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# Preschool children adapt grasping movements to upcoming object manipulations: Evidence from a dial rotation task

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### ABSTRACT

In adults, the motor plans for object-directed grasping movements reflects the anticipated requirements of intended future object manipulations. This prospective mode of planning has been termed second-order planning. Surprisingly, second-order planning is thought to be fully developed only by 10 years of age, when children master seemingly more complex motor skills. In this study, we tested the hypothesis that already 5- and 6-year-old children consistently use second-order planning but that this ability does not become apparent in tasks that are traditionally used to probe it. We asked 5- and 6-year-olds and adults to grasp and rotate a circular dial in a clockwise or counterclockwise direction. Although children's grasp selections were less consistent on an intra- and inter-individual level than adults' grasp selections, all children adjusted their grasps to the upcoming dial rotations. By contrast, in an also administered bar rotation task, only a subset of children adjusted their grasps to different bar rotations, thereby replicating previous results. The results indicate that 5- and 6-year-olds consistently use second-order planning in a dial rotation task, although this ability does not become apparent in bar rotation tasks.

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## Introduction

Every day, we interact and manipulate objects in our environment. Although such activities appear rather mundane, we exhibit considerable sophistication in planning and controlling these movements. Important in the current context, when someone grasps an object, the grasping act not only is determined by the characteristics of the object but already is adjusted to the requirements of planned subsequent actions. For example, the orientation of a grasp is adapted to a subsequent rotation of the grasped object, thereby enabling further, faster, and more accurate rotations (Coelho, Studenka, & Rosenbaum, 2014; Herbert, 2015; Short & Cauraugh, 1999; for a review, see Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012).

The ability to adapt grasping movements to intended object manipulations has been termed *second-order planning* (in contrast to first-order planning, which reflects only immediately perceivable constraints such as object shape or position; see Rosenbaum et al., 2012; Rosenbaum, Herbert, van der Wel, & Weiss, 2014). This ability is usually examined with tasks that require grasping and manipulating objects. A classic example is the so-called *bar transport task* (Rosenbaum et al., 1990). In this task, a horizontal bar on two stands needs to be grasped and placed vertically on its left or right end. Right-handed adults usually grasp the bar with an overhand grip (forearm prone) for placing the bar on its right end and with an underhand grip (forearm supine) for placing it on its left end. Left-handed grasps show the reverse pattern. Importantly, in all cases the initial grasp enables placing down the object in a comfortable end posture. Hence, the finding is termed the *end-state comfort effect* (Rosenbaum et al., 2012).

### *Development of second-order planning*

Surprisingly, it takes until about 10 years of age for children to start showing adult-like second-order planning in the bar transport task (Jovanovic & Schwarzer, 2011; Stöckel & Hughes, 2015; Stöckel, Hughes, & Schack, 2012; Thibaut & Toussaint, 2010; Weigelt & Schack, 2010; Wunsch, Pfister, Henning, Aschersleben, & Weigelt, 2016; for a review, see Wunsch, Henning, Aschersleben, & Weigelt, 2013). Similar results have been reported for other tasks such as rotating overturned glasses, using a spoon, hammering a peg, inserting swords into holes, and rotating fixed dowels and knobs (Comalli et al., 2016; Fuelscher, Williams, Wilmut, Enticott, & Hyde, 2016; Scharoun & Bryden, 2014; Smyth & Mason, 1997; van Swieten et al., 2010; Wilmut & Byrne, 2014b; Wunsch et al., 2016). Moreover, attempts to make the end-state of the object manipulation more salient did not alter grasp selections much (Knudsen, Henning, Wunsch, Weigelt, & Aschersleben, 2012; Manoel & Moreira, 2005; Thibaut & Toussaint, 2010).

The discrepancy in grasp selection between adults (e.g., Coelho et al., 2014; Comalli et al., 2016; Rosenbaum et al., 1990) and children, who adjust their grasps consistently to upcoming tasks, seems to be based on two aspects. First, only a subset of children show signs of second-order planning; typically, only 60% to 80% of 5-year-olds show the end-state comfort effect in the majority of trials (e.g., Hughes, 1996; Knudsen et al., 2012; Weigelt & Schack, 2010; Wunsch et al., 2016). Thibaut and Toussaint (2010) reported that 50% of 4-year-olds and 23% of 6-year-olds showed the end-state comfort effect in 20% of the trials or less. Some children did not adjust their grasps to the upcoming tasks in a single trial (24–40% of 4-year-olds in Comalli et al., 2016; 11% of 4-year-olds in Keen, Lee, & Adolph, 2014; 25% of 6-year-olds in Stöckel & Hughes, 2015). Second, children who show the end-state comfort effect do so less consistently than adults, often with considerable variability between children (Comalli et al., 2016; Keen et al., 2014).

In the current study, we focused on the first aspect. The differences between children's and adults' grasp selection may be explained in various ways. First, a subset of preschool children may simply not have second-order planning abilities. Second, preschool children may have the ability for second-order planning but still plan their grasps with respect to other criteria than adults (cf. van Swieten et al., 2010), are less efficient than adults (Fuelscher et al., 2016; Stöckel et al., 2012), or might not always be able to implement second-order planning (Comalli et al., 2016; Keen et al., 2014; Wunsch & Weigelt, 2016).

With the experiment presented here, we investigated whether the first explanation can be ruled out, and we argue that preschool children's second-order planning abilities may have gone unnoticed in previous studies for two reasons: First, second-order planning is often probed with tasks in which an object can be grasped in either a comfortable or rather uncomfortable way (Wunsch et al., 2013). To be counted as second-order planners in such tasks, participants need to be capable not only of second-order planning but also of selecting a rather uncomfortable initial grasp even though a comfortable habitual grasp offers itself. In addition, children need to prioritize end-state comfort over other constraints, which might not necessarily be the case due to task demands (Künzell et al., 2013).

Second, second-order planning becomes apparent when participants use different grasps for different object manipulations (Rosenbaum et al., 2012). In the bar transport task, this practically implies that participants assume a comfortable end state. However, both criteria are not identical in other tasks. For example, Wilmut and Byrne (2014a, 2014b) and Fuelscher et al. (2016) asked participants to rotate an octagonal knob. In this task, grasps can be adjusted systematically to different knob rotations without resulting in a comfortable end-state. Indeed, adults typically select grasps that represent a mixture of an initially comfortable grasp and a comfortable end-state (Herbert, 2015; Herbert & Butz, 2012; Lardy, Beurier, & Wang, 2012; Mutsaerts, Steenbergen, & Bekkering, 2006). Thus, whereas the end-state comfort criterion indicates the ability for second-order planning, second-order planning does not imply that a comfortable end-state is strictly required (Jovanovic & Schwarzer, 2017; Rosenbaum et al., 2012; Wunsch et al., 2016). Given that previous knob rotation experiments relied on the end-state comfort criterion for assessing prospective planning abilities (Fuelscher et al., 2016; Wilmut & Byrne, 2014a, 2014b), other forms of second-order planning may have been overlooked.

