

BRIEF REPORT

Effects of Multiple Planning Constraints on the Development of Grasp Posture Planning in 6- to 10-Year-Old Children

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This experiment examined how multiple planning constraints affect grasp posture planning in 6- to 10-year-old children ($n = 16$ in each group) by manipulating the intended object end-orientation (left end-down, right end-down) and initial precision demands (standard, initial precision) of a bar transport task. Results indicated that grasp posture planning was strongly influenced by multiple planning constraints. During the standard condition the sensitivity toward comfortable final hand postures (end-state comfort) was similar for all age groups in right end-down trials, and corresponded to values reported in adult populations. In contrast, there was an age-related increase in end-state comfort compliance during left end-down trials. During the initial precision condition end-state comfort was similar across all groups for left end-down trials. However, end-state comfort compliance was significantly lower for the 6-year-old children than in all other age groups for right end-down trials. In sum, the ability of children to plan their goal-related movements is influenced by the presence of task-related constraints that increase the overall cognitive demands of the task. The demands associated with selecting the appropriate grasp posture during the most cognitive demanding condition required more cognitive resources than 6- to 10-year-old children possess. Removing the conflict between the goal-directed and habitual systems reduces some of these costs, with data indicating that the ability to integrate multiple planning constraints first emerges at 7 years of age, and improves over the developmental spectrum.

Keywords: end-state comfort effect, anticipatory motor planning, motor development, cognitive costs

A characteristic of successful motor performance is the ability to plan and execute movements in such a fashion that everyday tasks can be accomplished. Humans use the goal-directed system and the habitual system to produce instrumental behavior (Dickinson & Balleine, 2002). The habitual system reflects the tendency of individuals to repeat behaviors that have led to desirable outcomes in the past, without consideration of the causal relationship between action and outcome, or the consequences associated with the selected action (Balleine & Dickinson, 1998; Creem & Proffitt, 2001; Daw, Niv, & Dayan, 2005). For example, Creem and Proffitt (2001) examined tool grasping and transport, and reported that participants grasped the objects with prototypical grasps, even if doing so resulted in cumbersome upper extremity postures.

The goal-directed system, by contrast, organizes actions with respect to the properties of the object (e.g., size, shape, location;

Jeannerod, 1981, 1984), the affordances that the object provides (e.g., Gentilucci, 2002), and future task demands (e.g., Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987; Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012). The influence of the goal-directed system has also been observed in children (cf. Keen, 2011; Wunsch, Henning, Aschersleben, & Weigelt, 2013). McCarty, Clifton, and Collard (2001) had 9-, 14-, 19-, and 24-month-old children grasp various objects (i.e., spoon and hairbrush used for self-feeding and for feeding a stuffed animal, magnet used to pick up a metal object, hammer), and found that only children older than 14 months of age were able to grasp the object with the appropriate radial grip. Thus, both infants and toddlers are in part able to anticipate the consequences of their actions and plan their movements when grasping everyday objects in everyday life (McCarty et al., 2001).

A number of researchers have examined how various constraints influence the planning of grasp postures during object manipulation (cf. Rosenbaum et al., 2012). In a seminal study, Rosenbaum et al. (1990) asked participants to grasp a horizontally positioned bar and place it in a vertical position to either a left or a right target. In this bar transport task, when the left side of the bar was placed to either the left or right target, all participants grasped the bar with an underhand grip. However, when the right side of the bar was to be placed to either target, participants always grasped the bar with an overhand grip. Thus, regardless of target location, participants grasped the object so that the hand ended in a comfortable posture.

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The sensitivity toward comfortable (and more controllable) final goal postures is called the *end-state comfort effect*, and indicates that people take future states into account (i.e., intended object end-orientation), and are able to integrate and evaluate multiple biomechanical and cognitive task demands when planning their goal-related movements.

This line of research has also provided the opportunity to investigate the relative weight that the goal-directed and habitual systems exert on grasp planning in developing populations. The majority of these studies utilize the bar transport task developed by Rosenbaum et al. (1990). In this paradigm, the habitual system and the goal-directed system both call for the adoption of an initial overhand grip when the bar is to be placed into the right target (right end-down trials), thereby facilitating the selection of the appropriate grasp posture. In contrast, when the bar is to be placed into the left target (left end-down trials) the habitual system and the goal-directed system call for different initial postures (overhand grip and underhand grip, respectively).

