal like reaching and grasping an object to either throw or place it; Rosenbaum et al., 2012), become evident during late infancy and toddlerhood in different types of tasks. The complexity of the final goal adjustment in a sequential action has been shown to affect the movement kinematics in the reaching and transportation phases, with lower peak velocities and less relative time to peak velocity (percentage of time to peak velocity; PPV) in more complex tasks (Chen, Keen, Rosander, & von Hofsten, 2010; Claxton, Keen, & McCarty, 2003). Furthermore, emerging proactive adjustment of object orientation during object transportation towards the goal in fitting tasks has been found in toddlers (Örnkloo & von Hofsten, 2007). In later pre-school years, longer movement initiation latencies (hereafter referred to as latency), as a response to increased task complexity, have been shown (Krajenbrink, Lust, Wilson, & Steenbergen, 2020). This indicates a need for increased time to plan, form and select an action plan. Furthermore, an emerging sensitivity to end-state-comfort (ESC) has been reported during this period (Jongbloed-Pereboom, Nijhuis-van der Sanden, Saraber-Schiphorst, Crajé, & Steenbergen, 2013). A developmental progression in performance on goal-directed sequential manual tasks, with increasing ability to use second-order planning, has then been observed during the preschool and early school years (Domellöf et al., 2020; Jongbloed-Pereboom et al., 2013; Jung, Kahrs, & Lockman, 2018; Krajenbrink et al., 2020; Wilmut, Byrne, & Barnett, 2013).

Regarding children with ASD, a review on reaching and grasping in ASD showed that children with ASD (at different ages) had both increased latency and longer movement durations compared to typically developing (TD) children (Sacrey et al., 2014). Later studies show atypical adjustment of prehension kinematics when grasping objects of different sizes in pre-school children with ASD (Campione, Piazza, Villa, & Molteni, 2016). At early school-age, children with ASD have less connection/chaining of sub-movements in sequential actions (Cattaneo et al., 2007) and less adjustment to ESC (Scharoun & Bryden, 2016) than TD controls. Furthermore, less functional feedforward mechanisms (Fabbri-Destro, Cattaneo, Boria, & Rizzolatti, 2009) and a greater need for movement correction in the later phases of a sequential movement have been reported in younger children with ASD (Forti et al., 2011). However, other results show no differences between children with and without ASD on measures including latency, movement durations, grasp preparation, ESC sensitivity, and chaining of sub-actions (Ansuini, Podda, Battaglia, Veneselli, & Becchio, 2018; Campione et al., 2016; Dowd, McGinley, Taffe, & Rinehart, 2012; Pascolo & Cattarinussi, 2012; van Swieten et al., 2010).

The inconsistences in research findings between different studies could be related to the different ages included, but also to the relatively extensive age range accepted in some studies (e.g. Cattaneo et al., 2007; Mari, Castiello, Marks, Marraffa, & Prior, 2003; Scharoun & Bryden, 2016; Stoit, van Schie, Slaats-Willemse, & Buitelaar, 2013; van Swieten et al., 2010). In support of this observation, a recent study (Rodgers, Travers, & Mason, 2018) showed that motor planning differed between children with ASD and TD children as a function of both age and task complexity. Thus, it is important to investigate aspects of motor planning and execution in

similarly aged children since the interaction between task complexity and child maturation appear to entail dynamic effects on atypical kinematics shown in ASD.

Motor planning ability in children with ASD may also relate to individual variability and the high incidence of neurodevelopmental comorbidities within this group of children. Indeed, recent reports (Cavallo et al., 2018; Foster et al., 2019) have highlighted the importance of research to consider the heterogeneity and individual variability within ASD. General cognitive capability has been shown to influence motor planning and control in some studies of children with ASD (Ansuini et al., 2018; Mari et al., 2003) but not in others (Cavallo et al., 2018). Additionally, deficits in motor memory systems have been suggested to contribute to a range of different sensorimotor impairments described in ASD (Neely et al., 2019).

In the present study, 6-year-old children with ASD and a TD control group matched for sex and non-verbal reasoning abilities performed a manual goal-directed sequential task consisting of several movement steps. The children were instructed to reach for and grasp a semi-circular peg and to transport it to and fit it into a semi-circular goal-slot that was either occluded or visible prior to measurement onset. The orientation of the goal-slot was experimentally manipulated to introduce varying motor planning constraints. The aim was to investigate possible group differences in motor planning and execution kinematics. Further, the purpose was also to explore potential differences in individual variability on the kinematic outcomes and the association between cognitive capabilities and kinematic measures in the ASD group.

We hypothesized that children with ASD would display longer latencies than TD children and that latencies would be shorter in visible compared to occluded conditions for all children. We further expected less movement adjustments to the goal-slot orientations, as expressed by PPV and peak velocity kinematics in the reach-to-grasp and transport phase, and less proactive peg adjustment in the children with ASD compared to the TD children. In relation to movement control and execution, the purpose was to investigate whether differences in movement segmentation and duration would be displayed across the movement phases.

## 2. Methods

### 2.1. Participants

Twelve children with ASD (6 girls; age M = 6.58 SD = 0.4) and 12 TD children (7 girls; age M = 6.58 SD = 0.5) participated in the study. The children with ASD were recruited through hospital records from the Habilitation Centre, Region Västerbotten, Sweden. To be included in the study the child needed to have an ASD diagnosis established within the Swedish public health care system but no established intellectual disability (ID) diagnosis. The TD children were recruited through advertisements in schools located close to the university and by convenience sampling. Further participant information is provided in Table 1.

All participants and parents gave their informed consent. The study was approved by the Umeå Regional Ethical Board registration (nr 2016/365-31) and conducted in accordance with the Declaration of Helsinki.

### 2.2. Preparation for participation

Many children with autism have difficulties with transitions and new environments and exhibit unusual or adverse responses to sensory aspects of the environment (American Psychiatric Association, 2013). To facilitate participation in the unusual setting and methods involved in the present study a child-oriented web-site was created to support familiarization and preparation for the investigation prior to participation. The web-site included photos and short video-clips describing the environment, the researchers, the technical equipment, the task and the routine for the investigation. A link to this web-site was distributed to all parents of participating children and thorough verbal information about the investigation set-up was given as preparation for participation. All

**Table 1**
Descriptive characteristics of the children.

| | ASD (n = 12) | | | TD (n = 12) | | |
|---|---|---|---|---|---|---|
| | *M* | SD | Range | *M* | SD | Range |
| Age | 6y7m | – | 6y0m-7y2m | 6y7m | – | 6y0m-7y4m |
| 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] |
| 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 (all three determined by WISC-V or WPPSI- IV); GEF = %-rank of global executive composite score on BRIEF; MABC-2= Total score on Movement ABC-2 checklist.; EHQ = Laterality index in absolute values determined by Edinburgh handedness questionnaire [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 with $p < .05$ by Mann-Whitney *U* test.

parents were encouraged to visit the web-site together with their child in preparation for participation.

### 2.3. Cognitive measures and parental questionnaires

The cognitive assessment was implemented for research purposes since previous literature raises questions about the relationship between IQ, fluid reasoning and working memory capabilities and motor planning. A licensed psychologist (author AB or ED) assessed intellectual function in twenty of the participants using the Swedish version of the Wechsler Intelligence Scale for Children, fifth edition (WISC-V) (Wechsler, 2014). Three of the children with ASD had within the previous year been assessed in a clinical setting with the Wechsler Preschool and Primary Scale of Intelligence, fourth edition (WPPSI-IV) (Wechsler, 2012). Due to the proximity in time between these clinical assessments and the testing occasion, outcomes from the clinical assessment were used for these three children. One parent to a child with ASD declined participation in the intellectual assessment.

