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Development of motor planning in children: Disentangling elements of the planning process



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ABSTRACT

Second-order motor planning of grasping movements is usually measured using tasks that focus on the relative (dis)comfort of end posture of the arm and hand regardless of the objective outcome of performance. This may underestimate the ability for forward planning in young children. In the current study, we aimed to examine the developmental mechanisms of motor planning in children using a task that necessitates second-order motor planning for its successful completion. We tested 311 children (aged 5–12 years) who were instructed to grasp and rotate a hexagonal knob over 60°, 120°, 180°, or 240°. The 180° and 240° rotation conditions necessitated adjustment of the preferred start grip for successful task completion. We examined successful or unsuccessful task completion, reaction time (RT), and movement time (MT) as a function of task demands (i.e., rotation angle) and age. Results showed that most children of all ages were able to successfully complete the task in the 180° rotation condition. In the most demanding 240° rotation condition, many children had difficulty in completing the task, but successful task completion increased with age. Time course analysis showed increased RT and MT with increasing task demands. Furthermore, whereas RT decreased with age for each rotation angle, MT remained stable with the exception of an increase in MT for the most demanding rotation condition. Together, these results exemplify that children aged 5–12 years are indeed able to engage in forward planning.

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With development, second-order motor planning proficiency increases, especially for more demanding movements, and the process becomes more efficient.

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Introduction

Motor planning is an important aspect of everyday motor behavior, underpinning much of the action repertoire of healthy individuals (Rosenbaum, Meulenbroek, & Vaughan, 2004). A key aspect of motor planning and control is the ability to anticipate the end of an upcoming action prior to commencing a movement (Johnson-Frey, McCarty, & Keen, 2004). In the case of manual actions such as reaching and grasping an object, the grasp is adapted not only to the characteristics of the object such as the shape (i.e., *first-order planning*) but also to the requirements of the subsequent action (i.e., *second-order planning*). Adults have the tendency to sacrifice comfort of the start posture to finish a task with the hand and arm in a biomechanically efficient and comfortable end posture, the *end-state comfort* (ESC) effect (Rosenbaum & Jorgensen, 1992). The ESC effect is taken as an indicator of second-order motor planning and thereby a mature feedforward or internal modeling system (Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012; Wolpert, 1997). As such, the reduced tendency of children to show ESC has been taken as an indicator of an immature internal modeling system (Fuelscher et al., 2016). However, in many of the tasks used, children are also able to successfully achieve the required task goal without adopting a comfortable end posture. Therefore it might not have been valid to infer immaturity of second-order planning ability from a reduced ESC strategy in these tasks (Adams, 2017). Young children may have been using an alternative strategy. In the current study, we examined the development of second-order motor planning in children using a task that necessitates second-order motor planning for its successful completion. In addition to successful or unsuccessful goal achievement, we examined reaction time (RT) and movement time (MT) to study the effects of movement demands on the motor planning process.

Current neurocomputational theories of motor control state that when an action is planned in advance, the motor parameters related to the action such as orientation, velocity, and force constitute a feedforward model (Kawato, 1999; Wolpert, 1997). The motor system generates a feedforward model of the prospective action that includes parameter estimates of its likely sensory consequences. The mechanism to monitor whether an action is unfolding as planned involves a comparison between the actual sensory feedback and the predicted feedforward model, with the resultant error signals used for real-time updating of the movement. This occurs with minimal latency, well before slow sensorimotor feedback becomes available. In addition, following this online modification of the unfolding movement, the error-based feedback is used to change and refine the subsequent feedforward models that are formed over repeated trials or learning experiences (Wolpert & Ghahramani, 2000).

It is believed that accurate feedforward models of movements are important for successful performance on tasks that examine second-order motor planning and that these models mature during development (Caeyenberghs, Wilson, van Roon, Swinnen, & Smits-Engelsman, 2009; Ruddock et al., 2016). Indeed, increased incidence of second-order motor planning that has been observed with age over childhood (e.g., Jongbloed-Pereboom, Nijhuis-van der Sanden, Saraber-Schiphorst, Craje, & Steenbergen, 2013; Smyth & Mason, 1997; Stöckel, Hughes, & Schack, 2012; Thibaut & Toussaint, 2010; Wunsch, Pfister, Henning, Aschersleben, & Weigelt, 2016) has been linked to the maturation of the feedforward or internal modeling system and the related capacity to represent action internally known as motor imagery (Fuelscher, Williams, Wilmut, Enticott, & Hyde, 2016; Toussaint, Tahej, Thibaut, Possamai, & Badets, 2013).

Others have hypothesized that it might not be valid to infer immaturity in second-order motor planning ability when ESC is not observed. Children are able to successfully complete the most frequently used motor planning tasks without adopting a comfortable end posture (Adams, 2017).

Moreover, children might not experience extreme joint angles as uncomfortable in the manner adults do, which may influence the expression of ESC (Rosenbaum, Herbort, van der Wel, & Weiss, 2014). This is supported by data showing reduced ESC effects for tasks that require a more complex start posture to achieve ESC (Jongbloed-Pereboom, Spruijt, Nijhuis-van der Sanden, & Steenbergen, 2016; Knudsen, Henning, Wunsch, Weigelt, & Aschersleben, 2012; Wunsch, Pfister, Henning, Aschersleben, & Weigelt, 2016). For example, Jongbloed-Pereboom et al. (2016) compared the performances of children, adolescents, and adults on three tasks: the cup task, the bar transport task, and the sword task. Results showed that the observed percentage of ESC was task dependent—highest for the cup task, followed by the bar transport task, and lastly the sword task. These differences in tendency to plan for ESC among tasks may be explained by variation in initial grip comfort, as illustrated in Fig. 1. Selecting a grip that maximizes ESC is efficient only in the event that the biomechanical costs of a difficult start posture are not excessive. Thus, depending on individual preferences with regard to subjective (dis-)comfort of the start and end postures, children could plan for the easiest start posture instead of planning for ESC. The potential role of grip types and related motor requirements for ESC planning had been highlighted before (Jovanovic & Schwarzer, 2017). This raises the question of whether the outcomes on these motor planning tasks are a good representation of children's motor planning ability. This issue was addressed in the current study by including two critical conditions that children cannot complete successfully without first planning for end state, reducing the role of their subjective (dis-)comfort.