A recent review article (Wunsch et al., 2013) summarizing the research on developmental grasp posture planning indicated that children as young as 3 years of age are able to select the appropriate grasp when the habitual system and the goal-directed system both call for an initial overhand grip (i.e., in right end-down trials). However, when the habitual system and the goal-directed system call for different initial postures (i.e., left end-down trials) end-state comfort improves with age, and reaches adult levels around 8 years of age. Thus, in contrast to the studies indicating that infants and toddlers are able to efficiently plan their grasp postures, this corpus of work indicates that the age at which goal-directed motor planning abilities emerge is strongly influenced by task constraints. The evidence indicates that the ability of children to integrate multiple constraints (i.e., by using the goal-directed system) during action planning improve across the developmental spectrum, but are not fully developed until children reach 8 years of age.

For example, increasing precision demands at the end of the movement biases children to use the goal-directed system (Manoel & Moreira, 2005; Thibaut & Toussaint, 2010). For example, in

Thibaut and Toussaint (2010) (Exp. 2), children aged between 4 and 10 years of age grasped a horizontally positioned pencil and made a dot or line on a piece of paper (low-precision task), traced a line from one location to another (another low-precision task), or drew a line in an alley without crossing the edges of the alley with the pencil (high-precision task). The authors found that the ability to satisfy end-state comfort in the low-precision tasks was only reliably observed for the 10-year-old children, and that end-state comfort satisfaction was lower for 8-year-old than 6-year-old children. In contrast, the preference toward comfortable end-states increased as a function of age for the pencil alley task, with higher end-state comfort satisfaction for the 8-year-old than 6-year-old children. Thibaut and Toussaint (2010) argued that grasp posture planning is influenced by perceived affordances and task constraints, as well as the reorganization of planning strategies that occurs around the age of 8 years. Thus, when the precision demands of the task were more readily apparent (pencil alley task), the 8-year-old children were better able to integrate all the necessary information and select grasps that afford a higher degree of final control, than when the constraints of the task were not clearly defined (pointing-with-pencil and tracing-with-pencil tasks).

In sum, tasks with greater cognitive demands bias children toward the habitual system, which is reflected by inconsistent grasp posture planning strategies. The interplay between the habitual and goal-directed systems is also influenced by motor and cognitive maturation, with the goal-directed system exerting a stronger influence on motor planning as children mature, which enables older children to mediate the bias toward the habitual system.

Building on this corpus of work, the present study examined how multiple planning constraints affect the relative weighting of the goal-directed and habitual system during grasp planning in children between 6 to 10 years of age. Specifically, we manipulated the object end-orientation (left end-down, right end-down) as well as the initial precision demands of the task (standard, initial precision). Grasp posture planning was examined using the standard children's version of the standard bar transport task (Figure 1A, Stöckel, Hughes, & Schack, 2012; Weigelt & Schack, 2010),

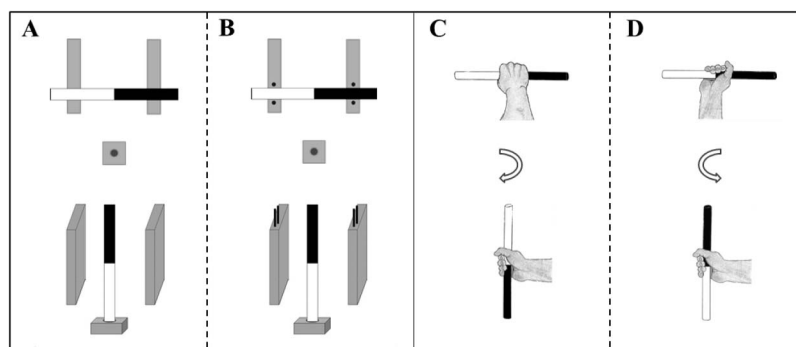


Figure 1. The apparatus used in the grasping and placing task consisted of a cradle, a wooden bar (one end of the bar was painted *black*, and the other end was painted *white*), and a target disk. Bird's eye view (top panel) and front view (bottom) of the apparatus during the standard condition (A) and the initial precision condition (B). In the initial precision condition, initial precision demands were increased by inserting metal pins into the holes located on the top of the support cradle. According to the end-state comfort effect, an initial overhand grip results in a comfortable final posture in the right end-down condition (C), whereas an initial underhand grip results in a comfortable final posture in the left end-down condition (D).

in which children reached for a horizontally oriented bar located on a support cradle, and placed the left or the right end of the bar into a target disk (i.e., standard condition). In another condition, metal pins were inserted into the support cradle (see Figure 1B), which required that the children lift the horizontally placed bar from the cradle without contacting the metal pins (i.e., initial precision condition). The addition of initial precision demands, therefore, was an extra behavioral constraint that children must consider when planning their grasp postures in the latter condition.