In the current study, we used a dial rotation task to address whether preschool children consistently use second-order planning. In this task, participants need to grasp and rotate a circular dial (such as the volume control on a stereo). The rotation is typically realized by a combination of finger movements, pronation or supination of the forearm, and adduction or abduction of the shoulder (Herbert & Butz, 2012; Lardy et al., 2012). Due to limits in joint mobility, these motions can be used to rotate an object by only a limited angle. This becomes evident when opening a bottle with a screw cap, which usually requires resetting the grasp several times during the opening movement. To compensate limits in joint mobility, the arm is rotated in a counterclockwise direction when grasping an object that needs to be rotated in a clockwise direction and vice versa (e.g., Herbert & Butz, 2012; Lardy et al., 2012; Mutsaerts et al., 2006). This adjustment of the grasp and the entire arm posture to an intended dial rotation reflects second-order planning (even if it may not maximize end-state comfort) because the finger configuration and arm posture used for grasping is selected based on the intended object manipulation. To test for second-order planning on an individual level, we analyzed for each participant whether grasp selections depended on the direction of the planned dial rotation. This criterion has already often been used to test for second-order planning in comparable tasks (e.g., Cohen & Rosenbaum, 2004; Herbert, 2015; Herbert & Butz, 2012; Mutsaerts et al., 2006; Seegelke, Hughes, Knoblauch, & Schack, 2013; Zhang & Rosenbaum, 2008).

We hypothesized that second-order planning abilities are more likely revealed with the dial task than with the bar transportation task because the dial task does not necessarily require the selection of a rather uncomfortable initial grasp and because participants do not necessarily need to reach a comfortable end-state to be classified as second-order planners.

For comparison, we also administered the frequently used bar transport task (e.g., Hughes, 1996; Manoel & Moreira, 2005; Smyth & Mason, 1997; Stöckel & Hughes, 2015, 2016; Thibaut & Toussaint, 2010; Weigelt & Schack, 2010; Wunsch et al., 2013, 2016). This allowed us to compare our sample of participants with previously reported samples. One should note that we designed the dial task to facilitate the manifestation of second-order planning. By contrast, the bar transport task aimed at replicating previous experiments to allow the comparison with previous results and also to serve as a control condition to ensure that we did not randomly obtain a sample with extraordinary high second-order planning skills. As a consequence, we concur that both tasks differ in various aspects that will make it impossible to provide causal explanations of possible performance differences. For an additional comparison, a young adult control group participated with scaled-up versions of the dial task and the bar transport task.

## Method

### Participants

A total of 24 5- and 6-year-olds (11 girls; mean age = 5.1 years,  $SD = 0.3$ ) from three kindergartens in Landsberg am Lech and Kaufering, Germany, participated in return for sweets. The sample size resulted from the limited opportunity to collect data in the facilities. Handedness was determined with the handedness scale of the Lateral Preference Inventory (Coren, 1993). According to the questionnaire, 15 children were right-handed and 9 had no hand preference. In addition, 24 adults (15 women; mean age = 28.3 years,  $SD = 9.8$ ) were recruited in Würzburg, Germany, and received payment or course credit. Of the adults, 19 were right-handed, 4 were left-handed, and 1 had no preference. Participants or their parents signed informed consent prior to the experiment. The study was approved by the ethics committee of the Department of Psychology at the University of Würzburg (GZEK 2017-08).

### Apparatus and procedure

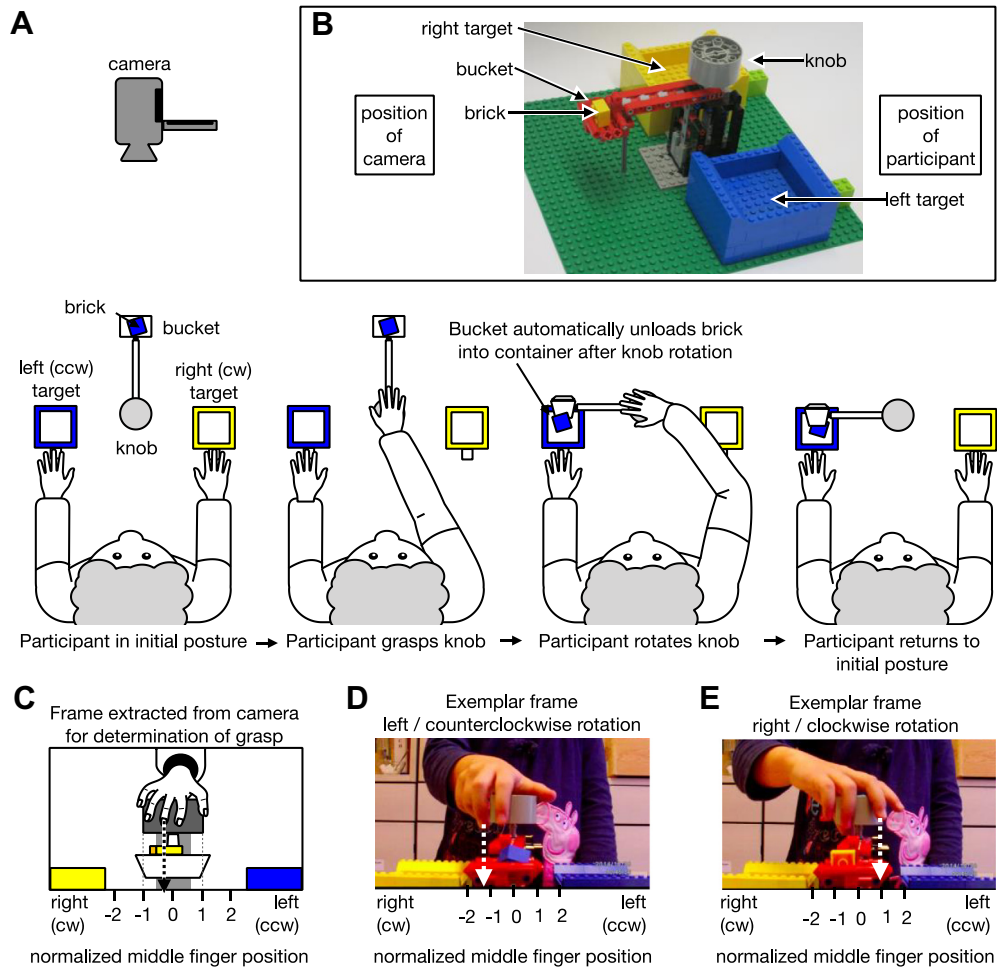
Participants stood in front of a table on which both tasks were set up. For the children, the table heights were between 55 and 58 cm, either from the ground or from a stool on which the children stood during the experiment. The adults' table was 74 cm high. A digital video camera was placed in front of the participants and centered on the initial position of the bar or dial.