Parents rated their child's hand preference on an age-modified version of the Edinburgh handedness questionnaire (Oldfield, 1971). The scores generated a laterality index, ranging from -1 (consistent left-hand preference) to 1 (consistent right-hand preference), used as a guide to determine which hand (the preferred) that was to be used in the manual goal-directed task. For children with non-established hand preference (scores between −.3 to .3), or no established preference on tasks that usually are highly lateralized (writing/drawing) (Fagard, Chapelain, & Bonnet, 2015), the manual goal-directed task was tried with both hands and the, by the child determined, most comfortable hand was then selected. Within the ASD group, seven children were classified as right-handed, three as left-handed, and two had no clear hand preference. All children in the TD group were classified as right-handed.

To describe the general motor abilities and executive functioning of the included children, the Movement ABC-2 checklist (MABC-2) (Henderson, Sugden, & Barnett, 2007) and the Behavioral Rating Inventory of Executive Function (BRIEF) (Gioia, Isquith, Guy, & Kenworthy, 2000) was filled out by the parents of the participating children (Table 1).

### 2.4. Sequential manual movement task

The children performed a goal-directed sequential manual movement task, transporting a semi-circular (straight side = 2.5 cm) peg from a start-holder to a goal-holder (Fig. 1). The task was presented on a table with individual adjustment of chair height and distance from the table to ensure comfortable task performance. The start- and goal-holders were positioned 25 cm from the hand starting point, horizontally aligned, with a distance of 25 cm between centers. The goal-holder had a centered semi-circular goal-slot which was presented at four different orientations, (0°, 90°, -90° and 180°) relative to the starting orientation of the peg (0°), introducing different motor planning constrains related to ESC. The goal-slot was either presented in full vision before measurement onset (visual condition), or revealed at measurement onset by the, synchronized with optoelectronic measurement onset, mechanical removal of a black cloth covering the goal-holder (occluded condition). For the visual condition, the children were asked to start when a light diode next to the goal-holder was lit. In the occluded condition, the children were asked to start when the cloth covering the goal-holder had been removed and they saw the orientation of the goal-slot.

The children performed the task with their preferred hand (i.e., reversed set-up for left-handed compared with right-handed

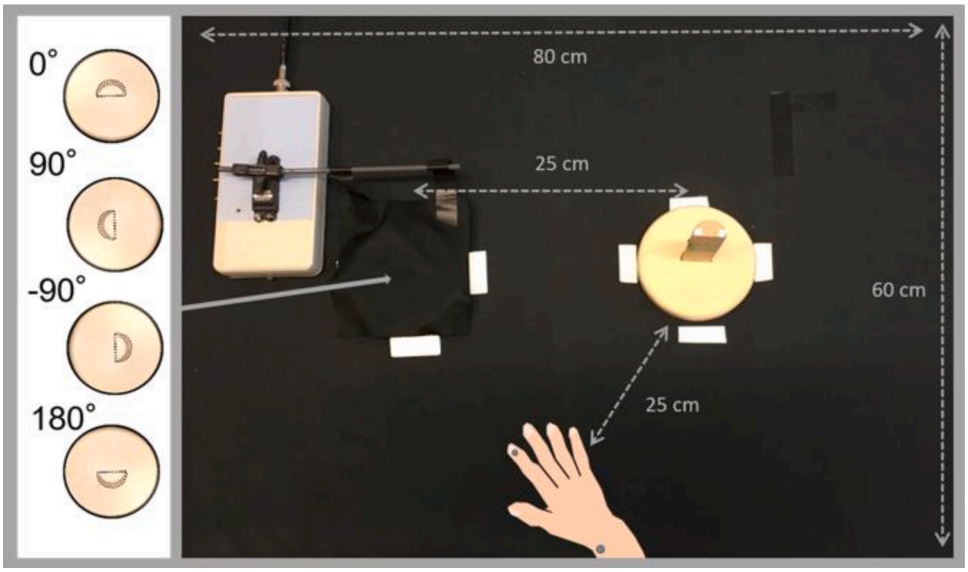


**Fig. 1.** Illustration of the experimental set-up including marker placement for a right-handed child in the occluded condition. The peg is positioned in the start holder to the right, about to be grasped, transported and fitted into the goal-slot (occluded under the cloth to the left) as one of the four different goal-slot orientations (illustrated in the panel to the left) becomes visible.

participants). An initial practice run with all four goal-slot orientations was performed in the visual condition. In the experiment, the children performed three blocks including all four goal-slot orientations, in both the visual and occluded condition (24 trials in total). The order within each block was randomized. Unsuccessful trials (e.g. dropping the peg, taking the peg with the wrong hand) were repeated at the end of respective block (ASD = 37 unsuccessful trials; TD = 11).

### 2.5. Data acquisition

Movements were recorded by a 6-camera optoelectronic system with a sampling frequency of 120 Hz (Qualisys Inc., Gothenburg, Sweden). This technique generates highly accurate quantitative spatio-temporal 3D kinematic data, suitable for studying movement organization and planning in children (Domellöf, Johansson, Farooqi, Domellöf, & Rönnqvist, 2013). The displacement of spherical passive reflective markers affixed to the participants were measured during task performance. An accompanying 2D video recording was made to each trial providing additional information to support data pre-processing. The markers were affixed to the left (radial styloid) side of the wrist (12 mm diameter) and to the index finger (7 mm) on performing hand of the child. The peg had two flat circular markers (5 mm) on each side of the top with a 20 mm centroid distance. One flat circular marker (5 mm) was also fitted in the goal-slot.

### 2.6. Data processing

The 2D information gathered from each camera was combined to 3D data in the Qualisys Track Manager (QTM) software. The QTM software was set to automatically gap-fill small (max 10 frames) 3D occlusions of the markers. All automatic gap-fills were examined and altered if deemed incorrect. Larger gap-fills were manually filled, if possible, and only accepted if inter-judge consensus was reached after visual inspection in the X, Y and Z plane and of the velocity profile.

Goal-directed sequential manual movements may be divided into various sub-phases (i.e., reach-, grasping-, arm transport-, place/release-, phases) (Lavoie et al., 2018; Ossmy, Han, Cheng, Kaplan, & Adolph, 2020). In this study, the task was divided into five movement phases: 1) latency; 2) reach-to-grasp (RTG); 3) grasp; 4) transport; and 5) fitting (Fig. 2). The criteria used for defining the onset and offset of each phase was: Latency (phase 1): Phase onset was set as the measurement start and offset was the frame where the tangential velocity of the wrist marker exceeded 20 mm/s when the child initiated reaching for the peg. RTG (phase 2): Phase onset was defined as the latency offset (phase 1) and offset was when the wrist marker, after the initial touch of peg (identified as a sharp increase in the tangential velocity of the peg markers), reached a low point in velocity that was equal to or below 10 % of the RTG peak velocity. In trials where the wrist marker did not have a velocity reduction to 10 % of the peak velocity, a low point in the velocity profile occurring after peg-touch was used as RTG offset. Grasp (phase 3): Phase onset was the initial touch of the peg and offset was the frame when the peg markers had moved 1 mm upwards in the vertical-plane. Transport (phase 4): Phase onset was defined as grasp offset (phase 3) and offset was the frame when the index finger had reached a low point or plateau in velocity after it had been moved