Focusing on end state, as done in previous studies (e.g., Wunsch, Henning, Aschersleben, & Weigelt, 2013), provides a window into second-order motor planning and can be complemented by measures of the time course of the movement up to the point of object contact and manipulation (Mutsaerts, Steenbergen, & Bekkering, 2005). The time course of a reaching movement can be divided into and analyzed by two different components: (a) RT or preparation time, defined by the interval between the stimulus onset and the start of the reach, and (b) MT, defined by the interval between the start of the reach and first object contact and manipulation. In general, more demanding movements result in longer preparation time compared with less demanding movements (Klapp, 1995). By examining the effects of different task constraints on these two time events, we can make inferences about whether the feedforward model is a complete parametrization of the movement before a reaching movement starts or whether the feedforward model needs to be corrected online during the reaching movement.

Several studies have examined the influence of task demands, focusing on the time course of a reaching movement (e.g., Mutsaerts et al., 2005; Rosenbaum, Vaughan, Barnes, & Jorgensen, 1992; Seegelke, Hughes, Knoblauch, & Schack, 2013). Mutsaerts et al. (2005), for example, used a hexagonal knob task (HKT) in which participants needed to rotate a knob either 60° or 120° using a pre-instructed grasping pattern. For healthy participants, they found an effect of rotation angle on RT only and not on subsequent MT. Thus, the feedforward model appeared to be a complete parameterization

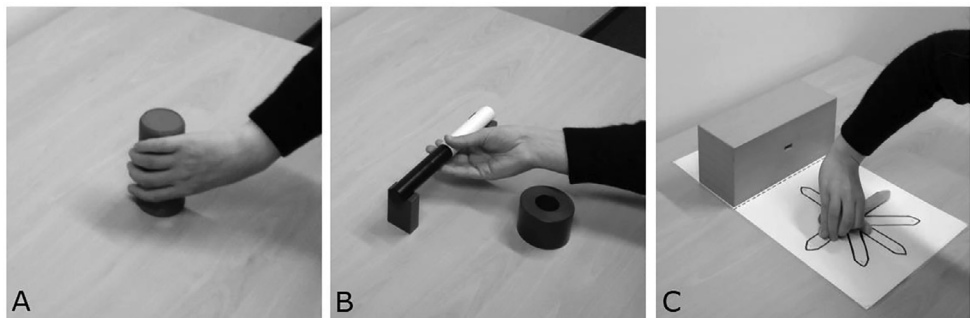


Fig. 1. Initial grips needed in order to reach end-state comfort for the cup task (A), the bar transport task (B), and the sword task (C). The cup task and the bar transport task require a pronated grasp and a supinated grasp, respectively, in order to reach a comfortable end state, whereas in the critical trials of the sword task children need to move their arm and hand in a lateral or medial position, which also demands an ulnar or radial deviation of the wrist.

of the movement before movement onset, with little evidence of error monitoring and correction during the movement phase. However, this was a relatively simple task given that the rotations were small and participants did not choose their grip. There is evidence suggesting that more demanding tasks enlist planning both before movement onset and during the reaching movement itself. [Rosenbaum et al. \(1992\)](#) had participants grasp and replace a cylindrical bar from a home position to one of eight target locations, which required rotation of the bar. Using a task with two grip choices and increased object rotation, they showed that the type of grip used (thumb away from or thumb toward the pointer end of the bar) had a significant influence on both RT and MT. Similarly, [Seegelke et al. \(2013\)](#) used a demanding task consisting of multiple action steps in which participants were instructed to grasp an object from a home position and place it to a first target, after which they needed to place it to a second target. Again, the replacing required rotation of the object. Results showed that both RT and MT increased with the number of action steps and the required degree of object rotation. Taken together, the effect that task demands can have on the time course of a reaching movement in adults is variable, suggesting that feedforward modeling can occur at multiple points in a movement cycle or that different attributes of a task may require multiple forms of parameterization at the level of feedforward control ([Wolpert & Kawato, 1998](#)) with internal feedback loops correcting movements online ([Scott, 2012](#)).

Taken together, studies in children generally showed increased ESC planning with increasing age, but it is unclear whether reduced ESC planning reflects an inability to use second-order motor planning. Next to grip selection, also the time course provides information about the second-order motor planning process but has been exclusively studied in adults so far. The current study focused on the development of second-order motor planning ability in children using a task that requires an accurate prediction of movement range and end-state position for its successful completion. Using a cross-sectional design, we tested 311 school-aged children (aged 5–12 years) on an adapted version of the HKT ([Mutsaerts et al., 2005](#); [Mutsaerts, Steenbergen, & Bekkering, 2006](#)). Children were instructed to grasp and rotate a hexagonal knob over 60°, 120°, 180°, or 240°. We added a 240° rotation condition to the original task ([Mutsaerts et al., 2006](#)) to increase movement demands. We examined performance on the HKT as a function of the required rotation angle and age.

On the one hand, if the low ESC rates found in younger children reflect immaturity of their second-order motor planning *ability*, we expected these children to be disadvantaged by a condition that requires adaptation of the initial grip. On the other hand, if these low ESC rates do not reflect children's actual second-order motor planning ability but are due to task constraints, we expected children of all ages to be able to adapt their initial grip in order to successfully complete the HKT. Given the strong association between movement preparation time and movement demands ([Klapp, 1995](#)) and the importance of both feedforward modeling and feedback control for visually guided movements ([Scott, 2012](#)), it was expected that RT and MT would increase with increased rotation angle. We also expected age-related differences in the effect of rotation angle on RT and MT; the gradual unfolding of feedforward modeling over childhood suggests that these corrections would be less efficient in younger children, delaying both RT and MT to a greater extent at larger angles of rotation ([Caeyenberghs et al., 2009](#); [Ruddock et al., 2016](#)). Finally, to compare the grip selection planning in our sample with that of previously reported samples and to compare results on the HKT with those on a previously used task, we also administered the cup task ([Adalbjornsson, Fischman, & Rudisill, 2008](#)). To our knowledge, this is the first study to examine the second-order motor planning process by analyzing grip selection, RT, and MT in a large cohort of children using a task in which effective motor planning is necessary for successful task completion.

Method

Participants

Participants were 311 children (161 boys and 150 girls) with ages varying from 5 years 1 month to 12 years 10 months ($M = 8$ years 11 months, $SD = 2$ years 2 months). Written informed consent was obtained from the parents/guardians, the schools, and the children themselves if 12 years of age.

Table 1

Participant characteristics for each age group separately (N = 311).