Fig. 1A and B illustrate the procedure and show the apparatus, which involved a custom-built bulk-handling crane. A bucket was attached to the crane's beam (11 cm). The beam and bucket could be rotated by a cylindrical dial by 90° in either direction. For the children, the dial's height was 2.4 cm and its diameter was 4.3 cm. For the adults, the height was 3.9 cm and the diameter was 6.4 cm. On either side of the crane was a blue or yellow container. The bucket automatically unloaded its contents when it was rotated to one of the containers. There were 10 blue and 10 yellow 2 × 2 Lego bricks (1.6 × 1.6 × 1.1 cm) that were used as cargo. Behind the containers were two start position grips.

Fig. 1A illustrates the procedure (a video of the task is provided in the online supplementary material as an electronic supplement to this article). Each trial of the dial task began when participants grasped the start position grips and when the experimenter had centered the beam. Then, the experimenter inserted a brick into the bucket. Bricks were randomly drawn by the experimenter with closed eyes from a bowl. The participants' task was to haul the brick into the container with the respective color. This was accomplished by grasping the dial, rotating it by 90° in a clockwise or counterclockwise direction, and then releasing the dial. After that, the experimenter pushed the beam to the starting position with the index-finger. When the participants dumped the brick in the wrong container, dropped the brick during the rotation, or when the crane malfunctioned, the brick was put back into the bowl and reused later. Otherwise, the brick was left in the container. Three blocks of 20 dial trials (10 rotations to the right and 10 to the left) were administered. Before each block, the bricks were retrieved from the containers, put back in the bowl, and stirred. The position of the containers (blue left/yellow right vs. yellow left/blue right) was counterbalanced over participants. Each participant needed to execute 30 clockwise and 30 counterclockwise dial rotations. The duration of the dial task was between 5 and 10 min in children ( $M = 6.9$  min) and between 4 and 6 min in adults ( $M = 4.9$  min).

The bar transport task is illustrated in Fig. 2. The bar used by the children was 16.8 cm long and had a diameter of 2.5 cm. The adult version was 25.2 cm long and had a diameter of 3.5 cm. Both bars were made out of wood and had a black and white end (Fig. 2D). The bar could be placed horizontally on two supports (height for children = 5.8 cm; height for adults = 8.8 cm). A blue target circle (diameter of 4 cm for children and 6 cm for adults) was located between the supports but displaced 10 cm toward the participant.

The trial procedure is illustrated in Fig. 2A and B. At the beginning of each trial, the participant placed his or her hands on the table and the experimenter placed the bar horizontally on the supports (with a pincer grip). Then, the experimenter told the participant which end of the bar was to be placed

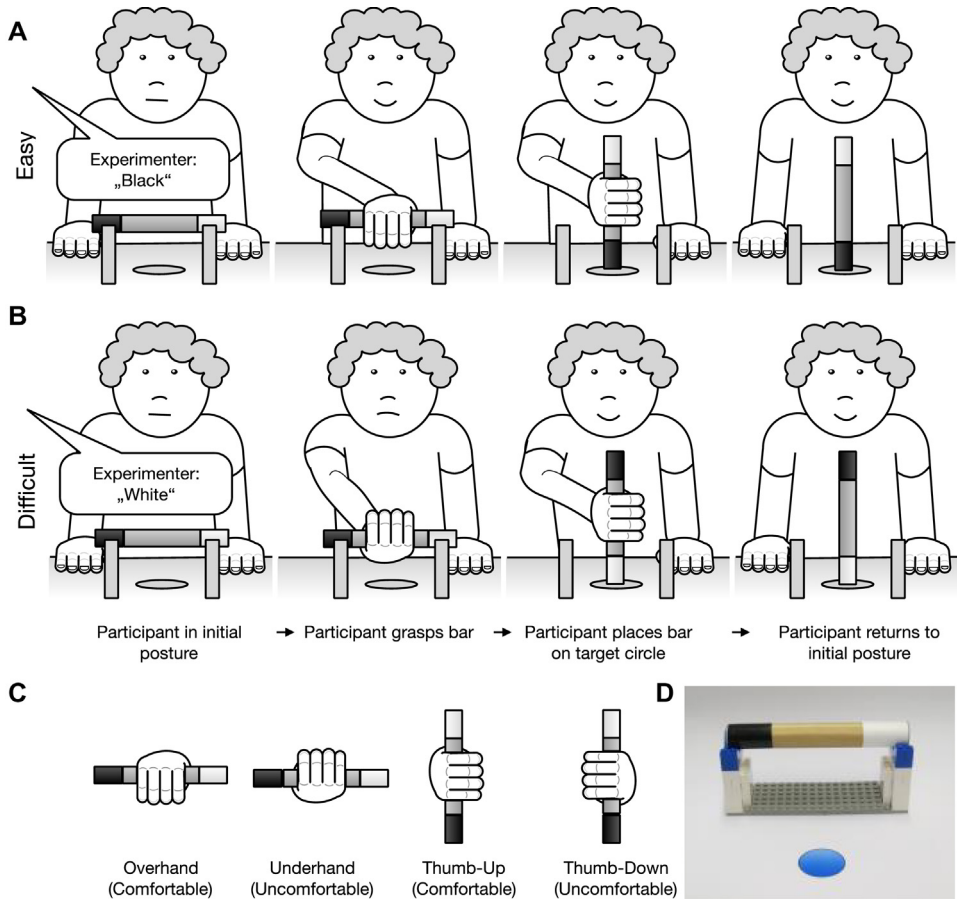


**Fig. 1.** Dial task. (A) The sequence of events in a trial. (B) The child version of the dial apparatus. (C) The figure shows how the normalized middle finger position (the screen position of the middle finger normalized by the screen size/position of the dial) relates to the grasp. Note that left and right are coded with respect to the participant's point of view. (D, E) The figures show exemplar frames of how the dial was grasped *before* counterclockwise and clockwise rotations. cw, clockwise; ccw, counterclockwise.

on the target by saying the German word for “black” or “white,” and the participant grasped the bar and placed it vertically on the target circle. The participant was free to use an overhand or underhand grasp and to use the left or right hand (cf. [Comalli et al., 2016](#); [Manoel & Moreira, 2005](#)).

Three repetitions of each combination of start position (left black, right black) and target color (black, white) were administered. These trials were grouped into six “easy” and six “difficult” trials. In easy trials, an initially comfortable overhand grasp with the dominant hand resulted in a comfortable end state ([Fig. 2A](#) and [C](#)). In difficult trials, only an initially uncomfortable underhand grasp or a comfortable grasp with the nondominant hand resulted in a comfortable end state. The order of trials was randomized and provided to the experimenter in the form of a list. Children completed the task in 1–2 min ( $M = 1.2$  min). All adults finished the task within 1 min.