Based on prior literature (Wunsch et al., 2013) we expect to observe an overall gradual improvement in end-state comfort satisfaction with age. Additionally, it is postulated that the cognitive costs associated with grasp selection would be greater for conditions in which initial precision requirements are added. If it is the case that increased cognitive costs negatively impact the ability of children to resolve the conflict between the habitual and goal-directed systems, then one might expect to observe lower overall end-state comfort satisfaction values and less consistent grasp strategies in the initial precision condition (compared to the standard condition).

It is likely that the addition of initial precision requirements will have a differential effect depending on object end-orientation. Specifically, it is hypothesized that the cognitive costs will be lowest for the condition in which children need not consider initial precision demands, and the habitual system and the goal-directed system both call for an initial overhand grip (i.e., right end-down trials in the standard condition). Cognitive costs are hypothesized to be moderate for conditions in which children must consider only one task constraint (i.e., initial precision, goal-state) when planning their grasp postures (i.e., left end-down trials in the standard condition, right end-down trials in the initial precision condition). In contrast, it is hypothesized that the cognitive costs will be greatest for the condition in which children must resolve the conflict between the habitual and goal-directed system while also considering initial precision demands when planning grasp postures (i.e., left end-down trials in the initial precision condition). If these hypotheses are correct, then it is expected that conditions with greater cognitive costs should have reduced end-state comfort values and less consistent grasp strategies, compared with conditions with low or moderate cognitive costs.

Method

Participants

A total of 80 6- to 10-year-old children ($n = 16$ in each age group) participated in the experiment (see Table 1). There were 10

left-handed children, and 70 right-handed children, as determined by the hand children used to draw a house and throw a ball. All children had normal or corrected to normal vision, and had no known neuromuscular disorders. Informed consent was obtained from the parents of the children prior to participation in the experiment. The experiment was approved by the local school authorities and the institutional review board, and conformed to the declaration of Helsinki.

Apparatus

The apparatus is depicted in Figure 1, and is similar to that used in previous bar transport studies (Rosenbaum et al., 1990; Stöckel et al., 2012; Weigelt & Schack, 2010). The objects consisted of a wooden bar (22 cm in length, 2 cm in diameter), painted black on one end and white on the other end. The bar rested on a support cradle that was placed on a height adjustable table and arranged to vertically coincide with the participants' body midline. The support cradle extended 25 cm from the top of the table, and was located 20 cm from the front edge of the table. On each side of the support cradle was a set of two holes (5 cm in depth, 0.51 cm in diameter). The start precision requirements of the task were increased by inserting a metal pin (10 cm in length, 0.5 cm in diameter) into each of the holes on the support cradle. The metal pins extended 5 cm from the top of the support cradle. The target was a cube (10 cm in length, 10 cm in width, 10 cm in height) with a round hole in the center (2.5 cm diameter), which was placed 10 cm in front of the supports. The starting position for each participant was marked by placing a piece of tape on the floor (10 cm length, 2 cm in width) 90 cm in front of the bar. Grasp postures were recorded using a video camera (Panasonic NV-DX 100) placed 3 m from the right horizontal plane of the apparatus.

Procedure

All children were tested separately, with only the experimenter and a teacher in the room. Upon entering the room, the table was adjusted to the height of the participant's chest. The nature of the task was then explained, with instructions specifying that the child should use the right hand to pick up the bar from the support cradle and place one end of the bar into the target disk. The experimenter instructed the child to lift the bar without contacting the metal pins during initial precision conditions. The start orientation of the bar (black end left, black end right) was manipulated, such that for half of the trials the black end of the bar was oriented to the left, and for the other half of the trials the black end of the bar was oriented to the right. The start orientation of the bar was counterbalanced across children.