Age (years)	Characteristics							
	n	Sex (M/F)	Dominant hand (L/R)	AVL (SD)	DCD-Q (SD)	DCDDaily-Q participation (SD)	DCDDaily-Q activities (SD)	DCDDaily-Q learning (SD)
5	35	15/20	3/32	15.14 (11.30)	56.80 (11.66)	40.94 (7.68)	36.20 (6.20)	0.42 (1.06)
6	39	19/20	5/34	15.96 (13.59)	60.24 (11.02)	37.97 (4.74)	33.37 (5.90)	1.03 (2.48)
7	37	22/15	2/35	11.07 (8.15)	61.62 (10.69)	34.60 (6.68)	31.08 (5.44)	0.49 (1.35)
8	35	22/13	3/32	13.30 (10.24)	62.24 (10.19)	34.71 (5.70)	29.58 (4.67)	0.52 (1.48)
9	54	24/30	9/45	13.21 (11.01)	63.43 (10.92)	31.98 (5.31)	27.31 (4.10)	0.69 (2.18)
10	45	21/24	5/40	12.94 (13.08)	65.09 (8.76)	33.67 (5.24)	27.38 (4.59)	0.52 (1.58)
11	41	26/15	5/36	9.77 (8.55)	66.12 (7.74)	33.37 (5.76)	26.86 (4.20)	0.76 (2.21)
12	25	12/13	0/25	8.70 (4.90)	66.90 (10.11)	33.21 (4.51)	26.00 (3.93)	0.53 (2.06)

Note. M, male; F, female; L, left; R, right; AVL, questionnaire focusing on attention-deficit/hyperactivity disorder symptoms; DCD-Q, questionnaire focusing on developmental coordination disorder symptoms; DCDDaily-Q, questionnaire focusing on difficulties in activities of daily living.

Together with the written informed consent form, parents were asked to fill in a health questionnaire. After consent, parents received three questionnaires by mail: the attention-deficit/hyperactivity disorder (ADHD) questionnaire (AVL; [Scholte & van der Ploeg, 2004](#)) focusing on ADHD symptoms, the DCD (developmental coordination disorder) questionnaire (DCD-Q, Dutch translation; [Schoemaker, Reinders-Messelink, & de Kloet, 2008](#)) focusing on DCD symptoms, and the DCDDaily-Q ([Moraal-van der Linde, van Netten, & Schoemaker, 2015](#)) focusing on difficulties in activities of daily living. These questionnaires provided insight into the attentional capacity and level of motor performance of the children. The response rate was approximately 95%, and scores were representative of the general population. Of the children, 7% fell within the clinical or subclinical area on the AVL (above the 90th percentile), 14% had a score indicating a “suspicion of DCD” on the DCD-Q, and 14% to 24% fell within the clinical or subclinical area on the subscales of the DCDDaily-Q (above the 85th percentile). None of the children was excluded based on questionnaire scores. For detailed participant characteristics, see [Table 1](#). The study was approved by the Ethics Committee Social Science of the Radboud University (ECSW-2017-035R1).

Materials

Hexagonal knob task

To assess motor planning ability, an adapted version of the HKT was used ([Mutsaerts et al., 2005, 2006](#)). The apparatus consisted of a circular platform that could be tilted at a slope between 0° and 90° relative to the table. A hexagonal knob with an arrow attached to one side was connected to the center of the platform and could fully rotate both clockwise and counterclockwise (see [Fig. 2](#)). A circle of 265 light-emitting diodes (LEDs), at 1.0 cm from the edge of the platform, was embedded in the platform. A start box was used for RT measurements with a time resolution of ± 20 –25 ms. In addition, rotation of the hexagon was registered by examining changes in motor position (threshold of a minimal change of 0.9°) with a time resolution of ± 20 –25 ms.

The HKT was programmed in Delphi. At the start of a new trial, children placed their dominant hand on the start box (see [Fig. 2](#)). First, the arrow automatically moved toward one of the six possible start positions (i.e., 0°, 60°, 120°, 180°, 240°, and 300°). Next, all LEDs lit up for a period of 1000 ms (priming cue) to alert children for the subsequent trial. This was followed by a random delay of 600–1500 ms, after which a path of LEDs lit up together, indicating the length of the rotation (starting

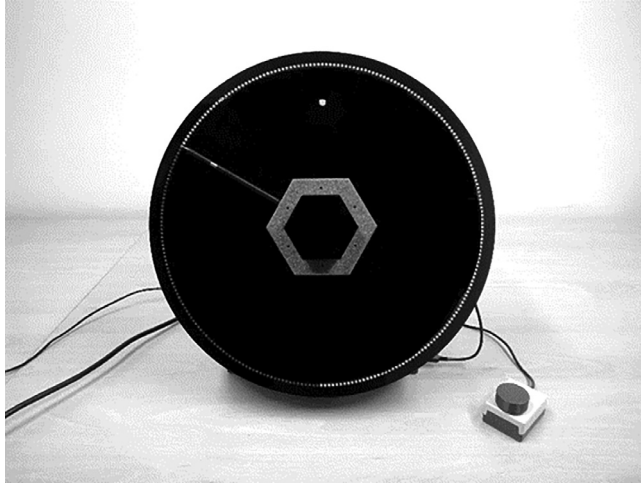


Fig. 2. The hexagonal knob task with the arrow pointing at 300° and the light-emitting diodes displaying an experimental trial with a clockwise rotation of 240°, setup for a right-handed child with the start box to the right of the platform.

cue). Children were instructed to use their dominant hand to grasp the hexagonal knob and rotate it along the path of LEDs until the arrow pointed toward the final LED in the path as fast as possible. They were instructed to complete the rotation in one single movement. It was specifically mentioned that readjustment of the initial grip and change of finger positions were not allowed. In addition, children were instructed that they should remain seated in the same position. Two rotation angles, the 180° and 240° angles, served as experimental rotations or so-called *critical rotations*. Here, children were required to sacrifice comfort of the start position in order to complete the task successfully (i.e., the arrow pointing at the final LED in the path). Two other rotation angles, the 60° and 120° angles, served as control rotations in which children were able to complete the task with a comfortable start posture. For each of the six start positions, all four rotation angles were repeated once, both clockwise and counterclockwise, resulting in a total of 48 trials. The trials appeared in a random order for each child. A video camera was used to record children's hand position and movements to allow offline scoring. All videos were coded by the first author. Two other raters both coded 20 videos of the subset of 311 videos. Inter-rater reliability was excellent, with an average intraclass correlation coefficient (ICC) of .932, 95% confidence interval (CI) [.923, .940], $F(957) = 14.69$, $p < .001$ between the first author and the first rater and .991, 95% CI [.990, .992], $F(958) = 108.53$, $p < .001$ between the first author and the second rater, calculated based on mean rating ($k = 2$), absolute agreement, two-way mixed-effects model.