The bar rotation task and the dial task were performed in counterbalanced order. The children performed the bar and dial tasks after participating in an unrelated dual-task experiment in which



**Fig. 2.** Bar transport task. (A) The sequence of events in an easy trial (assuming the participant is right-handed). (B) The sequence of events in a difficult trial (assuming the participant is right-handed). The cartoon participant uses an initially uncomfortable underhand grasp that results in a comfortable end-state and, thus, shows second-order planning. (C) The figure shows the terms that describe the possible grasps and end-states. (D) The child version of the bar transport task from the participant's view.

features of visual stimuli needed to be classified with finger button and foot pedal presses (Janczyk, Büschelberger, & Herbert, 2017).

#### Data reduction and analysis

For each trial in each task, the frame before and after the object manipulation was extracted from the videos. First, the frame before the bar manipulation was extracted when the participant grasped the bar but had not yet moved it. The frame after the bar manipulation was extracted when the bar was placed on the target. Second, the frame before the dial rotation was defined as the frame before the bucket first moved and the dial was grasped with at least two fingers. In addition, a frame was extracted after the dial rotation. Frames of trials in which the participant did not follow instructions or made an error, or in which the equipment malfunctioned, were not extracted.<sup>1</sup>

<sup>1</sup> We kept track of only the number of excluded trials in the child task, where 6.8% of the dial trials and 1.4% of the bar trials were excluded from analyses. These trials were repeated by the experimenter, and the repetitions were included in the analysis.



The frames of each participant were shown to four raters in randomized order. The frames of the dial task were cropped in such a way that neither the brick in the bucket nor the container was visible (i.e., raters did not know the target). For the dial task, the raters marked the position of the tip of the middle finger in the frame before dial rotation onset and coded the used hand. Fig. 1C–E shows a cartoon of such a frame and two exemplar frames. The screen coordinates of the middle finger (in pixels) were normalized by the screen size and position of the dial (in pixels). The higher the value, the farther the grasp is rotated in a counterclockwise direction (or to the left from the participant's view); the lower the value, the farther the grasp is rotated in a clockwise direction (or to the right). A value of  $-1$  means that the middle finger is on the right edge of the dial (from the participant's view), a value of  $0$  means that the middle finger is exactly in the middle of the dial, and a value of  $1$  means that the middle finger is on the left edge of the dial. The crane orientation after the rotation was automatically extracted using a custom Matlab script. For the bar transport task, the raters extracted whether an underhand grasp or an overhand grasp was used, which hand was used, and how the bar was oriented before and after the bar rotation.

The categorizations made by the majority of the raters (bar task: grip choice, hand, initial and final bar positions; dial task: hand) were used for analyses. Overall, all four raters agreed in 98.76% of all cases, three of four agreed in another 1.22% of all cases, and a single undecided case (0.02%) was classified by one of the authors. The mean of horizontal middle finger positions extracted by the four raters was used for further analyses of the dial task. Raters reached a high level of agreement. The absolute difference between any two raters was on average 11 pixels or 0.086 in terms of the normalized middle finger position, which is a small value in comparison with the effects reported below.

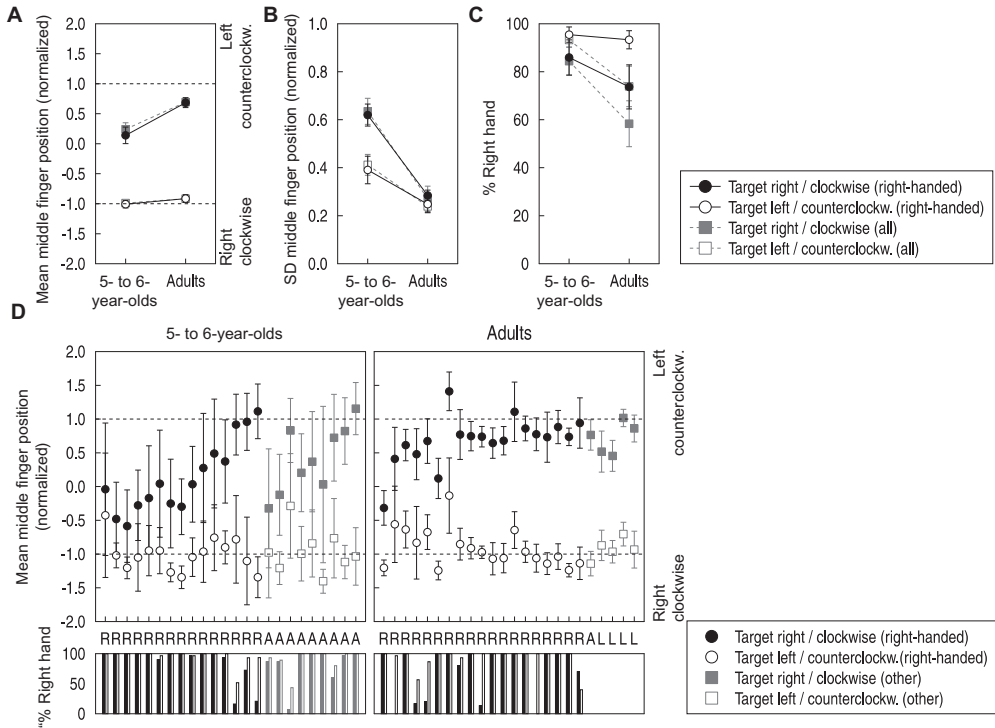
Due to errors of the experimenter (e.g., a brick was lost during one session, incorrect instructions read from list), a few trials were not administered as originally planned. In the dial task, the actually administered number of left and right rotations deviated on average by 0.2 trials from the planned 30 trials. In the bar trials, two or four repetitions instead of the planned three repetitions of a specific combination of initial and final bar positions were administered in 4.7% of all cases.

To allow the comparison of the bar and dial tasks despite the differences in the dependent variables, we categorized participants into those who showed second-order planning and those who did not. In the bar transport task, a participant was considered a second-order planner when the grasp resulted in a comfortable end-state in at least 83.3% (i.e., 5 of 6) of the difficult trials. This method for categorizing participants is frequently used for this task, albeit with differing thresholds (Hughes, 1996; Weigelt & Schack, 2010; Wunsch et al., 2013). In the dial task, a participant was considered a second-order planner when the middle finger in the frames before movement onset was significantly farther to the right for leftward (counterclockwise) rotations than for rightward (clockwise) rotations, according to an independent-sample one-sided  $t$  test computed on the individual trials of each participant. That is, for each participant, a separate  $t$  test was conducted. To guard against the possibility that a participant who selects grasps randomly is more likely to be classified as a second-order planner in one task than in the other, we tried to equate the criteria of both tasks as far as possible. To this end, we computed the probability that a participant who selects grasps randomly in the bar task is classified as second-order planner ( $p = .1094$ ) and used this probability as the  $\alpha$  value for the individual  $t$  tests in the dial tasks.