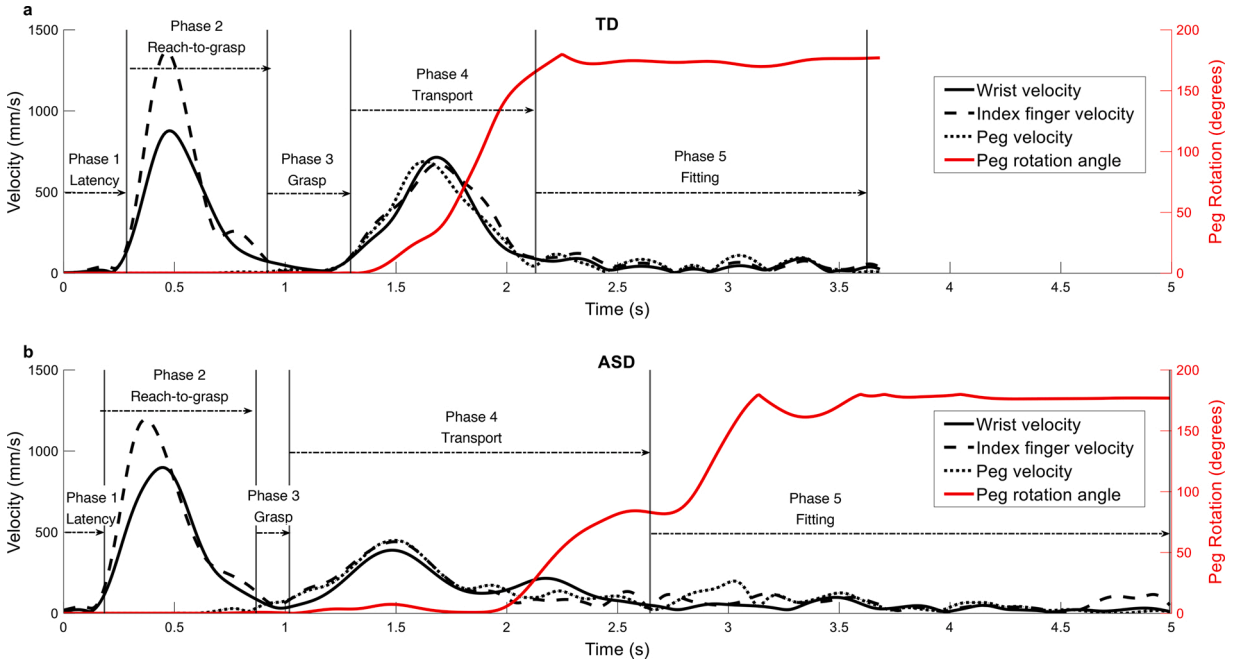


**Fig. 2.** (a-b) Illustration of the movement phases including parameters of interest derived from a 180° orientation trial from (a) a TD child, and (b) a child with ASD. Left y-axis denotes velocity of the wrist, index finger and peg, and right y-axis denotes peg rotation angle.

**Table 2**
Descriptive information of the un-modeled dataset with mean values, median values and mean transformed values for kinematic variables divided by group for each orientation and condition.

| Kinematic variables | Goal orientation | | | | | | | | Condition | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (SD)<br>Median<br>*Transformed mean value (SD)* | | | | | | | | Mean (SD)<br>Median<br>*Transformed mean value (SD)* | | | |
| | 0° | | 90° | | −90° | | 180° | | Visual | | Occluded | |
| | TD | ASD | TD | ASD | TD | ASD | TD | ASD | TD | ASD | TD | ASD |
| Latency (s) | .34(.16) | .55(.44) | .35(.16) | .65(.70) | .39(.24) | .50(.35) | .37(.22) | .59(.58) | .33(.16) | .56(.57) | .39(.23) | .59(.52) |
| | .28 | .38 | .29 | .38 | .31 | .37 | .31 | .34 | .28 | .35 | .31 | .39 |
| | *3.48(1.26)* | *2.84(1.56)* | *3.40(1.39)* | *2.86(1.95)* | *3.21(1.26)* | *2.88(1.48)* | *3.38(1.51)* | *2.91(1.77)* | *3.52(1.36)* | *3.01(1.73)* | *3.20(1.34)* | *2.75(1.68)* |
| **Reach to grasp phase** | | | | | | | | | | | | |
| PPV (%) | 39.22(8.29) | 36.75(10.99) | 36.96(7.50) | 38.28(10.63) | 37.80(7.66) | 33.24(8.23) | 36.13(7.63) | 35.34(11.02) | 37.28(7.63) | 36.25(10.53) | 37.73(8.03) | 35.79(10.48) |
| | 38.18 | 35.71 | 37.14 | 39.08 | 38.22 | 33.96 | 35.14 | 33.98 | 37.05 | 35.25 | 37.31 | 34.59 |
| Peak velocity (mm/s) | 818(127) | 715(178) | 812(191) | 712(157) | 827(175) | 720(190) | 804(172) | 732(188) | 816(179) | 724(171) | 814(177) | 716(183) |
| | 795 | 700 | 784 | 688 | 801 | 714 | 792 | 712 | 801 | 711 | 780 | 691 |
| Duration (s) | .80(.18) | .92(.25) | .81(.25) | .84(.21) | .80(.20) | .92(.30) | .81(23) | .92(.31) | .79(.21) | .89(.26) | .83(.22) | .91(.28) |
| | .75 | .86 | .74 | .83 | .78 | .86 | .78 | .85 | .75 | .85 | .78 | .85 |
| | *-.25(23)* | *-.12(.27)* | *-.26(.28)* | *-.21(.26)* | *-.25(.25)* | *-.14(30)* | *-.23(.26)* | *-.13(31)* | *-.27(.25)* | *-.15(.28)* | *-.22(.25)* | *-.14(.29)* |
| MU | 1.73(.93) | 2.23(1.19) | 1.56(.75) | 1.95(.88) | 1.50(.71) | 2.27(1.08) | 1.77(.85) | 2.30(1.25) | 1.68(.83) | 2.14(1.10) | 1.60(.81) | 2.23(1.14) |
| | 1.00 | 2.00 | 1.00 | 2.00 | 1.00 | 2.00 | 2.00 | 2.00 | 1.00 | 2.00 | 1.00 | 2.00 |
| | *.43(.49)* | *.68(.51)* | *.35(.43)* | *.57(.46)* | *.31(.41)* | *.71(.49)* | *.47(.45)* | *.70(.51)* | *.41(.45)* | *.64(.49)* | *.37(.44)* | *.68(.50)* |
| **Grip phase** | | | | | | | | | | | | |
| Duration (s) | .26(.18) | .42(.39) | .31(.19) | .43(.33) | .34(.25) | .47(.43) | .35(.20) | .40(.35) | .30(.20) | .44(.39) | .33(.22) | .41(.35) |
| | .21 | .29 | .24 | .30 | .25 | .34 | .29 | .28 | .24 | .30 | .25 | .31 |
| | *-1.49(.54)* | *-1.16(.74)* | *-1.34(.56)* | *-1.12(.75)* | *-1.28(.65)* | *-1.06(.75)* | *-1.20(.55)* | *-1.21(.74)* | *-1.36(.56)* | *-1.12(.77)* | *-1.30(.60)* | *-1.16(.72)* |
| MU | .51(.94) | 1.17(1.73) | .58(.84) | 1.28(1.60) | .82(1.14) | 1.49(2.10) | .77(1.07) | 1.27(1.84) | .59(.91) | 1.42(1.85) | .75(1.10) | 1.17(1.77) |
| | .00 | 1.00 | .00 | 1.00 | .00 | 1.00 | .00 | 1.00 | .00 | 1.00 | .00 | 1.00 |
| | *.29(.44)* | *.57(.60)* | *.34(46)* | *.61(.64)* | *.44(.53)* | *.67(.66)* | *.44(.50)* | *.60(.63)* | *.35(.46)* | *.66(.65)* | *.41(.51)* | *.57(.60)* |
| **Transport phase** | | | | | | | | | | | | |
| Residual angle (%) | | | 11.68(18.12) | 29.11(29.36) | 16.21(20.06) | 33.43(25.79) | 25.99(31.54) | 47.61(40.50) | 17.29(25.34) | 34.35(31.17) | 18.79(24.27) | 40.06(36.42) |
| | - | - | 5.08 | 16.73 | 10.17 | 25.14 | 11.40 | 40.40 | 8.39 | 21.75 | 10.64 | 25.46 |
| | | | *2.83(1.94)* | *4.63(2.79)* | *3.43(2.11)* | *5.34(2.25)* | *4.22(2.88)* | *5.99(3.45)* | *3.36(2.46)* | *5.17(2.78)* | *3.63(2.37)* | *5.51(3.14)* |
| PPV (%) | 49.16(10.11) | 48.59(12.98) | 49.89(11.73) | 49.45(12.81) | 47.11(13.50) | 51.70(13.41) | 50.38(15.68) | 48.68(13.72) | 49.01(12.50) | 50.26(13.02) | 49.36(13.43) | 48.76(13.42) |
| | 48.61 | 47.66 | 50.38 | 48.67 | 47.52 | 51.82 | 50.60 | 48.54 | 49.41 | 50.89 | 49.42 | 48.20 |
| Peak velocity (mm/s) | 651(171) | 559(205) | 628(164) | 591(206) | 563(171) | 551(205) | 516(177) | 536(189) | 587(189) | 543(176) | 592(166) | 574(222) |
| | 636 | 533 | 632 | 554 | 553 | 525 | 553 | 495 | 599 | 519 | 588 | 531 |
| Duration (s) | .77(.17) | .93(42) | .82(.38) | .88(.30) | 1.01(.36) | 1.05(.46) | 1.00(.47) | 1.11(.54) | .88(.38) | .99(.45) | .91(.38) | 1.00(.45) |
| | .72 | .86 | .74 | .83 | .93 | .91 | .80 | .98 | *.79* | .89 | .81 | .90 |
| | *-.29(.21)* | *-.14(.37)* | *-.26(.32)* | *-.18(.36)* | *-.04(31)* | *-.03(.39)* | *-.08(.39)* | *.01(.44)* | *-.19(.33)* | *-.09(.39)* | *-.15(.34)* | *-.08(.40)* |
| MU | 1.39(.67) | 1.90(1.40) | 1.76(1.54) | 1.73(.86) | 2.20(1.46) | 2.53(1.48) | 2.48(1.86) | 2.47(1.78) | 1.99(1.63) | 1.99(1.37) | 1.93(1.38) | 2.32(1.53) |
| | 1.00 | 2.00 | 1.00 | 1.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| | *.24(.39)* | *.48(.54)* | *.40(.50)* | *.44(.46)* | *.62(.57)* | *.77(.57)* | *.70(.61)* | *.70(.62)* | *.49(.57)* | *.52(.55)* | *.49(.54)* | *.67(.57)* |
| **Fitting phase** | | | | | | | | | | | | |
| Duration (s) | .74(.32) | 1.12(.67) | .98(.57) | 1.32(.61) | .97(.48) | 1.76(1.00) | 1.68(1.24) | 3.51(5.33) | 1.02(.69) | 1.85(1.59) | 1.19(.94) | 2.11(3.99) |
| | .69 | 1.01 | .89 | 1.35 | .87 | 1.48 | 1.35 | 2.34 | .83 | 1.39 | .91 | 1.45 |
| | *-.39(.42)* | *-.04(.55)* | *-.17(.55)* | *.14(.56)* | *-.14(.47)* | *.41(.58)* | *.28(.72)* | *.86(.83)* | *-.15(.56)* | *.34(.64)* | *-.04(.64)* | *.37(.74)* |
| MU | 4.00(2.07) | 5.76(2.98) | 5.00(3.33) | 6.97(3.38) | 5.00(2.52) | 9.09(4.82) | 9.03(7.37) | 18.90(31.99) | 5.35(4.09) | 9.70(8.77) | 6.28(5.46) | 11.19(23.78) |
| | 4.00 | 5.00 | 4.00 | 7.00 | 4.00 | 8.00 | 7.00 | 12.50 | 4.50 | 7.00 | 5.00 | 7.00 |
| | *1.26(.51)* | *1.62(.52)* | *1.41(.65)* | *1.79(.61)* | *1.49(.50)* | *2.06(.58)* | *1.99(.66)* | *2.45(.81)* | *1.49(.59)* | *2.00(.73)* | *1.59(.70)* | *1.98(.70)* |