For each trial, the grasping pattern was categorized by determining the position of the thumb at the moment of grasping the hexagonal knob, which resulted in five possible grasping patterns: numbers 1, 2, 3, 5, and 6 (Fig. 3). After the thumb position was scored for each trial, the grasping patterns (i.e., position of the thumb) was recoded for left-handed children. In addition, the trial information (i.e., start position and direction of the rotation) was recoded for left-handed and right-handed children, such that in the end similar hand and arm movements had the same coding (e.g., a 120° clockwise rotation starting at 300° for right-handed children was the same as a 120° counterclockwise rotation starting at 60° for left-handed children).

Next, based on the grasping pattern, it was determined whether each trial was successfully completed or not. This was based on the fact that it was biomechanically impossible for the thumb to be on position 4, which was ensured by adjustments to the task setup during the practice session. Thus, with a grasp starting with the thumb on position 1, it was possible to rotate the hexagonal knob up to 120° both clockwise and counterclockwise. With the thumb on position 2 or 6, it was possible to rotate the knob 60° to one side and up to 180° to the other side. With the thumb on position 3 or 5, it was not possible to rotate the knob to one side, but the knob could be rotated up to 240° to the other side. Fig. 4 provides an overview of the different grasping patterns. Importantly, some specific combinations of

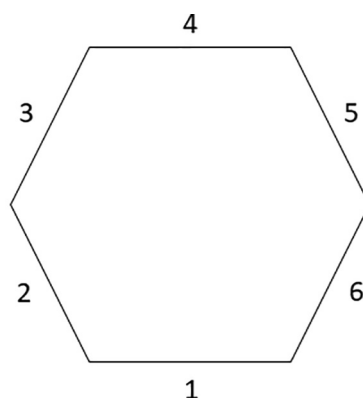


Fig. 3. Scoring of thumb position when grasping the hexagonal knob.

thumb position and required rotation angle would lead to unsuccessful task completion. For example, if the knob needed to be rotated 180° counterclockwise and was grasped with the thumb on position 1, the thumb would need to end at position 4, which was biomechanically impossible (see top row in Fig. 4). Critically, based on the size of the required rotation angle, the direction of the rotation, and the grasping pattern that the child adopted, a score of 1 (i.e., successful task completion) or 0 (i.e., no successful task completion) was assigned for each trial for each child. *Planning accuracy* was defined as the mean percentage of successful trials calculated for each rotation angle (i.e., 60°, 120°, 180°, and 240°).

In addition, two time events were registered for each trial for each child: RT (i.e., the interval between the starting cue and the moment the hand released the start box) and MT (i.e., the interval between the moment the hand released the start box and the commencement of the rotation movement).

Cup task

The cup task was based on the design by Adalbjornsson et al. (2008). A cylindrical cup was placed upside down in front of the child 15 cm from the edge of the table (see Fig. 5). The child was asked to

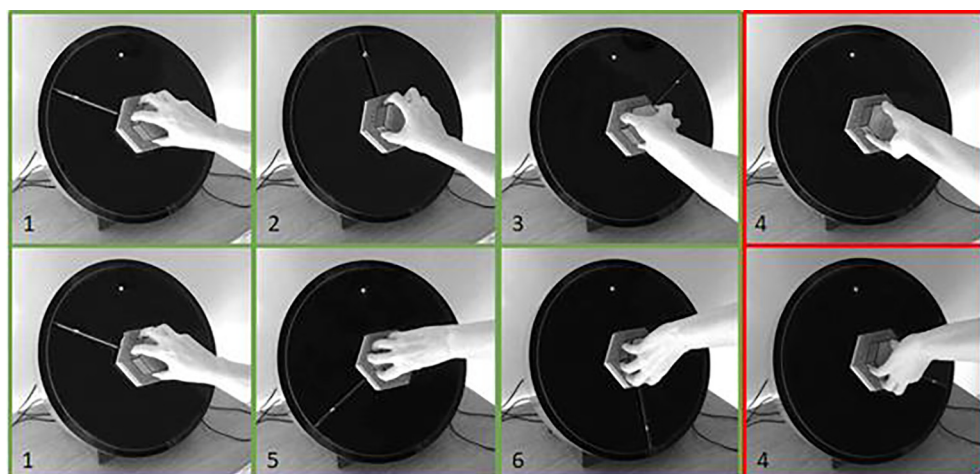


Fig. 4. Illustration of the different grasping patterns, depicted as a lateral rotation (top row) and a medial rotation (bottom row). The green and red frames indicate what grasping patterns were biomechanically possible (green; grasping patterns 1, 2, 3, 5, and 6) and impossible (red; grasping pattern 4). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)



Fig. 5. The cup task.

grasp the cup with the dominant hand and to turn it over. Six trials were assessed. A video camera was used to record the child's hand position and movements to allow offline scoring. A score of 1 (i.e., action ended in pronation) or 0 (i.e., action did not end in pronation) was assigned for each trial for each child. The percentage of comfortable end postures was the outcome measure.

Procedure

Of the 320 children recruited, 311 completed all experimental conditions. The experiment took place at the school of each child and took approximately 20–30 min to complete. Children performed the test session individually. Children were seated so that they could comfortably reach the hexagonal knob and the cup without fully extending the forearm. The session started with a general explanation of the study. Then, children were asked to write down their name on the session form, which served to determine hand preference (Jongbloed-Pereboom et al., 2013). Next, both motor planning tasks were assessed. First, children performed 3 trials of the cup task. Second, children received instructions about the HKT. Following the instructions, children performed a practice session. During this practice session, adjustments were made to the slope of the platform and the distance of the apparatus to the front edge of the table, based on each child's active range of motion. These adjustments were made to ensure that for each child the same five grasping patterns (i.e., with the thumb on positions 1, 2, 3, 5, and 6) were possible, but a grasping pattern with the thumb on position 4 was biomechanically impossible (Figs. 3 and 4). These adjustments ensured that children needed to adjust their grasping pattern for the critical rotations in order to complete the required rotation movement. Before the first experimental trial, each child was asked to grasp the hexagonal knob without rotating it, which was repeated four times (after every 12 trials) to determine the child's preferred initial grasping pattern. Each child performed a total of 48 trials on the HKT. Finally, another 3 trials of the cup task were assessed.