## Results

### *Dial task*

Fig. 3A–C show the mean positions of the middle finger when grasping the dial, the mean of the participantwise standard deviations of the middle finger position, and the percentages of right-hand grasps when considering only right-handed participants (black). For comparison, the data of all participants (gray) are displayed as well. Fig. 3D shows how individual participants grasped the dial and which hand they used. All participants adjusted their grasps to the upcoming rotation. Some participants supported this adjustment by using different hands for different rotations, but most participants used (almost) exclusively one hand for the dial task. Moreover, adults were more



**Fig. 3.** (A) Mean middle finger position by age and rotation direction. The black lines show the data of the analyzed right-handers. The gray lines show the data of all participants. The dashed horizontal lines show the horizontal positions of the dial's border in the extracted frames. Error bars show  $\pm 1$  standard error of the mean. (B) Mean participantwise standard deviations of the middle finger position by age and rotation direction. (C) Mean percentages of right-hand dial rotations by age and rotation direction. (D) Middle finger positions and hand choices by individual participants. Error bars show  $\pm 1$  standard deviation. The letters on the x axis indicate the handedness of each participant (R = right, L = left, A = ambidextrous). The dashed lines show the horizontal positions of the dial's border in the extracted frames. The data of ambidextrous and left-handed participants are plotted as gray squares.

consistent in their grasp choices on an intra- and inter-individual level. To test these descriptions statistically, we conducted split-plot analyses of variance (ANOVAs) with a within-participant factor of rotation direction (left, right) and a between-participant factor of age group. Significant effects involving the dial target are followed up with  $t$  tests for each age group. We included only the right-handed participants in the following analysis.<sup>2</sup>

The mean middle finger position is presented in Fig. 3A. Adults generally positioned their middle finger farther to the left (from their view, counterclockwise) than the 5- and 6-year-olds,  $F(1, 32) = 10.138$ ,  $p = .003$ ,  $\eta_p^2 = .241$ . In addition, participants placed their middle finger farther to the left before rotations to the right and farther to the right before rotations to the left,  $F(1, 32) = 315.531$ ,  $p < .001$ ,  $\eta_p^2 = .908$ . This difference was larger for adults than for children,  $F(1, 32) = 8.540$ ,  $p = .006$ ,  $\eta_p^2 = .211$ , for the interaction. Follow-up paired  $t$  tests revealed that both children and adults used different grasps for rotations in different directions, children:  $t(14) = 7.878$ ,  $p < .001$ ,  $d_z = 2.034$ ; adults:  $t(18) = 21.134$ ,  $p < .001$ ,  $d_z = 4.848$ .

The participantwise standard deviations of the middle finger positions reflect the intra-individual variability of grasps in the dial task (Fig. 3B). It was larger in children than in adults,  $F(1, 32) = 25.665$ ,

<sup>2</sup> An analysis of all participants would have yielded the same pattern of results, with the exception of a main effect of age group on hand selection, which can be attributed to the higher number of left-handers in the adult group.



$p < .001$ ,  $\eta_p^2 = .445$ . In addition, intra-individual variability was larger for rotations to the right,  $F(1, 32) = 19.228$ ,  $p < .001$ ,  $\eta_p^2 = .375$ , and this difference was particularly pronounced in children,  $F(1, 32) = 10.067$ ,  $p = .003$ ,  $\eta_p^2 = .239$ . Follow-up paired  $t$  tests revealed significantly higher intra-individual variability in grasps for rotations to the right than to the left in children,  $t(14) = 3.892$ ,  $p = .002$ ,  $d_z = 1.005$ . In contrast, there was no significant difference between rotation directions in adults,  $t(18) = 1.337$ ,  $p = .198$ ,  $d_z = 0.307$ . Thus, the intra-individual variability in grasp selections was larger for children than for adults, especially for rotations to the right.

Fig. 3C shows the percentages of right-hand grasps. Participants used the right hand more frequently for rotations to the left,  $F(1, 32) = 7.042$ ,  $p = .012$ ,  $\eta_p^2 = .180$ . There was no significant difference between age groups,  $F(1, 32) = 0.893$ ,  $p = .352$ ,  $\eta_p^2 = .027$ , and no significant interaction,  $F(1, 32) = 0.852$ ,  $p = .363$ ,  $\eta_p^2 = .026$ . The effect of dial target on hand selection was not significant in children,  $t(14) = 1.819$ ,  $p = .090$ ,  $d_z = 0.470$ , and reached significance in adults,  $t(18) = 2.226$ ,  $p = .039$ ,  $d_z = 0.511$ . Overall, the rotation direction tended to affect hand selections.

Finally, we compared the inter-individual variability of grasps between both age groups. A Levene test indicated that the variability of middle finger position between children ( $SD = 0.535$ ) was higher than that between adults ( $SD = 0.359$ ) for rotations to the right,  $F(1, 32) = 4.842$ ,  $p = .035$ . No difference between children ( $SD = 0.242$ ) and adults ( $SD = 0.283$ ) was found for rotations to the left,  $F(1, 32) = 0.519$ ,  $p = .476$ .

#### *Effect of block on grasp selection in dial task*

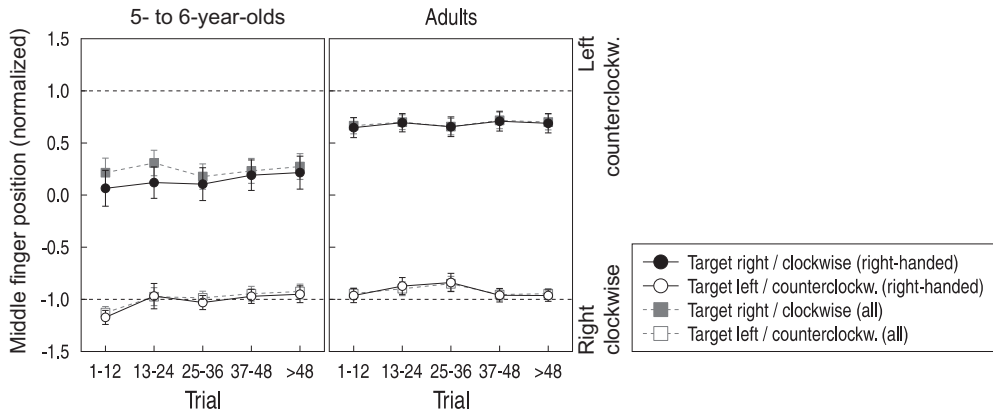
Because the dial task involved more trials than the bar task, we investigated whether second-order planning benefitted from the additional exposure to the task. The trials of the dial task were split into five blocks (1–12, 13–24, 25–36, 36–48, >48). A split-plot ANOVA on the mean normalized middle finger position with within-participant factors of block and rotation direction (clockwise, counterclockwise) and a between-participant factor of age group was computed for right-handed participants.<sup>3</sup> Fig. 4 shows the results. Adults' grasps were generally farther to the left,  $F(1, 32) = 10.396$ ,  $p = .003$ ,  $\eta_p^2 = .245$ . The participants rotated their hands against the direction of the upcoming dial rotation before grasping,  $F(1, 32) = 316.271$ ,  $p < .001$ ,  $\eta_p^2 = .908$ . This effect was larger in adults than in children,  $F(1, 32) = 8.077$ ,  $p = .008$ ,  $\eta_p^2 = .202$ ,  $\varepsilon = .746$ . There was no main effect of block,  $F(4, 128) = 2.036$ ,  $p = .114$ ,  $\eta_p^2 = .060$ ,  $\varepsilon = .746$ , and no interaction between block and age group,  $F(4, 128) = 1.329$ ,  $p = .270$ ,  $\eta_p^2 = .040$ ,  $\varepsilon = .746$ . Most important, there was no interaction between block and rotation direction,  $F(4, 128) = 0.909$ ,  $p = .445$ ,  $\eta_p^2 = .028$ ,  $\varepsilon = .806$ , and no three-way interaction,  $F(4, 128) = 0.397$ ,  $p = .769$ ,  $\eta_p^2 = .012$ ,  $\varepsilon = .806$ . Hence, children and adults adapted their grasps to the different rotations from the first trials onward.