At the start of each trial, the participant stood at the starting position with their hands relaxed by their sides. After receiving instructions about which end of the bar to insert into the target disk, the child grasped the bar with the right hand using a full power grip (Napier, 1956), and inserted the required end into the target disk. After holding the bar at the target location for 3 s, the child placed their hand back to their side, and waited for the next trial to begin. Children were informed that movement accuracy was of utmost importance, and that they should perform the task at a comfortable speed. However, no specific instructions were given about how to grasp the bar (i.e., overhand or underhand).

Table 1
Participant Demographics

Age-group	Mean age in months (<i>SD</i>)	Male	Female	Left-handers	Right-handers
6-year-olds	79.5 (2.9)	6	10	1	15
7-year-olds	87.6 (2.3)	10	6	2	14
8-year-olds	101.4 (4.0)	11	5	1	15
9-year-olds	111.2 (3.4)	6	10	2	14
10-year-olds	124.3 (3.2)	7	9	4	12

Children performed a total of 16 trials, comprised of the 2 start orientation (black end left, black end right) \times 2 bar end-orientation (black end-down, white end-down) \times 2 precision (standard, initial precision) conditions, with children performing each trial twice. The individual conditions were presented in a randomized order. The entire testing session lasted approximately 15 min.

Data Analysis

Trials in which the incorrect end of the bar was placed in the target disk, or the bar contacted the metal pins (during initial precision conditions) were counted as errors and not included in analysis. The total number of rejected trials due to errors was less than 3% of the data, and was equally distributed across conditions and participants. Given the low error rate, mean substitution was used to replace missing values.

End-state comfort satisfaction was defined by initial grasps that resulted in thumb up postures at the end of the movement (Rosenbaum et al., 1990; Stöckel et al., 2012; Weigelt & Schack, 2010). Thus, for left end-down trials, end-state comfort was defined by the adoption of initial underhand grasp postures. For right end-down trials, end-state comfort was defined by the adoption of initial overhand grasp postures. Because the data did not meet the assumptions of parametric statistical analysis, (i.e., homogeneity and normal distribution), the proportion of trials in which end-state comfort was satisfied was determined for each participant, and normalized using an arcsine transformation.

Grasp posture planning consistency was determined by calculating the number of trials in which the children adopted an end-state comfort compliant grasp posture for each condition. As with previous research (Hughes, Seegelke, & Schack, 2012a; Thibaut & Toussaint, 2010) values at either extreme (zero or four trials) would indicate that children selected the same strategy across trials.

Results

Preliminary data analysis did not reveal any differences in grasp posture planning between left- and right-hand dominant children, $t(78) = -1.263$, $p = .323$. Therefore, the data were collapsed across handedness, and analyzed using a repeated measures anal-

ysis of variance (RM ANOVA) with age group (6-year-olds, 7-year-olds, 8-year-olds, 9-year-olds, 10-year-olds) as the between subjects factor, and precision (standard, initial precision) and bar end-orientation (left end-down, right end-down) as within subjects factors. Partial eta-squared (η_p^2) values were calculated for all F tests as an indicator of effect size. Results with p values < 0.05 were considered significant. Significant main effects and interactions were compared using the Tukey procedure.

End-State Comfort

The proportion of trials in which initial grasp postures resulted in comfortable end postures is displayed in Figure 2. In line with previous work, the proportion of trials in which end-state comfort was satisfied was higher when the right end of the bar was placed in the target disk (right end-down, 81%), compared with when the left end of the bar was placed in the target disk (left end-down, 66%), $F(1, 4) = 8.328$, $p = .005$, $\eta_p^2 = 0.100$. The main effect of precision was also significant, $F(4, 75) = 57.631$, $p < .001$, $\eta_p^2 = 0.435$. The proportion of trials in which end-state comfort was satisfied was higher for the standard (86%) than the initial precision condition (62%).

The interaction between age group, bar end-orientation, and precision was also significant, $F(4, 75) = 2.530$, $p = .047$, $\eta_p^2 = 0.119$. Post hoc comparisons revealed significant group differences for the standard condition in which the left end of the bar was placed in the target disk, with lower end-state comfort values for 6-year-old (58%) and 7-year-old children (72%) than all other age groups (8-year-olds = 88%; 9-year-olds = 86%; 10-year-olds = 84%), all $ps < 0.01$. The difference between 6- and 7-year old children was not significant, $p > .10$. Moreover, end-state comfort values were similar across all age groups for the standard condition in which the right end of the bar was placed in the target disk (6-year-olds = 89%; 7-year-olds = 95%; 8-year-olds = 95%; 9-year-olds = 98%; 10-year-olds = 91%), all $ps > 0.10$.