Data processing and analyses

Due to registration errors, data were missing for 53 of the total 14,928 trials (0.36%). In addition, 593 of the remaining 14,875 trials (3.99%) were classified as invalid because of extremely long RTs and/or MTs (i.e., a time score > 3 standard deviations from the corresponding mean) or abnormally short RTs (<200 ms). These invalid trials were excluded from data analyses. The average RT and MT for each child at each rotation angle (i.e., 60°, 120°, 180°, or 240° rotation) were used in the analysis.¹

¹ We also ran the analyses with the averaged RT and MT of the successfully planned trials only. This resulted in a loss of data because some children ($n = 46$) did not plan any of the 240° trials successfully. The interpretation of the results remained the same, and therefore we decided to report the results of both successfully and not successfully performed trials.

All analyses were performed using SPSS Version 22 (released in 2013) (IBM Corp., Armonk, NY, USA). Alpha level was set at .05. When the assumption of sphericity was violated, Greenhouse–Geisser corrections were performed. Because both the RT data and MT data were positively skewed, log transformations were performed.

To assess the effect of rotation angle and age, a repeated-measures multivariate analysis of variance (MANOVA) was conducted with rotation angle as a within-participants factor, age (in days) as a covariate, and planning accuracy, RT, and MT as dependent variables. Repeated contrasts were used to analyze the effect of rotation angle on the dependent variables. In case of significant interaction terms, post hoc analyses were performed. Furthermore, to compare the percentage comfortable end postures on the cup task with the planning accuracy on the HKT, Wilcoxon signed-rank tests were performed.

Results

Fig. 6 shows the grasping pattern distribution for the different rotation angles. The length of the bars represents the percentage of grasps as a function of thumb position on the hexagonal knob. Without rotation, children preferred grasping pattern 1 or 2. As anticipated, the observed grasping patterns changed according to the direction and size of the required rotation angle. The grasping pattern distribution of each age group can be found in Part 1 of the online [supplementary material](#). Results of the repeated-measures MANOVA are described below for planning accuracy, RT, and MT separately. Although age was a continuous variable in the analysis, for visualization purposes we used age groups in the figures below.

Planning accuracy

Fig. 7 shows the average *planning accuracy* for the four rotation angles by age group. The repeated-measures MANOVA showed significant effects of rotation angle, $F(1.68, 518.32) = 1061.10, p < .001, \eta_p^2 = .77$, age, $F(1, 309) = 21.35, p < .001, \eta_p^2 = .07$, and rotation angle by age interaction, $F(1.68, 518.32) = 27.82, p < .001, \eta_p^2 = .08$. In accordance with the hypothesis, post hoc analyses revealed a significant effect of age specifically on the planning accuracy for the 180° rotations, $F(1, 309) = 4.78, p = .029, \eta_p^2 = .02$, and the 240° rotations, $F(1, 309) = 34.71, p < .001, \eta_p^2 = .10$, but not for the 60° rotations, $F(1, 309) < 0.001, p = .996, \eta_p^2 < .01$, or the 120° rotations, $F(1, 309) = 0.89, p = .347, \eta_p^2 < .01$. Planning accuracy is almost maximal across all ages in these control conditions (i.e., 60° and 120° rotation conditions). In the critical 180° and 240° rotation conditions, planning accuracy increased across age.

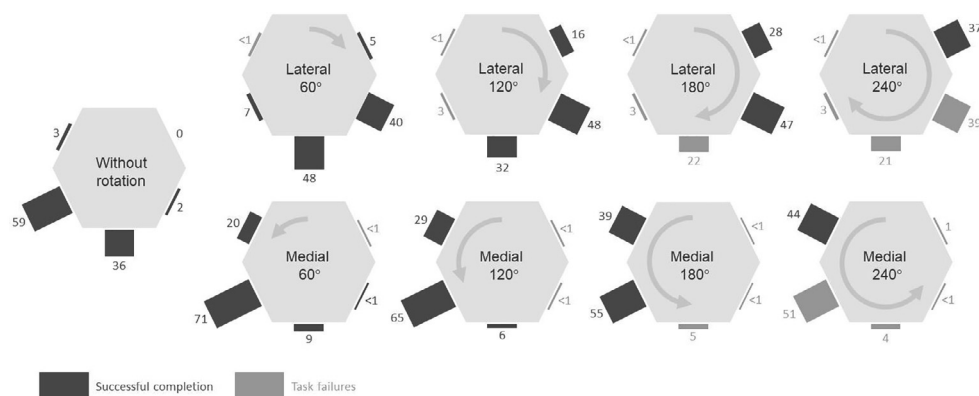


Fig. 6. Grasping pattern distribution for the different rotation angles. The length of the bars and related numbers display the percentage of grasps with the thumb at that particular side of the hexagon. Results are visualized for right-handed children (data of left-handed children are mirrored in the figure).

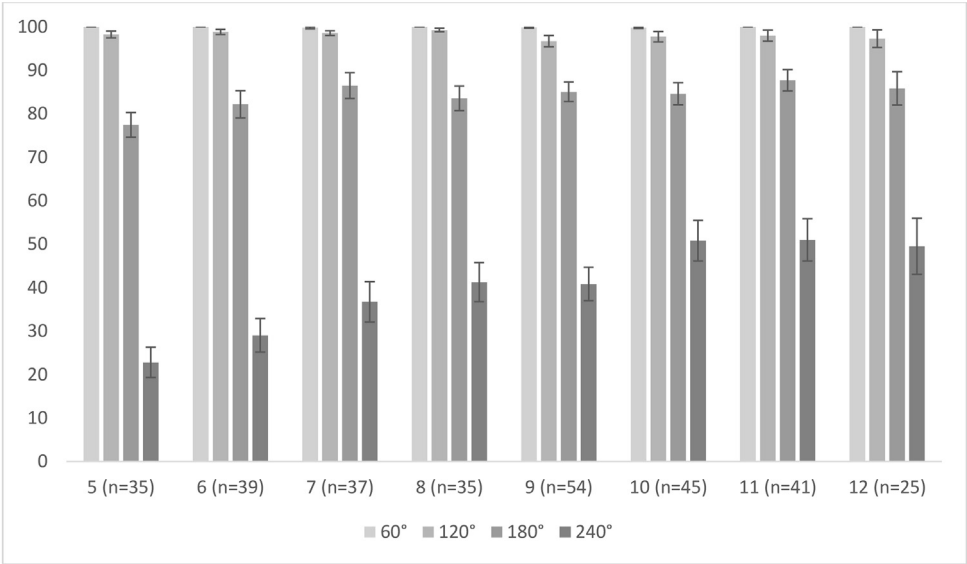


Fig. 7. Mean planning accuracy (i.e., percentage successfully performed trials) of all four rotation angles, visualized by age (in years). Error bars represent standard errors.