#### *Bar transport task*

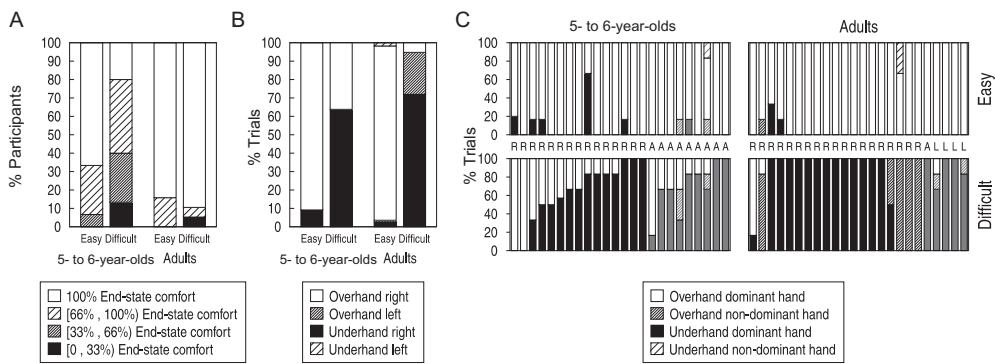
Fig. 5 provides more detailed information on grasp choices in the bar transport task. Only data of right-handed participants were used for analyses. Fig. 5A shows the percentages of participants ending the bar rotations in various percentages of trials. Nearly all adults consistently ended in a comfortable posture in easy and difficult trials (Fig. 5C). By contrast, children revealed a higher inter-individual variability, especially in difficult trials. Fisher's exact test revealed differences between children and adults in difficult trials ( $p < .001$ ) but not in easy trials ( $p = .300$ ).

Fig. 5B shows the average percentages of grasp choices of right-handed participants. Between-participant  $t$  tests revealed no differences in the percentages of the different grasp choices between age groups in the easy trials (all  $ps \geq .209$ ). In the difficult trials, by contrast, adults used a left-handed overhand grasp more frequently than children,  $t(18) = 2.453$ ,  $p = .025$ ,  $d_s = 0.751$ . In turn, children used the right-handed overhand grasp more frequently than adults,  $t(21.487) = 3.245$ ,  $p = .004$ ,  $d_s = 1.189$ . Underhand grasps with the right hand were used with comparable frequency ( $p = .554$ ), and underhand grasps with the left hand were never used. An inspection of the individual

<sup>3</sup> Greenhouse–Geisser corrected  $p$  values, but uncorrected  $df$  values, are reported. The analysis of all participants did not reveal significant effects or interactions involving the factor block (all  $ps \geq .226$ ).



**Fig. 4.** Grasp over blocks in the dial task. The chart shows the normalized position of the middle finger when grasping the dial for leftward and rightward dial rotations and for different blocks of trials. The horizontal dashed lines show the horizontal positions of the dial's border in the extracted frames. Error bars show  $\pm 1$  standard error of the mean.



**Fig. 5.** (A) Distribution of the percentages of trials with comfortable end-state for right-handed participants. (B) Percentages of grasps/hand used by right-handed participants. (C) Grasp choices of individual participants. The letters on the x axis indicate the handedness of each participant (R = right, L = left, A = ambidextrous). The data of ambidextrous and left-handed participants are plotted in gray.

grasp choices (Fig. 5C) reveals that all children used the dominant hand in the majority of trials. By contrast, several adults realized a comfortable end-state in difficult trials by grasping the bar with the nondominant hand.

Finally, various dependent variables have been used in the literature to describe the end-state comfort effect in children. To enable a comparison of the current bar transport task with similar tasks in previous studies, we applied the classification criteria of these studies to our data (using the data of all participants). Table 1 shows that our sample of children was similar to those in other reports.

#### Task comparison

Finally, we compared the percentages of second-order planners in both age groups. Again, we analyzed only the data of right-handed participants. Fig. 6A shows the percentages of right-handers classified as second-order planners. The frequency of second-order planners across age groups was compared with two-sided Fisher's exact test. In the bar transport task, the difficult trials are used to

**Table 1**

Comparison with previous reports of bar transport task with normally developing children using the previous reports' criteria.

Criterion	Source	Total trials	Age (years)	Result (%)	n
Comfortable end-state in at least two of three difficult trials	Weigelt and Schack (2010)	6	5.7	70	17
	Wunsch et al. (2016)	6	5.4	62	26
	Current experiment <sup>a</sup>	12	5.1	67	24
Comfortable end-state in at least three of four difficult trials	Hughes (1996)	8	4.0	71	28
	Current experiment <sup>b</sup>	12	5.1	63	24
Percentage of difficult trials with comfortable end-state	Manoel and Moreira (2005)	10	5.2	59 <sup>c</sup>	6
	Smyth and Mason (1997)	16	5.0–6.0	64 <sup>d</sup>	25
	Stöckel and Hughes (2015)	8	6.6	58	16
	Thibaut and Toussaint (2010, Experiment 1)	20	6.3	66	30
	Thibaut and Toussaint (2010, Experiment 2)	12	6.5	75 <sup>e</sup>	20
	Toussaint, Tahej, Thibaut, Possamai, and Badets (2013)	20	5.9	55 <sup>f</sup>	32
	Current experiment	12	5.1	68	24

<sup>a</sup> Only the first three critical trials were analyzed.<sup>b</sup> Only the first four critical trials were analyzed.<sup>c</sup> Extracted from their Fig. 3.<sup>d</sup> Extracted from their Fig. 4.<sup>e</sup> Mean of three tasks extracted from their Fig. 5.<sup>f</sup> Extracted from their Fig. 2.

determine second-order planning. Here, fewer children (47%) than adults (95%) were classified as second-order planners ( $p = .004$ ). In easy trials, 87% of children and 95% of adults ended their movements in a comfortable posture in at least 5 of 6 trials ( $p = .571$ ). In the dial rotation task, all children and adults were classified as second-order planners. Finally, the proportion of participants who were classified as second-order planners in the dial task, but not in the bar transport task, was larger for the children than for the adults (Fisher's exact test,  $p = .004$ ). Fig. 6B shows that a comparable pattern of results emerges for ambidextrous participants<sup>4</sup> and the entire set of participants.