*Note*: SD = Standard deviation; PPV = Percentage time to peak velocity; MU = Movement units; TD = Typical development; ASD = Autism spectrum disorder.

into the area of the goal-holder (20 mm from the goal marker in the fronto-parallel plane). Fitting (phase 5): Phase onset was defined as the transport offset (phase 4) and offset was the frame when the tangential velocity of the wrist marker exceeded 60 mm/s in the process of returning the hand to the starting position after the peg had been placed in the goal-holder. All events were identified using unfiltered data. To verify correct identification of the phases, additional inspections of 2D video recordings and 3D marker displacements were made when needed.

After extracting peg rotation data, 55 trials (9.5 % of the total trial amount) were excluded from further processing as the children

**Table 3**
F statistics, p-values and 95 % confidence intervals for the main effects as well as F statistics and p-values for significant interactions.

| Kinematic variable | Fixed effects: Main effects and significant interactions | 95% Confidence interval |
|---|---|---|
| | G: F(1, 24) = 1.53, $p$=.23 | TD:2.76-3.96, ASD:2.24-3.45 |
| **Latency** | O: F(3, 476) = .19, $p$=.91 | 0°:2.67-3.59, 90°:2.64-3.55, -90°:2.69-3.60, 180°:2.57-3.51 |
| | **C: F(1, 476) = 4.65, $p$=.032** | Visual:2.78-3.66, Occluded:2.55-3.42 |
| **Reach to Grasp phase** | | |
| | G: F(1, 24) = 1.45, $p$=.24 | TD:35.44-39.51, ASD:33.70-37.85 |
| PPV | **O: F(3, 494) = 2.62, $p$=.050** | 0°:35.96-39.77, 90°:35.59-39.37, -90°:33.41-37.42, 180°:33.90-37.60 |
| | C: F(1, 491) = .04, $p$=.84 | Visual:34.94-38.16, Occluded:35.08-38.32 |
| | **GxO: F(3, 494) = 2.73, $p$=.043** | |
| | G: F(1, 24) = 3.97, $p$=.058 | TD:749-880, ASD:660-791 |
| Peak velocity | O: F(3, 490) = .53, $p$=.66 | 0°:718-819, 90°:710-810, -90°:731-835, 180°:718-818 |
| | C: F(1, 489) = .02, $p$=.88 | Visual:723-818, Occluded:721-817 |
| | G: F(1, 24) = 1.75, $p$=.20 | TD:-.36- -.13, ASD:-.26- -.02 |
| Duration | O: F(3, 490) = 1.96, $p$=.12 | 0°:-.27- -.09, 90°:-.31- -.14, -90°:-.27- -.09, 180°:-.27- -.09 |
| | C: F(1, 489) = 1.50, $p$=.22 | Visual:-.29- -.12, Occluded:-.27- -.10 |
| | **G: F(1, 24) = 7.43, $p$=.012** | TD:.25-.53, ASD:.51-.80 |
| MU | **O: F(3, 491) = 3.01, $p$=.030** | 0°:.44-.68, 90°:.34-.57, -90°:.37-.61, 180°:.48-.70 |
| | C: F(1, 489) = .16, $p$=.69 | Visual:.43-.64, Occluded:.41-.62 |
| **Grip phase** | | |
| | G: F(1, 24) = 1.78, $p$=.20 | TD:-1.55—1.10, ASD:-1.35–.89 |
| Duration | O: F(3, 503) = 1.72, $p$=.16 | 0°:-1.48—1.13, 90°:-1.42—1.06, -90°:-1.34–.98, 180°:-1.37—1.02 |
| | C: F(1, 503) = .04, $p$=.84 | Visual:-1.40—1.06, Occluded:-1.39—1.05 |
| | G: F(1, 24) = 3.91, $p$=.060 | TD:.20-.56, ASD:.44-81 |
| MU | O: F(3, 504) = 1.51, $p$=.21 | 0°:.30-59, 90°:.33-.61, -90°:.41-.70, 180°: .39-.67 |
| | C: F(1, 503) = .13, $p$=.72 | Visual:.38-.64, Occluded:.36-.63 |
| **Transport phase** | | |
| | **G: F(1, 23) = 19.19, $p$<.001** | TD:2.89-4.10, ASD:4.71-5.96 |
| Residual angle | **O: F(2, 361) = 10.04, $p$<.001** | 90°:3.21-4.30, -90°:3.80-4.96, 180°:4.57-5.65 |
| | C: F(1, 357) = 1.05, $p$=.31 | Visual:3.79-4.78, Occluded:4.05-5.04 |
| | G: F(1, 24) = .04, $p$=.85 | TD:46.31-51.90, ASD:46.64-52.31 |
| PPV | O: F(3, 506) = .08, $p$=.97 | 0°:46.21-51.57, 90°:46.74-52.03, -90°:46.99-52.20, 180°:46.54-52.07 |
| | C: F(1, 503) = .16, $p$=.69 | Visual:47.28-51.73, Occluded:46.84-51.32 |
| | G: F(1, 24) = .88, $p$=.36 | TD:529-650, ASD:489-610 |
| Peak velocity | **O: F(3, 503) = 8,63, $p$<.001** | 0°:552-649, 90°:558-654, -90°:497-595, 180°:478-574 |
| | C: F(1, 502) = 2.19, $p$=.14 | Visual:515-604, Occluded:535-625 |
| | **GxO: F(3, 503) = 3,07, $p$=.028** | |
| | G: F(1, 24) = .96, $p$=.34 | TD:-.31–.02, ASD:-.22–.07 |
| Duration | **O: F(3, 502) = 18,98, $p$<.001** | 0°:-.31–.09, 90°:-.32–.11, -90°:-.14-.08, 180°:-.15-.07 |
| | C: F(1, 502) = .44, $p$=.51 | Visual:-.23–.02, Occluded:-.22–.01 |
| | G: F(1, 24) = 1.22, $p$=.28 | TD:.34-.65, ASD:.45-.76 |
| MU | **O: F(3, 503) = 17.24, $p$<.001** | 0°:.25-.51, 90°:.30-.55, -90°: .56-.82, 180°:.58-.83 |
| | C: F(1, 502) = 2.14, $p$=.14 | Visual:.41-.64, Occluded:.47-.70 |
| | **GxC: F(1, 502) = 4.65, $p$=.032** | |
| **Fitting phase** | | |
| | **G: F(1, 23) = 22,39, $p$<.001** | TD:-.25-.04, ASD:.21-.50 |
| Duration | **O: F(3, 503) = 48,15, $p$<.001** | 0°:-.34–.08, 90°:-.14-.12, -90°:.01-.28, 180°:.45-.70 |
| | C: F(1, 502) = .78, $p$=.38 | Visual:-.01-.22, Occluded:.04-.26 |
| | **G: F(1, 23) = 19.47, $p$<.001** | TD:1.38-1.70, ASD:1.85-2.16 |
| MU | **O: F(3, 503) = 47.46, $p$<.001** | 0°:1.31-1.59, 90°:1.47-1.74, -90°:1.64-1.92, 180°:2.11-2.38 |
| | C: F(1, 501) = .35, $p$=.55 | Visual:1.63-1.87, Occluded:1.66-1.90 |