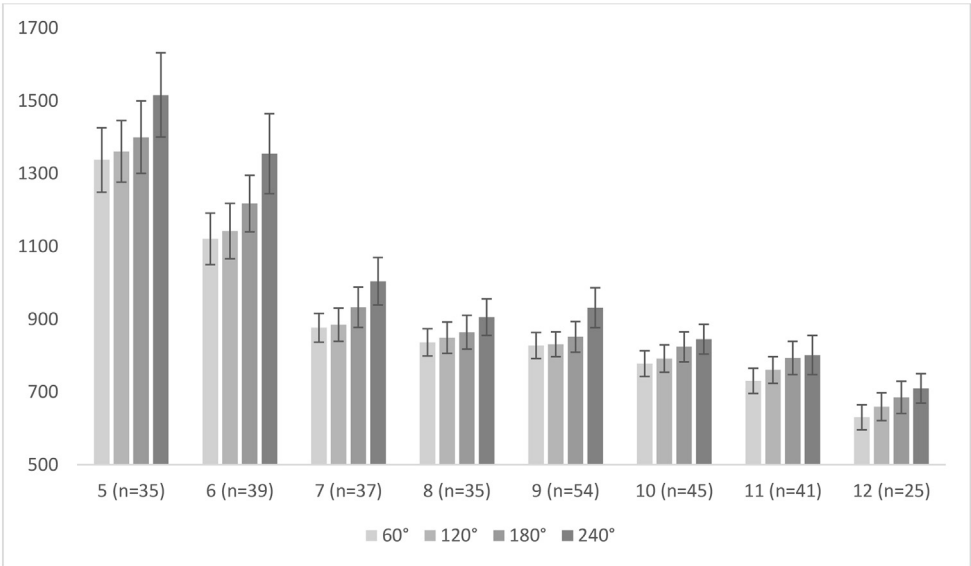


Fig. 8. Mean reaction times (in milliseconds) of all four rotation angles, visualized by age (in years). Error bars represent standard errors.

Reaction time

Fig. 8 shows the average RT at each rotation angle per age group. The repeated-measures MANOVA of the (log-transformed) RT data showed a significant main effect of rotation angle, $F(2.81, 868.64) = 42.81, p < .001, \eta_p^2 = .12$. In accordance with the hypothesis, repeated contrasts revealed that

RT was higher for the 120° rotations compared with the 60° rotations, $F(1, 309) = 4.75, p = .030, \eta_p^2 = .02$, for the 180° rotations compared with the 120° rotations, $F(1, 309) = 12.72, p < .001, \eta_p^2 = .04$, and for the 240° rotations compared with the 180° rotations, $F(1, 309) = 28.51, p < .001, \eta_p^2 = .08$. A significant main effect of age, $F(1, 309) = 107.18, p < .001, \eta_p^2 = .26$, showed significantly reduced RT with age. Finally, the interaction between age and rotation angle was not statistically significant, $F(2.81, 868.64) = 1.46, p = .225, \eta_p^2 < .01$, indicating that the reduction in RT with age was seen at all rotation angles.

Movement time

Fig. 9 shows the average MT at each rotation angle per age group. The repeated-measures MANOVA of the (log-transformed) MT data showed a significant main effect of rotation angle, $F(1.96, 606.18) = 219.64, p < .001, \eta_p^2 = .42$, but not for age, $F(1, 309) = 0.81, p = .369, \eta_p^2 < .01$. The interaction between rotation angle and age was significant, $F(1.96, 606.18) = 14.04, p = .001, \eta_p^2 = .04$. In contrast to the hypothesis, post hoc analyses revealed a significant (positive) age effect on MT for the 240° rotations only, $F(1, 309) = 6.67, p = .010, \eta_p^2 = .02$, and not for the 60° rotations, $F(1, 309) = 0.90, p = .344, \eta_p^2 < .01$, 120° rotations, $F(1, 309) = 0.16, p = .686, \eta_p^2 < .01$, or 180° rotations, $F(1, 309) = 0.83, p = .362, \eta_p^2 < .01$. This indicates that MT increased with age for the 240° rotation condition but did not vary with age for the other rotation conditions.

Cup task

Results on the cup task are represented in Table 2. As can be seen, the percentage of comfortable end postures increased gradually between 5 and 8 years of age, after which children reached adult level and a ceiling effect occurred. Wilcoxon signed-rank tests revealed that performance accuracy on the cup task ($Mdn = 100.00, M = 85.48, SD = 28.57$) was higher than performance accuracy on the critical rotation conditions of the HKT—for the 180° rotation condition ($Mdn = 90.91, M = 84.18, SD = 17.47$), $z = -2.41, p = .016$, and for the 240° rotation condition ($Mdn = 40.00, M = 40.20, SD = 30.21$), $z = -13.54, p < .001$.

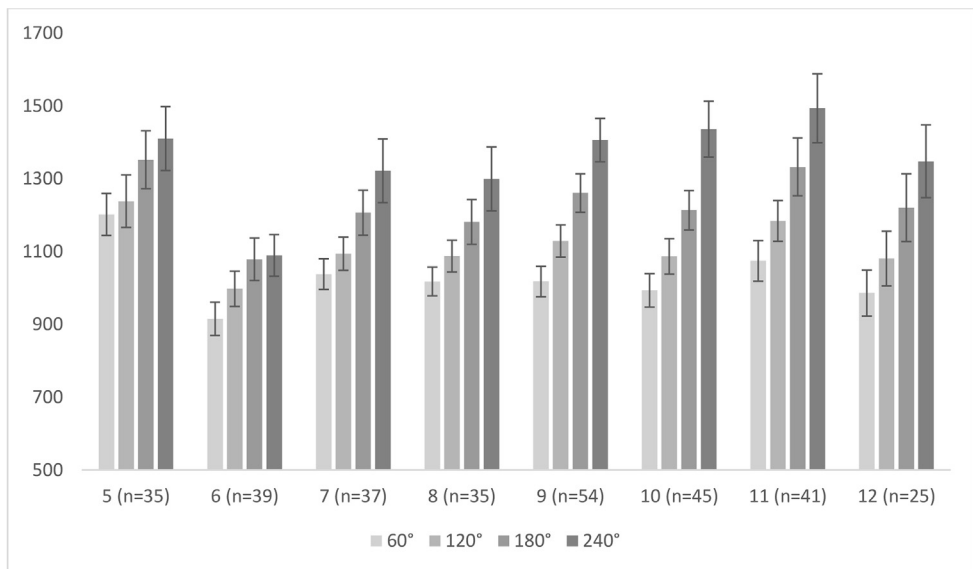


Fig. 9. Mean movement times (in milliseconds) of all four rotation angles, visualized by age. Error bars represent standard errors.