No group differences were observed for the initial precision condition in which the left end of the bar was placed in the target disk (6-year-olds = 66%; 7-year-olds = 53%; 8-year-olds = 45%; 9-year-olds = 58%; 10-year-olds = 53%), all $ps > 0.10$. Binomial tests were used to ascertain whether end-state comfort levels differed from chance levels (50%), and indicated that end-state

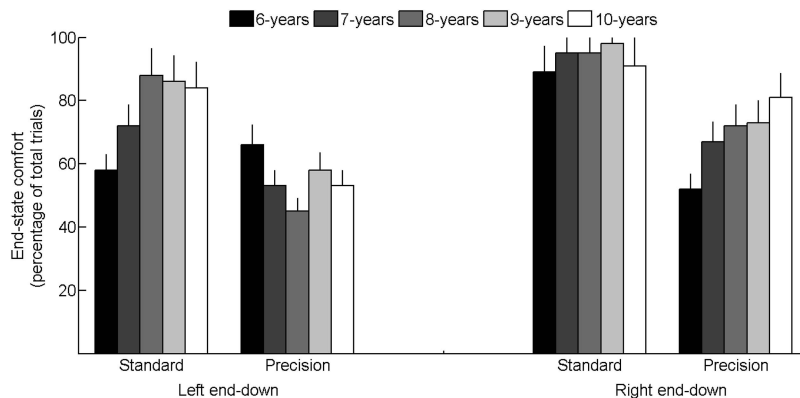


Figure 2. Proportion of trials in which end-state comfort was satisfied for the left and right end-down trials of the standard and initial precision conditions. Error bars indicate standard deviation.

comfort values were higher than chance levels for the 6-year-old age group ($p = .004$), but at chance levels for all other age groups (all $ps > 0.05$).

For the initial precision condition in which the right end of the bar was placed in the target disk, end-state comfort was significantly lower for the 6-year-old children (52%) compared with all other age groups (7-year-olds = 67%; 8-year-olds = 72%; 9-year-olds = 73%; 10-year-olds = 81%), all $ps < 0.05$. There were no significant differences in end-state comfort for all other age groups, all $Fs < 1$. Binomial tests indicated that end-state comfort levels were at chance levels for the 6-year-old children ($p = .096$), but that children in the 7- to 10-year old age groups selected end-state comfort grasp postures at levels higher than expected by chance (all $ps < 0.05$).

Grasp Posture Consistency

We first assessed grasp posture consistency during right end-down trials (see Figure 3). During the standard condition 75% of 6-year-old children *always*, one child (6.3%) *almost always*, and three children (18.8%) used an end-state compliant grasp posture in *half* of the trials. Grasp consistency improved in children aged between 7- and 10-years, with at least 87.5% of children selecting an end-state compliant grasp posture in all trials. Grasp posture planning in the initial precision condition was not as consistent as observed in the standard condition. We found that 37.5% of 6-year-old children always used an end-state compliant grasp posture, 18.8% used an end-state grasp in half of the trials, 18.8% used an end-state posture in one trial, and 25% never used an end-state compliant grasp posture. In children aged between 7 and 10 years of age, the number of children who always satisfied end-state comfort increased (6-year-olds = 56.3%; 7 to 10-year-olds = 62.5%). However, there were still a number of children who never satisfied end-state comfort (6- to 9-year-olds = 18.8%; 10-year-olds = 6.3%), or employed less consistent grasp strategies.

Next we examined grasp posture consistency in left end-down trials (see Figure 4). During the standard condition 37.5% of children in the 6-year-old age group always used an end-state compliant grasp posture, while 25% of children never selected an end-state compliant grasp posture. Grasp posture selection was

more consistent in children aged between 7 and 10 years of age. 56.3% of 7-year-old children, and 62.5% of children aged between 8 and 10 years always selected an end-state compliant grasp posture, and the number of children who almost always used an end-state grasp posture ranged between 12.5% and 25% of children. The number of children who never used an end-state compliant grasp posture also decreased with age (6-year-olds = 25%; 8- and 9-year-olds = 0%; 10-year-olds = 6.3%). Grasp posture planning was less consistent during the initial precision condition, as indicated by the lower number of children always selected an end-state compliant grasp posture (6-year-olds = 37.5%; 7-year-olds = 37.5%; 8-year-olds = 31.3%; 9-year-olds = 37.5%; 10-year-olds = 18.8%), and an increase in the number of children who used an end-state grasp in half, or one of, the trials.