*Note*: PPV = Percentage time to peak velocity; MU = Movement units; G = Group; O = Orientation; C = Condition; TD = Typical development; ASD = Autism spectrum disorder.

during the transport phase (phase 4) had rotated the peg incorrectly to the goal-slot orientation, i.e., the action was planned to a different goal-slot orientation than the actual, and subsequently had to correct this error when at the goal. Thirty-nine of these excluded trials (71 %) came from the children with ASD (0° = 9, 90° = 9, -90° = 21) and 16 (29 %) from the TD children (0° = 8, 90° = 3, −90° = 5). Additionally, partial parameter data in 46 trials were excluded from further analysis due to missing data.

### 2.7. Outcome variables

Kinematic data was smoothed with a forward and reversed 6 Hz Butterworth filter to a resulting order of 4 and outcomes were extracted using customized MATLAB (The Mathworks Inc.) scripts. Based on previous literature, outcomes related to motor planning were identified as: latency (the duration of phase 1); PPV of the wrist (frame of peak velocity/ total number of frames in the phase x 100) in both the RTG (phase 2) and the transport phase (phase 4); wrist movement peak velocity in the RTG (phase 2) and transport phase (phase 4); residual angle (RA), defined as the relative difference between peg rotation angle at the end of the transport phase (phase 4) and the angle of the goal-slot orientation (remaining percentage to a goal-slot angular orientation match) in the 90°, −90° and 180° orientations. Lower RA indicates peg-rotation during the action preceding fitting. Outcomes related to motor execution and movement control were movement durations and wrist movement segmentation in terms of number of movement units (MU; defined as an accumulated increase and decrease in velocity of at least 20 mm/s with an acceleration or deceleration exceeding 5 mm/s$^2$; von Hofsten, 1991) extracted for all five phases, respectively.

To explore associations between cognitive capabilities and kinematic measures individual phase-specific means of each kinematic variable were calculated, except for MU and movement duration where means of the whole movement were calculated. Individual SDs derived from these mean calculations were then used as a measure of trial-to-trial intra-individual variability.

### 2.8. Statistical analyses

Linear mixed effects models were used to test for fixed effect differences of: Group (ASD vs. TD); goal-slot orientation (0°; 90°; -90°; 180°); and visual condition (visual vs. occluded) for the extracted kinematic variables of interest using SPSS (version 26). The trials were clustered within participant and a random effect for participant was included in each model. Follow-up pairwise comparisons were made for significant main effects with Bonferroni correction. Interaction effects were followed up with designated linear mixed effects models of the interacting factors. Effect sizes (corresponding to Cohen's $f^2$) was calculated by $f^2 = \frac{R_2^2 - R_1^2}{1 - R_2^2}$ where variance explained by the full model is represented by $R_2^2$ and $R_1^2$ represents the variance explained by the model without the independent variable of interest (see Lorah, 2018 for specifics). Several outcomes were transformed to improve normality: latency was transformed using a reciprocal transformation (1/x), RA with a square root transformation ($\sqrt{x}$) and duration and MU data were transformed using the natural logarithm (Ln(x)), and for MUs in the grasp phase (phase 3), Ln(x+1) was used. For variables not fully meeting assumptions of normality, results were verified without multivariate outliers.

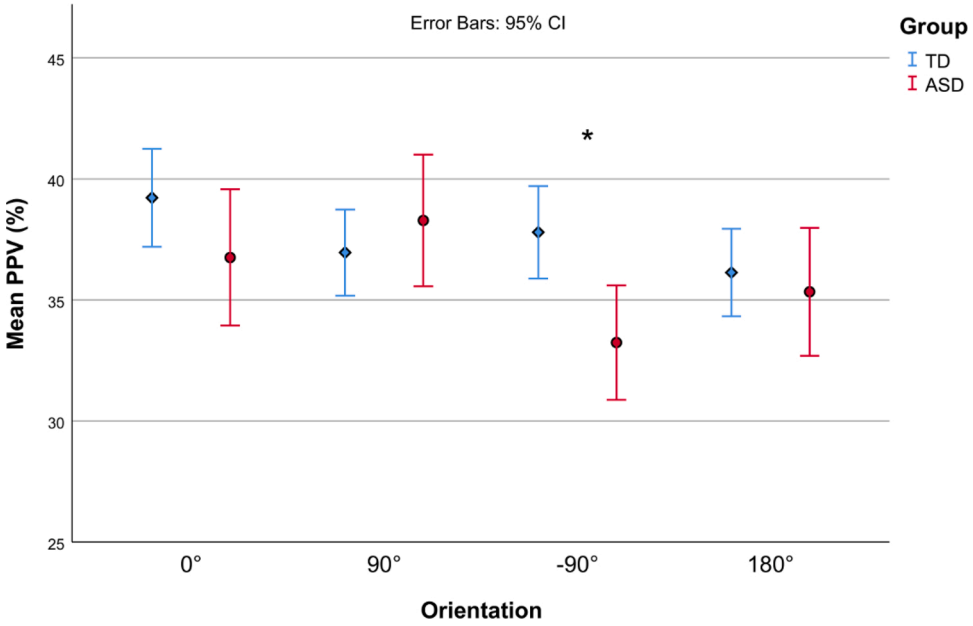


**Fig. 3.** Mean percentage time to peak velocity (PPV) during reach-to-grasp as a function of orientation for the respective group. Note: The Y axis range has been adjusted to enlarge the illustration of the data and facilitate visual examination. TD = Typical development (◊); ASD = Autism spectrum disorder (○); PPV = Percentage time to peak velocity; CI = Confidence interval. *p < .05.