Table 2

Percentage of comfortable end postures on the cup task per age group.

Age (years)	Percentage of comfortable end-postures	
	<i>M</i>	<i>SD</i>
5	60.48	40.84
6	72.65	36.17
7	83.33	26.35
8	92.86	18.65
9	88.89	24.87
10	93.70	18.22
11	94.31	21.92
12	96.67	10.76

Discussion

The aim of the current study was to examine the second-order motor planning process in a large group of children using the HKT, a paradigm that necessitated adjustment of the initial grip in order to successfully complete the task and provided insight into the planning process by measuring RT and MT. The results that we found with regard to task completion were twofold. First, in line with our argumentation, we found that many children across all ages (5–12 years) were able to successfully complete the HKT under conditions of relatively low task demands (i.e., 180° rotation condition). This supports the hypothesis that young children do have the *ability* for second-order motor planning if demanded in order to successfully complete the rotation movement. Second, however, under conditions of relatively high task demands (i.e., 240° rotation condition), many children had difficulty in successfully completing the HKT despite a developmental increase in performance. The analysis of the time course of the second-order motor planning process showed increased RT and MT with increasing task demands. Furthermore, whereas RT decreased with age, for each rotation angle, MT remained relatively stable. Together, this suggests that with development, the second-order planning process becomes more accurate and efficient, which is reflected in reduced RTs but not MTs. If anything, MT for the most complex rotations was relatively higher in older children, perhaps suggesting that they integrate online adjustments to a greater extent when planning for end state (at the expense of time).

As expected, nearly all children were able to successfully complete the 60° and 120° rotations, which required no adaptation of the preferred grip. In contrast, for the 180° and 240° rotation conditions, children needed to sacrifice initial grip comfort in order to complete the required movements successfully. The vast majority of children were able to successfully complete the 180° rotations ($M = 84\%$). However, performance was reduced in the more demanding 240° rotation condition ($M = 40\%$). This difference in planning accuracy between the 180° and 240° rotation conditions may be explained by difficulties with the internal representation of 240° rotation movement. Because the initial grip needed to complete the 240° rotation deviates more from the preferred grip without rotation, we can argue that for the children in our study it was more difficult to imagine performing a 240° rotation than to imagine performing a 180° rotation. In addition, the 240° rotations require an unnatural grip, one that children (especially at a young age) may have little experience with at this point in their development. Because it has been shown that children's performance on a grip selection task like the HKT is associated with the ability to represent a motor action internally using motor imagery (Fuelscher, Williams, Wilmut, Enticott, & Hyde, 2016; Toussaint, Tahej, Thibaut, Possamai, & Badets, 2013), the task demands related to the 240° rotation condition may have been too high. This suggestion is supported by the grip type data. As shown in Fig. 6, for the 240° rotations many children used a grasp with the thumb on position 2 or 6 (as depicted in Fig. 3), whereas successful completion required a grasping pattern with the thumb on position 3 or 5 (as depicted in Fig. 3). This indicates that most children adjusted their initial grip to some extent for these trials, suggestive of feedforward modeling, but not enough to complete successful rotation of the knob.

The high percentage of successful task completion on the 180° rotation condition supports the hypothesis that when second-order motor planning is necessary in order to complete the task, children are indeed able to take into account the end state of their movements and adapt their start grip accordingly. This suggests that other motor planning tasks may have underestimated the second-order motor planning ability of children. However, we found that overall the percentage of comfortable end postures on the cup task was higher than the percentage successful task completion on the HKT. This contradicts the above hypothesis because the cup task has a reduced need for second-order motor planning compared with the HKT given that the former can be completed with an uncomfortable end posture. At the same time, the comparison may be somewhat biased. The cup task has only two options to start and end the movement and involves a familiar object with many assumed associations with a comfortable end posture (e.g., pouring milk). The percentages of comfortable end postures that we found on the cup task are comparable to the results of [Jongbloed-Pereboom et al. \(2016\)](#). In their study, across age groups, the cup task had the highest percentage of comfortable end states when compared with the bar transport task and the sword task ([Jongbloed-Pereboom et al., 2016](#)). The task demands of the HKT are higher than those of the cup task, which is known to be of importance for second-order motor planning ([Bhoyroo, Hands, Steenbergen, & Wigley, 2020](#)). To further delineate the importance of task demands, familiarity, and necessity to plan, future research could systematically compare performance on tasks that vary on these factors.

It has been stressed before that in cases where children fail to select a grasp resulting in ESC, this does not necessarily mean that they are not planning their grasps. Using an octagon task in which participants needed to rotate the octagon in one, two, or three movement sequences, [Wilmut and Byrne \(2014\)](#) demonstrated that adults and 10- to 12-year-old children mainly used an ESC strategy. For younger children, however, there were other constraints affecting movement selection as they used different strategies equally: ESC, start-state comfort, and no-initial-rotation strategy. Similarly, when placing fewer restrictions on the grip that participants are allowed to use, studies have shown that children solve grip selection tasks by using both their hands ([Comalli et al., 2016](#); [Herbort, Büschelberger, & Janczyk, 2018](#)) or by changing their grip during a trial ([Comalli et al., 2016](#)). Whereas younger children generally seem to use more variable strategies to solve grip selection tasks compared with adults, the results of our study suggest that under conditions of low task demands many children, even at 5 years of age, are able to take into account the end state of an action and consistently sacrifice comfort of the start grip if this is required for successful task completion.