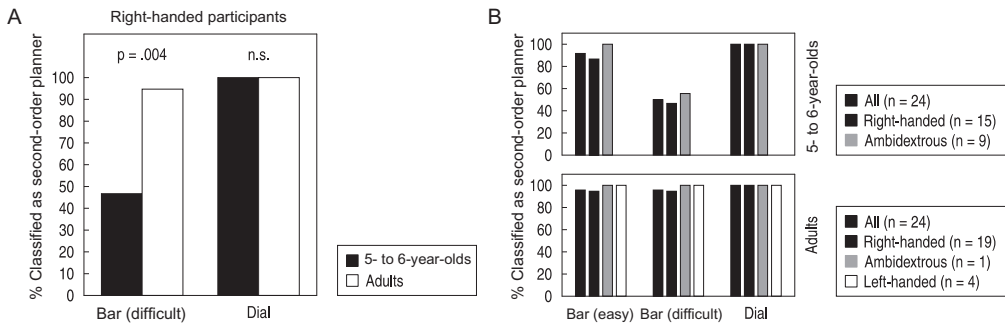
## Discussion

Although preschool children have a broad motor repertoire (e.g., climbing, cycling, drawing), in many experimental tasks they do not adjust their grasps to upcoming object manipulations as consistently as adults do. In the current study, we tested the hypothesis that preschool children in fact have the ability for second-order planning but that this ability is not manifested in the often used bar transport task. This hypothesis was borne out by our experiment. Comparable to previous reports (Table 1), only about half of the children adjusted their grasps consistently to upcoming bar rotations, and some did not do so on even a single trial. In the dial task, however, all children adjusted their grasps to the upcoming dial rotations and, thus, revealed second-order planning.

### Grasp selection strategies

In both tasks, participants could adapt to different object manipulations by selecting a specific hand or by adjusting the orientation of the hand when grasping the object (Comalli et al., 2016; Keen et al., 2014; Manoel & Moreira, 2005). In the dial task, most participants used the dominant hand (almost

<sup>4</sup> The difficulty of a bar task trial depends on the participant's handedness. For ambidextrous participants, the preferred hand in the bar task (over all trials) has been used to group the trials into easy and difficult trials. This can be justified because 8 of 10 ambidextrous participants used only one hand (6 right, 2 left) and the remaining 2 used the right hand in 75% of trials. Nevertheless, the data of the ambidextrous participants in the bar task should be treated with caution.



**Fig. 6.** (A) Percentages of second-order planners by task and age. The chart shows the percentage of right-handed participants classified as second-order planners. (B) Percentages of second-order planners by handedness, task, and age. The chart shows that the percentages of second-order planners are comparable for different subgroups as well as the entire group of participants. For ambidextrous participants, bar task difficulty was determined based on the preferred hand in the bar task. For comparison, data from the easy bar task trials also are shown.

exclusively. These participants adapted their grasps to different task demands by selecting a more clockwise-rotated grasp for counterclockwise rotations and a more counterclockwise-rotated grasp for clockwise rotations. A few participants selected which hand to use depending on the upcoming rotation. These participants tended to rotate the dial clockwise with the left hand and counterclockwise with the right hand.<sup>5</sup> Both strategies were used by children and adults alike. However, adults were more consistent in their grasp choices than children on both the inter- and intra-individual levels.

An unexpected finding was that the variability of grasps between groups and between children was relatively large for clockwise rotations but not for counterclockwise rotations. An inspection of the videos suggests that morphological constraints limited grasp variability in the latter case. Participants usually grasped the dial with a bent elbow and, thus, could realize a part of the dial rotation by pivoting the shoulder (i.e., moving the elbow inward or outward; cf. Fig. 1A). During grasping movements on clockwise trials, they typically moved the elbow outward and upward, toward a relatively awkward initial posture. From this posture, they moved the elbow downward again to rotate the dial clockwise, back toward a relatively comfortable posture (elbow near trunk). On clockwise trials, thus, participants needed to decide how far they wanted to lift the elbow (investing energy and comfort) in order to facilitate the dial rotation and may have differed in their decisions. This strategy, however, cannot be applied for counterclockwise rotations. Because it is impossible to move the elbow inward by a considerable amount (e.g., because the upper arm would collide with the torso), participants could not assume a start posture that would result in a relatively comfortable end-state. Hence, participants needed to start with a relatively comfortable posture (elbow near trunk) and then move the elbow upward and outward during the rotation regardless of their second-order planning abilities. Consequently, grasp variability for counterclockwise rotation might have been low.

Although all children and adults showed second-order planning, grasp selections of children and adults clearly differed. However, this does not imply that preschool children are less proficient planners. First, the optimal grasps for children and adults might differ because it is currently unclear what grasps constitute optimal performance in comparable tasks (Rosenbaum et al., 2014). Hence, the differences in average grasp selection do not allow conclusions about the accuracy of planning. Second, children's higher intra-individual variability could reflect a generally higher variability in movement execution (Schneiberg, Sveistrup, McFadyen, McKinley, & Levin, 2002) and, therefore, might not necessarily be attributed to limitations in second-order planning.

In the bar transport task, most children always used the right hand. Whereas some children consistently used an underhand grasp in difficult trials, other children never did so and some varied their

<sup>5</sup> Surprisingly, some of these participants (one child, two adults) used the left hand relatively frequently, although they were right-handers. An inspection of the handedness scores and the videos of these participants revealed no obvious reason for this behavior.

grasps throughout the experiment. By contrast, most adults consistently showed the end-state comfort effect. Unlike children, some adults used overhand grasps with the nondominant hand to reach a comfortable end state. This suggests that adults might apply different strategies to avoid awkward arm postures during the object manipulation (cf. [Coelho et al., 2014](#)).

In addition, for the bar transport task, it is difficult to draw conclusions about an individual's planning abilities from an absent or inconsistent end-state comfort effect. A reduced end-state comfort effect could be not only the result of limited planning abilities (e.g., [Fuelscher et al., 2016](#); [Stöckel et al., 2012](#)) but also the result of differences in the planning criteria. For example, children might prioritize initial comfort to facilitate grasping movements.

In summary, the data support the conclusion that preschool children can prospectively adjust their grasps to an upcoming object manipulation. Whereas this ability might not become apparent in the bar transport task, it is consistently revealed in the dial task. In both tasks, children select grasps less consistently than adults. However, it is unclear whether this points to limitations in the accuracy and consistency of second-order planning in children or to different planning criteria.