Group (ASD vs. TD) differences in intra-individual variability were tested using Mann-Whitney U Tests. Effect sizes were calculated by dividing the ranked Z-score by the square root of N ($r = Z / \sqrt{N}$). Further, associations between means of each kinematic outcome and full scale intelligence quotient (FSIQ), fluid reasoning index (FRI) and working memory index (WMI) were described in the ASD group using Spearman's correlation.

## 3. Results

Table 2 presents descriptive information about the un-modeled data including mean values with SD, median values and mean transformed values for kinematic parameters split by group for each orientation and condition.

Table 3 presents F statistics, p-values and 95 % confidence intervals for the main kinematic effects, and F statistics and p-values for significant interactions.

### 3.1. Latency

There was a main effect of visual condition ($p$=.032, $f^2$ = .011) with increased latency durations when the goal was occluded prior to start than when it was visible. The significance of the effect did not remain when multivariate outliers were removed ($p$=.059).

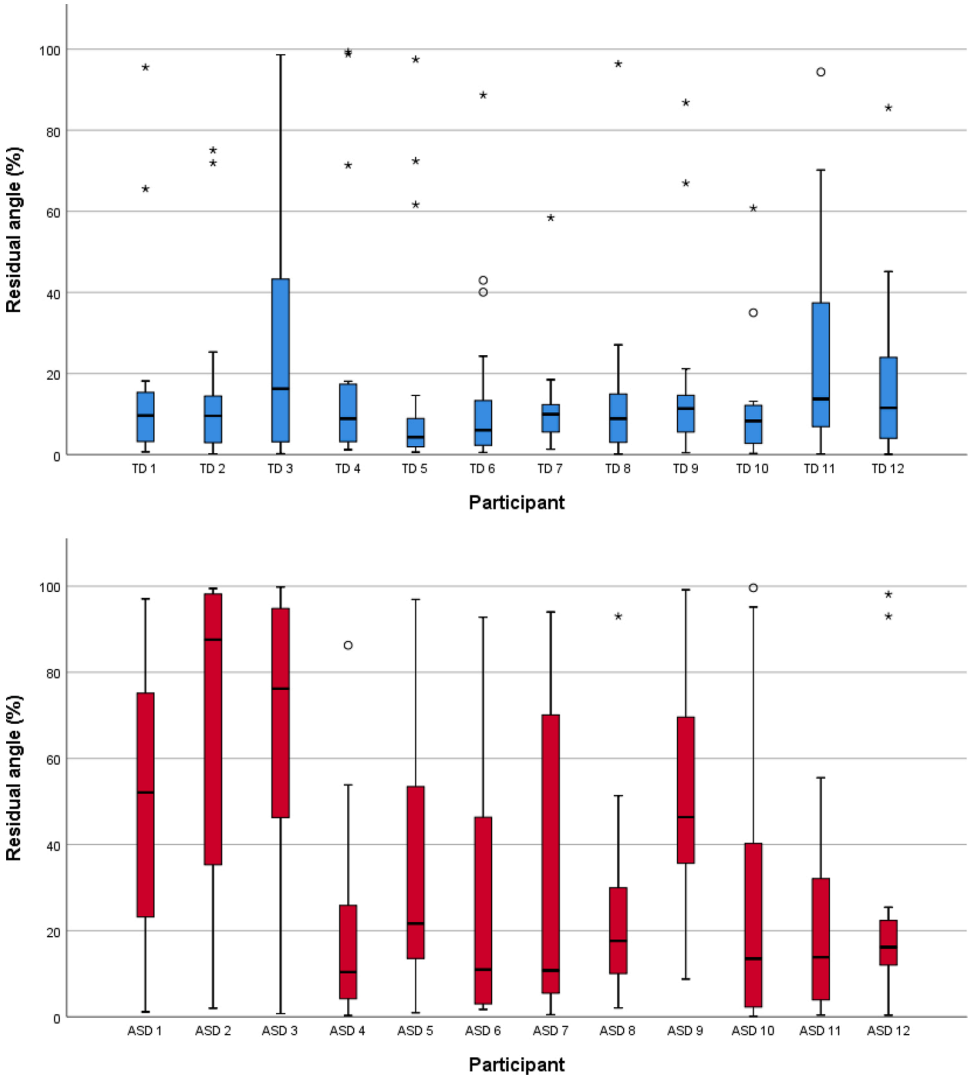


**Fig. 4.** Individual boxplots of the residual angle (RA) for the respective group. Note: TD = Child with typical development (blue); ASD = Child with autism spectrum disorder (red); Fluid reasoning index performance below average for participant ASD 1-3. Boxes denote first-third quartile, solid line indicates median, and whiskers 1,5*interquartile range.

### 3.2. Percentage time to peak velocity (PPV)

A borderline main effect for goal-slot orientation ($p$=.050, $f^2$ = .049) was found for the PPV in the RTG phase. Follow-up pairwise comparisons showed no significant difference between any of the four orientations, but a pattern of lower PPV's in the -90° and 180° compared to the 0° and 90° goal-slot orientations (Table 3). A significant interaction between group and goal-slot orientation ($p$=.043) was found. Follow-up analyses showed a significant ($p$=.028) group difference for the -90° orientation where the ASD group had lower