With regard to the time course of the second-order motor planning process, we found the expected increase in RT with larger rotation angles (namely, more demanding movements). These results suggest that the size of the rotation angle was incorporated into the feedforward model before movement onset for children across all ages. In addition, there was also an effect of rotation angle on MT, with increasing MT for larger rotation angles. This indicates that children continue the second-order planning process after movement onset. The MT data suggest that the feedforward model was updated and corrected online based on internal feedback loops while the hand was already in motion. This is in line with our hypothesis based on current neurocomputational theories of motor control, which state the importance of both feedforward modeling and feedback control ([Scott, 2012](#)), and previous studies demonstrating the effects of experimental manipulations such as type of action and number of action steps on both RT and MT ([Fleming, Klatzky, & Behrmann, 2002](#); [Rosenbaum et al., 1992](#); [Seegelke et al., 2013](#)). We explored the possibility that the increase of MT with increasing rotation angle was solely explained by increased difficulty in adopting the required starting posture, that is, the extra physical rotation of the arm and wrist. This would indicate that the differences in MT among the 60°, 120°, 180°, and 240° rotations are due to movement execution rather than movement planning. We compared the average MTs of the most extreme initial grasps (i.e., the thumb on positions 3 and 5 as depicted in [Fig. 3](#)) among the subsequent 60°, 120°, 180°, and 240° rotations (detailed analysis and results are described in Part 2 of the [supplementary material](#)). Here, we still found pronounced differences in MT for the four rotation angles even though movement execution was the same. Thus, it is unlikely that variation in MT across rotation angles is explained by biomechanical differences in movement execution alone.

Focusing on changes in the time course across age, we found that RT was reduced with increasing age regardless of rotation condition. In contrast, MT remained unchanged across age for the 60°, 120°, 180°, and 240° rotations.

and 180° rotations. Although it is surprising that the MT for these rotation conditions was the same for 5- to 12-year-old children given the big differences with regard to their motor experiences, similar results have been reported when studying reaching for visual targets (Favilla, 2006). Using a task in which participants needed to slide a cursor on a tablet to reach a visual target, Favilla (2006) demonstrated that whereas RT and precision of response increased across age, MT of 6-year-old children was already similar to that of adults.

Unexpectedly, for the 240° rotation condition, the MT increased with increasing age. An additional analysis (described in Part 3 of the [supplementary material](#)) showed that a speed–accuracy trade-off cannot explain this finding. Alternatively, we speculate that this prolonged MT, which allows for online corrections, is a precursor to improved planning accuracy. With increasing age, children may become more prone to task failures and are more likely to change their strategy. Longer MT allows these children more time to select their grip despite this not yet being an accurate grip.

It is well acknowledged that the ability to use feedforward models gradually improves with age over childhood and adolescence and into early adulthood, as evidenced by experimental studies (e.g., Caeyenberghs, Wilson, van Roon, Swinnen, & Smits-Engelsman, 2009; Fuelscher, Williams, Wilmut, Enticott, & Hyde, 2016; van Roon, Caeyenberghs, Swinnen, & Smits-Engelsman, 2008). When children interact with their environment, they gain experience with the coupling between movement commands, the environment, and their effects on the moving body. That way, children will become increasingly capable of making predictions about the changes of their body and its kinematics and detecting deviations from what is predicted. With experience, these feedforward models become more accurate and precise. Studies found that feedforward control develops rapidly between 6 and 10 years of age and that this change is consistent with the maturational unfolding of the neural networks that support motor planning, specifically enhanced frontoparietal coupling (Braddick & Atkinson, 2013; Caeyenberghs et al., 2009). In our study, it seems that children's feedforward model became more accurate with increasing age, as reflected in a small increase in successful task completion in the 240° rotation condition. Our finding that RT steadily decreased with increasing age suggests that in children the improvements in the use of feedforward control are mainly reflected in more rapid formation of the feedforward model. The finding that MT remains largely stable across age suggests that the use of feedback control while the hand is in motion does not change across 5- to 12-year-old children, although for the most demanding rotation movements there seems to be an increase in online correction with increasing age.

It is important to mention that other factors may also underlie the age-related differences in performance on the HKT. The development of second-order motor planning and grip selection may also rely on a child's cognitive skills and development, underpinned by factors such as spatial awareness and visuospatial working memory (Stöckel & Hughes, 2016). To successfully complete the HKT, a child needs to be able to mentally represent the required degree of rotation to reach the goal state and, when the action is planned, maintain that action plan over the duration of movement and subsequent trials. Individual differences in these cognitive skills may have also contributed to variation in the second-order motor planning process. Still, compared with other previously used tasks in which children need to remember verbal instructions (e.g., Wilmut & Byrne, 2014), the cognitive demands on the HKT can be considered relatively low because the path from the start to the goal is visually depicted during the whole movement.

The current study has a few limitations that provide clear avenues for future research. First, we observed that the children made sure that at the end of each trial the arrow pointed toward the final LED in the path even if this, for example, meant that they needed to move their chair backward, stand up, or release a few fingers from the knob. In these cases, the experimenter provided feedback with regard to their task performance (e.g., "Did you notice that your thumb released the knob?"). The respective trial was registered as unsuccessful. The verbal or nonverbal responses of some children indicated that they did not realize that the trial was not performed successfully and therefore they might not have been inclined to change their strategy. Thus, although we made individual adjustments to the task setup to ensure that the critical trials could hardly be completed without anticipatory grip planning, our results may still underestimate the children's actual second-order motor planning ability. For future research, it would be interesting to focus on these other strategies that children may use in order to complete the goal of the task. Second, a related issue was that in a

few cases children were able to hyperextend their elbow in such a way that they could complete 180° and 240° rotations without adjusting their initial grip. We recommend that future studies measure the joint mobility of the children to be able to examine whether this affects performance on the task. Third, the current study showed that even with high necessity to take into account the end state of a movement, implementation of second-order planning was not consistently achieved over all trials in 12-year-old children. A study comparing older children with adults is warranted to examine whether the costs of the initial start posture necessary to complete the 240° rotations are high for adults as well. Moreover, such a study would provide insight into the relative contribution of feedforward modeling and feedback control in adults under varying conditions of task demands.

In sum, the results of the current study contribute to unveiling the principles underlying motor planning and its development. We found that children demonstrate a high degree of second-order planning using a task that necessitates second-order motor planning for its successful completion. Children across all ages adapted their grasps to subsequent task demands, but performance was dependent on task demands, with decreasing percentages of successfully completed trials for more demanding rotation movements. In addition, we found that both RT and MT were longer for more demanding rotation movements for children across all ages. With development, the process of forming a feedforward model seems to become more efficient, which is reflected in a decrease in RT. MT, on the other hand, remained the same across age except for the most demanding 240° rotation condition.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jecp.2020.104945>.

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