Discussion

In general, the results of the standard conditions are congruent with previous research (Stöckel et al., 2012; Thibaut & Toussaint, 2010; Weigelt & Schack, 2010). Overall, end-state comfort and grasp consistency was higher for right end-down trials than left end-down trials. End-state comfort compliance was similar for all age groups in right end-down trials, and corresponded to values reported in adult populations in which the bar transport task was employed (e.g., Hughes et al., 2012b; Rosenbaum et al., 1990). In left end-down trials, the percentage of children who consistently satisfied end-state comfort increased over the developmental spectrum, and reached levels typically observed in adult populations around 8 years of age. Results of the standard condition, thus, reinforce the idea that the development of anticipatory motor planning is influenced by the goal-directed and habitual systems (Stöckel & Hughes, 2015; Stöckel et al., 2012). Specifically, grasp posture selection is facilitated when the habitual and goal-directed systems favor identical initial grasps (i.e., right end-down trials). In contrast, when the habitual and goal-directed systems favor different grasps (i.e., left end-down trials) only children aged 8 years and older were able to effectively consider future task demands (i.e., end-state comfort) and mediate the bias toward overhand postures (habitual system).

Results of the study also demonstrated that grasp posture planning was strongly influenced by the addition of initial precision

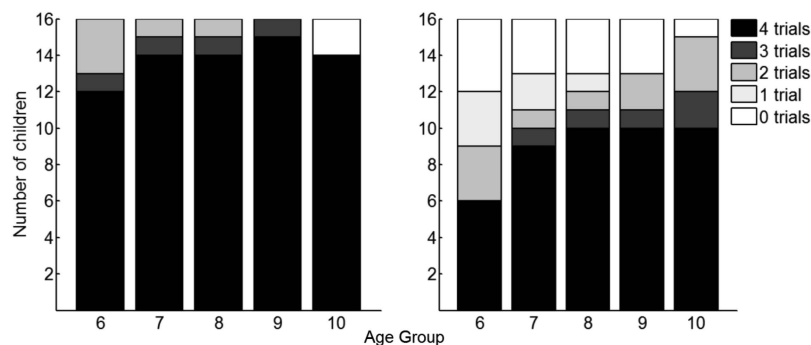


Figure 3. Numbers of children who employed an end-state comfort compliant grasp posture in 0, 1, 2, 3, and 4 trials during left end-down trials. The left panel refers to trials in which initial precision demands were absent (standard condition). The right panel refers to trials in which initial precision demands were added (initial precision condition).

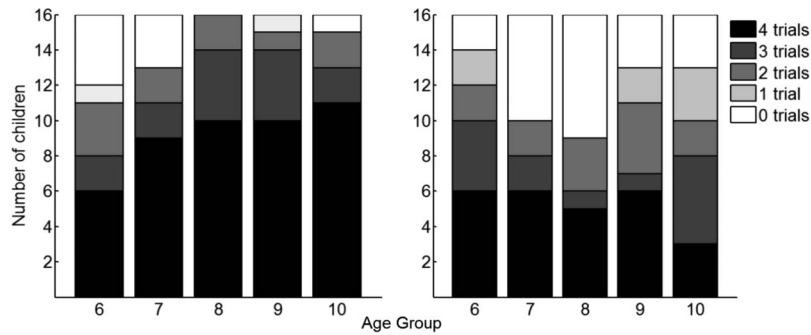


Figure 4. Numbers of children who employed an end-state comfort compliant grasp posture in 0, 1, 2, 3, and 4 trials during right end-down trials. The left panel refers to trials in which initial precision demands were absent (standard condition). The right panel refers to trials in which initial precision demands were added (initial precision condition).

demands. Regardless of object end-orientation (left vs. right end-down) the proportion of children who employed consistent grasp posture planning strategies was higher when initial demands were absent, compared with when they were present. Additionally, end-state comfort satisfaction was similar and near chance levels for all age groups ($M = 55\%$) during the left end-down trials of the initial precision condition. In contrast, there was a slight indication of age-related effects on grasp posture planning during right end-down trials of the initial precision condition, with lower end-state comfort values for the 6-year-old children (52%) than all other age groups ($M = 73\%$).