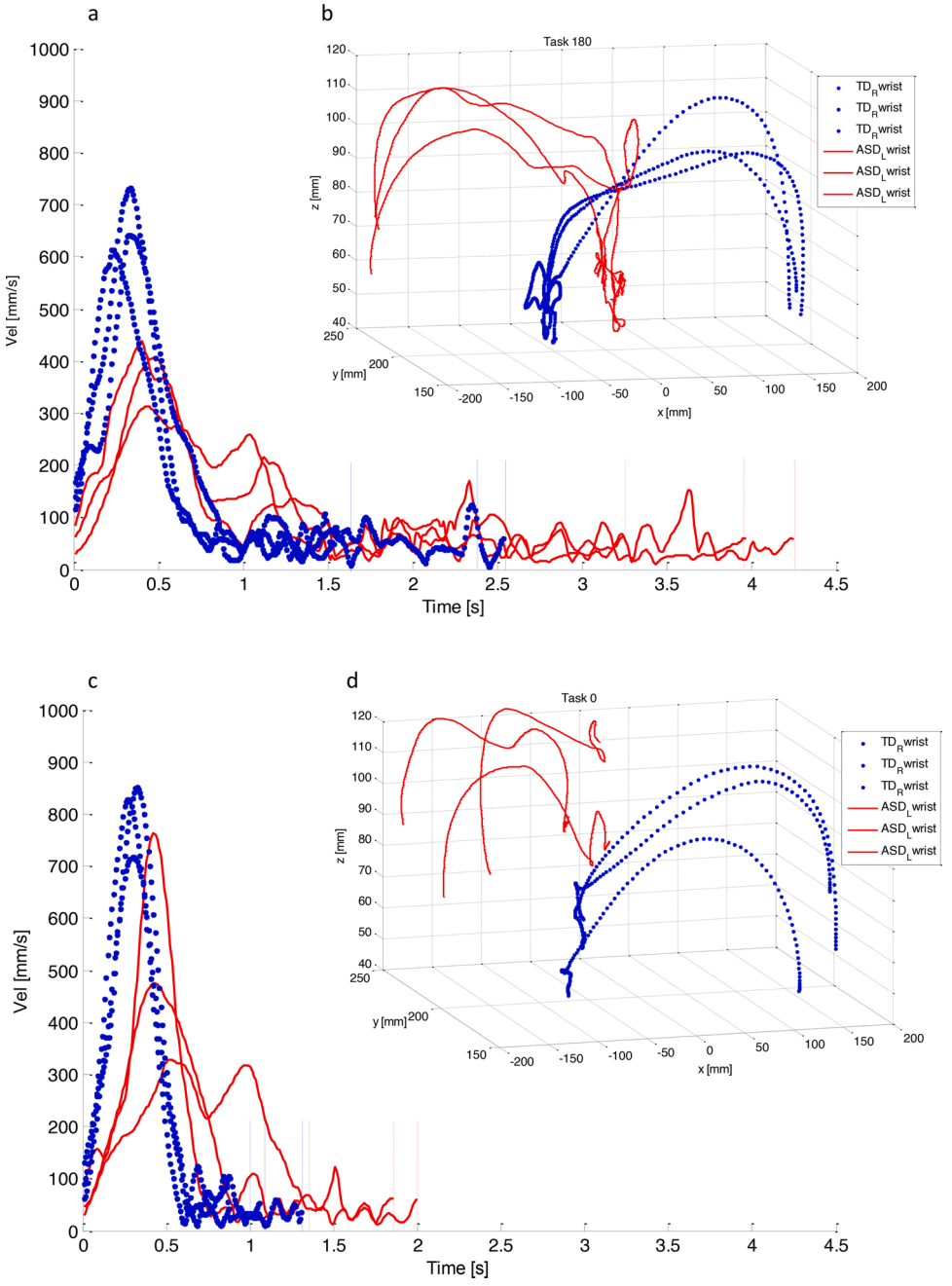


**Fig. 5.** (a-d) Examples of the wrist marker velocity profiles of three 180° (5a) and 0° (5c) orientation trials and the corresponding 3D movements profiles (5b,d) for the transport plus the fitting phase (phase 4-5, see Fig. 2) extracted from the occluded condition. The figures include three trials performed by the same two children, one TD child (right-handed) and one child with ASD (left-handed), superimposed in the same figure. The dashed vertical lines in the velocity profiles indicate the end of the respective fitting phase (the first three lines are from the TD child performances independent of task). The X- and Y-axis are adjusted to the same sizes for comparison between the two children (TD vs. ASD) and between respective task (180° vs. 0°).

PPV values than the TD group (Fig. 3).

No significant main effects of group, orientation nor condition were found for the PPV in the transport phase.

### 3.3. Peak velocity

No main effects of group, orientation nor condition was found for the wrist peak velocity in the RTG phase.

In the transport phase, a main effect of goal-slot orientation ($p < .001$, $f^2 = .062$) and a significant interaction between group and goal-slot orientation ($p = .028$) was found for wrist peak velocity. Pairwise comparisons of the main effect of goal-slot orientation showed that the children had lower peak velocities in the -90° and 180° compared with the 0° and 90° goal-slot orientations. Follow-up within-group analyses of the interaction effect showed that goal-slot orientation differences in wrist peak velocity were only significant for the TD group ($p < .001$). Further, between group differences were only evident in the 0° goal-slot orientation where the ASD group had significantly lower peak velocities ($p = .021$) compared to the TD group.

### 3.4. Residual angle (RA)

A significant main effect of group ($p < .001$, $f^2 = .131$) and goal-slot orientation ($p < .001$, $f^2 = .054$) was found for RA. The ASD group showed higher RA percentages compared with the TD group (Fig. 4 show individual performance in respective group). Follow-up pairwise comparison between the goal-slot orientations showed higher RA percentages on the 180° compared to the 90° goal-slot orientation.

### 3.5. Movement units (MU)

Analyses of movement segmentation in the separate phases showed a significant main effect of group ($p = .012$, $f^2 = .099$) and goal-slot orientation ($p = .030$, $f^2 = .025$) for MU in the RTG phase. The children with ASD had more MUs compared with TD children. Pairwise comparison between the goal-slot orientations showed that the children overall had more MUs in the 180° than in the 90° goal-slot orientation.

No significant main effects for group, orientation nor condition was found for MUs in the grip phase.

A significant main effect of goal-slot orientation ($p < .001$, $f^2 = .099$) and interaction between group and visual condition ($p = .032$) was found for MUs in the transport phase. Pairwise comparison of the different goal-slot orientations showed that the children overall had more MUs in the 180° and −90° compared with the 90° and 0° goal-slot orientations. Further, the children with ASD had more MUs in the occluded condition compared to the visible condition ($p = .022$) in the transport phase. No difference between conditions was found among TD children.

A significant main effect of group ($p < .001$, $f^2 = .160$) and goal-slot orientation ($p < .001$, $f^2 = .249$) was found for MUs in the fitting phase, where the children with ASD had more MUs compared to the TD children. Pairwise comparison between the different goal-slot orientations showed that the children over all had more MUs in the 180° compared to all other goal-slot orientations as well as more MUs in the -90° compared to the 0° goal-slot orientation.

### 3.6. Movement duration

Analyses of the duration of the separate phases showed no significant main effects of group, orientation nor condition in the RTG or grip phase.

A main effect of goal-slot orientation was found ($p < .001$, $f^2 = .081$) in the transport phase where pairwise comparison showed that the children had longer movement durations for 180° and −90° compared to 90° and 0° goal-slot orientations.

A main effect of group ($p < .001$, $f^2 = .168$) and goal-slot orientation was found ($p < .001$, $f^2 = .256$) for duration in the fitting phase where the ASD group showed longer movement durations compared to the TD group. Pairwise comparison between goal-slot orientations showed that the children had shorter movement durations in the 0° compared to all other goal-slot orientations and the longest movement durations were obtained in the 180° compared to all other goal-slot orientations. Movement durations in the 90° and -90° goal-slot orientation did not differ significantly from each other.

In Fig. 5 the velocity and the corresponding 3D profiles from the transport and the fitting phase of three 180° and 0° goal-slot orientation trials of a TD child and a child with ASD is exemplified.

### 3.7. Intra-individual variation

The ASD group had higher intra-individual variation than the TD group on the following outcomes: latency ($U = 35$, $p = .035$, $r = 0.43$: [ASD *Mdn* = 0.27; range = 0.039–1.08],[TD *Mdn* = 0.13; range = 0.037−0.30); PPV in the RTG phase ($U = 29$, $p = .014$, $r = 0.50$: [ASD *Mdn* = 9.27; range = 6.31–15.39],[TD *Mdn* = 6.52 ; range = 4.20–11.12]); RA ($U = 35$, $p = .035$, $r = 0.43$: [ASD *Mdn* = 32.32; range = 17.50–37.11],[TD *Mdn* = 23.0; range = 13.23–35.04]); total movement duration ($U = 25$, $p = .007$, $r = 0.55$: [ASD *Mdn* = 1.4; range = 0.80–9.11],[TD *Mdn* = 0.67; range = 0.47–1.55]); total MUs ($U = 27$, $p = .010$, $r = 0.52$: [ASD *Mdn* = 6.65; range = 4.28–54.77],[TD *Mdn* = 3.42; range = 2.17–10.09]).

### 3.8. Associations between kinematic and cognitive measures

Within the ASD group, significant correlations were evident between: Mean RA and FSIQ ($r_s$=−.64, $p$=.034); Mean RA and FRI ($r_s$=−.63, $p$=.038); WMI and total MUs ($r_s$=−.71, $p$=.023); and WMI and total movement duration ($r_s$=−.78, $p$=.008).