In general, the data are consistent with the three-stage model for the acquisition of anticipatory planning skills ([Wunsch & Weigelt, 2016](#)). According to this model, children start to adapt their grasps to different tasks at 3 or 4 years of age. However, until 10 years of age, the links between different grasps and the associated end states remain weak. This, then, results in high inter- and intra-individual variability, as observed in the preschool children in the current experiment. Only at the final stage are grasps consistently adjusted to the upcoming task, as observed in adults.

#### *Relation to previous experiments*

The bar transport task was administered to allow a comparison of the current sample with those of previous experiments. Adults usually show the end-state comfort effect consistently in the bar task and related tasks ([Coelho et al., 2014](#); [Comalli et al., 2016](#); [Rosenbaum et al., 1990](#); [Wunsch et al., 2016](#)), and this was also found in the current experiment. [Table 1](#) shows that also children's grasp selections in the current bar transport task were very similar to previous reports when applying the respective criteria. Moreover, grasp selections for bar rotations revealed remarkable similarities to grasp selections for tool-use actions. [Comalli et al. \(2016\)](#) reported that 4-year-olds showed the end-state comfort effect in 38% of trials when grasping a hammer for hammering. Interestingly, in the hammering study, children sometimes used the nondominant hand, but adults never did so. In our experiment, right-handed children always used the dominant hand, but some right-handed adults used a left-hand overhand grasp in difficult trials. [Keen et al. \(2014\)](#) reported that 11% of right-handed 4-year-olds grasped a spoon (with the bowl pointing to the right) with an ulnar grip in all trials, resulting in nonfunctional grasps for feeding. This corresponds closely to the 13% of children who never showed the end-state comfort effect in our bar transport task. In summary, the results obtained with the bar transport task closely replicate those from previous studies, suggesting that our sample of participants was also comparable to those of previous studies.

Object manipulation tasks with circular or polygonal objects have been frequently used to study second-order planning in adults (e.g., [Haggard, 1998](#); [Herbert & Butz, 2012, 2015](#); [Lardy et al., 2012](#); [Mutsaerts et al., 2006](#); [Seegelke et al., 2013](#); [Zhang & Rosenbaum, 2008](#)). These experiments show that adults use different grasps for different rotations. This pattern was replicated in the current experiment. The current data also show that all tested adults consistently show this effect on an individual level (cf. [Mutsaerts et al., 2006](#)).

Comparable tasks have also been used with children ([Fuelscher et al., 2016](#); [Wilmot & Byrne, 2014a, 2014b](#)). In these experiments, children were asked to grasp and rotate an octagonal knob. The percentage of grasps that resulted in a comfortable end-state increased from about 30–50% in 4- to 6-year-olds to about 70–80% in young adults. The data of our dial task mirror these results by showing that preschool children tend to select less distinct grasps for clockwise and counterclockwise rotations, which are consequently less likely to end in comfortable postures. A key difference between both tasks is the categorization of the grasps. [Fuelscher et al. \(2016\)](#) and [Wilmot and Byrne \(2014a, 2014b\)](#) associated grasps with different strategies ([van Swieten et al., 2010](#)). The only strategy that reflected second-order planning was the end-state comfort strategy, which required

rotations to end in a comfortable posture. By contrast, we checked whether grasps were systematically adjusted to the upcoming dial rotation (for similar analyses, see, e.g., [Cohen & Rosenbaum, 2004](#); [Herbert, 2015](#); [Jovanovic & Schwarzer, 2017](#); [Mutsaerts et al., 2006](#); [Seegelke et al., 2013](#); [Zhang & Rosenbaum, 2008](#)). This criterion subsumes grasps that result in a comfortable end-state but also reflects other second-order planning strategies such as a compromise between start-state and end-state comfort. In general, our data are consistent with those reported earlier and also substantiate that the vast majority of preschool children (100% in our sample) are—in principle—capable of second-order planning.

### *Speculation on the relationship between the dial and bar tasks*

Because the dial task differed in various aspects from the bar transport task, it is impossible to pinpoint the factors that caused the differences between the tasks. In the following, we nevertheless discuss potential reasons for the task differences, although we concur that further controlled comparisons of the tasks would be necessary to substantiate these speculations (for a better controlled comparison of both tasks in adults, see [Herbert & Butz, 2015](#)).

The differences between tasks could partially be a result of the statistical properties of the different tasks and analyses. We used a relatively common classification strategy for the bar transport task and tried to find an equivalent criterion with respect to the probability of false positives for the dial task. Due to the higher trial number and the continuous dependent variable, the dial task may be more sensitive.

However, an inspection of the data revealed that some participants never showed the end-state comfort effect in the bar transport task but consistently adjusted the grasp to the task in the dial task.<sup>6</sup> Thus, statistical power cannot fully explain the task differences. We speculate that the different object shapes may have affected the implementation of second-order planning differentially. In the bar task, second-order planning becomes apparent only when a relatively uncomfortable initial grasp is preferred over a comfortable initial grasp. It might be difficult for some preschool children to inhibit the selection of the comfortable habitual grasp because inhibition is still developing during childhood. Indeed, the development of inhibition (e.g., as measured in a Go/NoGo task) corresponds to the development of performance in the bar task ([Brocki & Bohlin, 2004](#); [Carlson, 2005](#); [Williams, Ponesse, Schachar, Logan, & Tannock, 1999](#); but see [Stöckel & Hughes, 2016](#)). By contrast, it might be easier to integrate habitual and prospective aspects of grasp selection into the dial task ([Herbert & Butz, 2012](#)).

The dial task may have been more interesting and engaging to children. However, because enrichments of the bar transport task have been reported to not affect grasp selections substantially ([Knudsen et al., 2012](#); [Manoel & Moreira, 2005](#); [Thibaut & Toussaint, 2010](#)), it is unlikely that this caused the differences in apparent second-order planning abilities.

Finally, object manipulations were instructed verbally, and the instruction needed to be memorized in the bar transport task. By contrast, in the dial task, the goal was defined by the color of the cargo brick and remained visible throughout the trial. Again, this task difference is unlikely to account for differences in grasp selections, as suggested by an experiment with visually instructed bar rotations ([van Swieten et al., 2010](#)). Here, only about 50% of 5- to 8-year-olds showed the end-state comfort effect.

### *Conclusion*

Previous research has reported that children do not systematically adjust their grasps to different object manipulations until 10 years of age. Different explanations have been suggested for the protracted development of grasp selection for object manipulation. One possible reason is that some children cannot incorporate the demands of upcoming object manipulations into their plans for grasping movements. Our data show that this explanation is unlikely in the case of preschool children. When the preschool children performed the often applied bar task, many could not be classified as

<sup>6</sup> One of the children who never adjusted the grasp to the bar task had the second largest difference in grasps for clockwise and counterclockwise rotations in the dial task. The other one ranked 8th out of 15.



second-order planners by various criteria—some did not show evidence of second-order planning on even a single trial—and this replicated results reported by earlier work. By contrast, each individual participant adjusted her or his grasp to an upcoming object manipulation in a dial task. Thus, pre-school children—as a rule—have the ability for second-order planning.

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