## 4. Discussion

In line with our expectations, the results showed that children with ASD displayed less proficient motor planning performance and more segmented movements than TD children. The most striking result was that the children with ASD had less proactive peg-adjustment compared to TD children. Movement execution difficulties in the ASD group was primarily displayed at the end of the sequential movement, i.e. in the fitting phase. This is most likely related to less optimal motor planning. Intra-individual variability was also higher in the ASD group on both movement execution and planning measures, affecting overall performance (Fig. 4). Unexpectedly, no group difference in latency was evident, although intra-individual variability was higher in the ASD than TD group. Furthermore, outcomes related to motor planning were associated with cognitive capabilities in the ASD group, supporting the suggestion that difficulties with motor memory may contribute to sensorimotor impairments in ASD (Neely et al., 2019).

The distribution of the feedforward and feedback mechanisms in the RTG phase (phase 2) was operationalized by the PPV. The different goal-slot orientations induced reaching movements with various proportions of visual control. Greater need for feedback processing, indicated by longer relative deceleration phases (lower PPV), was evident for the more extreme orientations. In line with previous findings (Forti et al., 2011), no overall group difference was found for PPV in the RTG phase. An interpretation is that younger children generally have more segmented movements and depend more on feedback control processes guiding prehension movement in this type of sequential task (Domellöf et al., 2020). Motor planning problems in young children with ASD might therefore become evident later in the sequential movement, an argument supported by previous observations (Forti et al., 2011). However, the groups differed on the -90° orientation, where the ASD group displayed greater dependence on feedback control processes (lower PPV) than the TD group. It is possible that this orientation requires a more unusual movement and may thus induce greater demands on perceptual processing and flexible motor planning, both specifically problematic in ASD (Hannant, Tavassoli, & Cassidy, 2016; Rodgers et al., 2018). The number of −90° orientation trials excluded in the ASD group due to execution of the wrong rotation further supports this interpretation. Moreover, Krajenbrink et al. (2020) showed that motor planning accuracy is affected by how unusual a movement is.

The difference in number of MUs found between 180° and 90° orientation in the RTG phase suggests a more comfortable grip preparation relative to the less complex goal orientation across groups. However, in general, the ASD group showed more wrist MUs than TD during RTG, indicating generally more awkward planning of the grip.

In line with previous research (Campione et al., 2016) we found no difference for RTG peak velocities. However, in the ASD group, an interaction effect was found on transport peak velocities with less discrimination between end-point orientations in accordance with our hypothesis and previous findings (Forti et al., 2011). The TD group showed anticipation of the final goal, with slower movement velocity for the more difficult goal-slot orientations. No such anticipatory velocity adjustment was shown in the ASD group.

Fitting the peg optimally into the goal-slot was at the core of the action. As hypothesized, compared to TD children, the children with ASD showed less proactive peg adjustment to the goal-slot orientations, indicating motor planning difficulties. The RA was in general <20 % in the TD children, in agreement with previous studies (Domellöf et al., 2020). For the ASD group, the RA range was 20–60 % with large intra-individual variability (Fig. 4). Pro-activity in grip formation and adjustment of object orientation have previously been used as measures of motor planning, with outcomes showing a developmental progression in the coordination of translations and rotations when fitting objects into apertures (Domellöf et al., 2020; Jung et al., 2018; Örnkloo & von Hofsten, 2007). Hence, the less coordinated translation and rotation (i.e. first transporting the peg to the goal location and then, in a more secondary process, rotating it to fit the goal orientation) in the children with ASD reflect more fragmented movements compared to the TD group.

The ability to generate rapid and efficient movements is very important in daily life. It is crucial in relation to timing, and it can be frustrating in daily activities if movements are slow and inefficient. A frequent finding in the literature is that individuals with ASD have longer movement durations (Sacrey et al., 2014). Less is known about how movement organization influences movement durations in sequential goal-directed actions. Our results showed no group differences in movement durations in neither the RTG, grip, nor transport phase. It was only in the fitting phase that movement duration was longer for the ASD group compared to the TD group. The ASD group also displayed more MUs in the fitting phase compared to the TD group, indicating less efficient fitting of the peg into the goal. These results add support to ideas that aspects of movement planning, rather than motor processing, underlie movement execution deficits in ASD (Zheng et al., 2019). In contrast to findings by Fabbri-Destro et al. (2009), goal-slot orientation did not influence reaching or grasping times in any of the groups. Longer movement duration was only evident for the larger orientation angles in the transport and fitting phases, where also differences in MUs were evident. Inconsistencies with previous findings might be related to age-range, since dynamic effects of task complexity and maturation have been shown for movement duration in ASD (Rodgers et al., 2018).

Longer latencies can be expected as a response to increased task complexity (Krajenbrink et al., 2020) as more complex actions require more time to plan, form and select an action plan. In ASD, increased latencies have been shown (Sacrey et al., 2014), although findings are conflicting (Dowd et al., 2012; Stoit et al., 2013). We found no between-group difference in latency, although greater intra-individual variation in ASD than TD. A lack of latency effects in young children could be related to immature inhibitory mechanisms (Domellöf & Säfström, 2020; Domellöf et al., 2020) and developmentally related to compensatory strategies in older children with ASD (Rodgers et al., 2018). The increased rotation-errors in the ASD group (71 % of exclusions) could indicate less

inhibitory control. In further support of inhibition difficulties, the ASD group showed more MUs in the occluded condition during transport. In line with our hypothesis, the overall shorter latencies in the visible condition indicate that some non-motor aspects of movement and/or executive planning could be accounted for before measurement onset across both child groups. The effect was however weak.

Furthermore, the children with ASD showed less consistent performance, shifting between inefficient and efficient movements, leading to less efficient general performance compared to the TD group (Fig. 4). This suggests that generalization difficulties associated with ASD not only affect higher cognitive abilities such as social skills (Brown & Bebko, 2012) but also more basic functions such as motor planning and the ability to generalize efficient movement strategies. In line with previous research (Ansuini et al., 2018), motor planning functioning was also linked to cognitive capabilities in the children with ASD. Elevated motor planning difficulties was found for ASD children with below average FSIQ/fluid reasoning performance level, however, this relation alone did not cause the significant group differences. It is important to note that the range in cognitive performance indicates that no children with more moderate/severe cognitive disability were included in the study and this probably affects the results in term of performance proficiency. Stronger working memory abilities were associated with fewer MUs and shorter movement duration in the ASD group. These results support the suggestion that difficulties with consolidation or retrieval of motor memory representations may contribute to sensorimotor impairments in ASD (Neely et al., 2019). Taken together, the results indicate that while younger children with ASD plan and adjust movement execution in relation to the goal to some extent, they do not modulate their initial movements to the extent needed for rapid and efficient goal fitting movements.

The relatively small sample size together with the typically observed neurodiversity in the group of children with ASD (Table 1) may affect the generalizability of the findings presented here. In addition, the present study cannot give information if described atypical motor planning in sequential movements is specific for ASD or shared with other neurodevelopmental conditions. Intellectual disability is frequent in the ASD population. The groups of children in the present study, however, have matching non-verbal reasoning abilities, limiting the influence of more profound cognitive delay on the results. The role of executive and general motor abilities in predicting kinematic performances was not tested as it goes beyond the objective of the present study, but would be an interesting issue for further studies. Future research involving larger samples, preferably also child groups with diverse neurodevelopmental difficulties, is needed to corroborate the present findings and tell whether they are specific for ASD.

## 5. Conclusion

In this study, the children with ASD showed impairments compared with TD children in their ability to plan and execute sequential goal-directed manual actions. Movement execution difficulties were mainly manifested toward the end of the goal-directed action, probably linked to reduced motor planning related to the end-point goal. The results further highlight that even though most of the children with ASD had occurrences of equally proficient performance as TD children, they showed less stable performance on several kinematic variables, indicating difficulties with motor memory representations and motor planning. A majority of manual actions consist of sequential movements. The challenges with such actions are evident for the children with ASD, and can in part explain the everyday motor problems encountered. Our results stress the importance of investigating motor planning and action performance difficulties/diversity in developing children with ASD using detailed measurement technology. Apart from potential clinical importance, this may also have implications for theories on predictive impairment as a salient mechanism in ASD.

## Declaration of Competing Interest

The authors report no declarations of interest.

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