The observation that end-state comfort values ranged between 45% and 66% during the left end-down trials, but improved with age for right end-down trials, for the initial precision condition indicates that the cognitive costs associated with grasp posture planning were higher when the goal-directed and habitual systems were in conflict with one another, compared with when they called for the same grasp posture (Herbort & Butz, 2011; Stöckel et al., 2012). Based on the current data, we hypothesize that the demands associated with selecting the appropriate grasp posture during left end-down trials of the initial precision condition required more cognitive resources than children between 6 and 10 years of age possess. Removing the conflict between the goal-directed and habitual systems reduces some of these costs, with data indicating that children from 7 years of age start to integrate the addition of initial precision demands into the action plan, with improvements in planning increasing as children age.

The results of the present study support the hypothesis that conditions with greater cognitive costs lead to reduced end-state comfort values and less consistent grasp strategies, compared with conditions with low or moderate cognitive costs. We postulate that the selection of an appropriate initial grasp posture requires that participants consider the task demands (e.g., precision demands) and body states (e.g., comfort and control of the effector) at both the temporally proximal and temporally distal action segments (Seegelke, Hughes, Knoblauch, & Schack, 2013). We hypothesize that the cognitive costs associated with grasp posture planning were higher for the initial precision condition than the standard condition (Hughes et al., 2012a). The increased cognitive costs apparent during the initial precision condition interfered with the ability to consider and integrate information at both the temporally

proximal and temporally distal action segments into a single action plan (Seegelke et al., 2013; Stöckel & Hughes, 2015).

There is growing evidence from developmental (Stöckel & Hughes, 2015) and adult populations (Logan & Fischman, 2011; Weigelt, Rosenbaum, Huelshorst, & Schack, 2009) that cognitive functions and grasp posture planning are strongly linked. For example, Stöckel and Hughes (2015) recently demonstrated that successful unimanual and bimanual grasp posture planning performance is positively correlated with working memory and planning and problem-solving abilities in normally developing 5- and 6-year-old children. It would certainly be worthwhile to extend this line of work to examine how these executive functions correlate to grasp posture planning behavior across tasks of varying complexity and across the developmental spectrum.

This study provides new evidence about the role of cognitive costs on grasp posture planning development. However, there are several limitations to the current study which may inform future directions in this line of research. One limitation of the present study is that only two levels of initial precision were used. It is recommended that future researchers manipulate the number of initial precision conditions in a systematic fashion in order to obtain a more accurate picture of how an initial precision influences grasp planning behavior in developmental populations. For example, the distance between the metal pins on the support cradle (e.g., close vs. distant pins) could be varied, which would alter the initial precision requirements of the movement task (thereby changing second-order motor planning requirements).¹

There is growing evidence that the interplay between the habitual and goal-directed systems is influenced by object familiarity and experience (Barrett et al., 2007; Gentilucci, 2002; Herbort & Butz, 2011; van Elk, Viswanathan, van Schie, Bekkering, & Grafton, 2012). As such, it is possible that the manipulated object in the present study (a wooden dowel) did not have clear action connotations, which may not have adequately facilitated motor responses corresponding with the feature position. It would certainly be worthwhile to employ everyday objects (e.g., hairbrush, cup, spoon) to examine how familiarity and experience with an object

¹ We thank an anonymous reviewer for this suggestion.

alters the relative weight of the goal-directed and habitual systems during object manipulation tasks of varying complexity.

As in other studies that have examined the development of anticipatory motor planning, the current study measured behavior at only the macroscopic grasp posture planning level. There is growing evidence, at least for neurologically healthy adults, that task constraints do not influence motor planning (grasp posture) and motor execution (kinematic) equally (Hughes et al., 2011; Seegelke et al., 2011; Seegelke et al., 2015). For example, Hughes et al. (2011) examined how physically connecting two objects influences grasping and placing movements to congruent or incongruent object end-orientation targets. The authors found that physically connecting the two objects altered the transport (i.e., motor execution) but not the grasping (i.e., motor planning) component of the movement. In contrast, the congruency of the object end-orientation targets influenced both components of the task (i.e., both motor planning and execution). In sum, these results indicate that constraints may not elicit equal effects on both the motor planning and execution level.

Recent technological advances would provide the possibility to examine motor planning and execution while manipulating everyday objects in naturalistic situations (Allievi, Arichi, Gordon, & Burdet, 2014; Campolo, Laschi, Keller, & Guglielmelli, 2007; Campolo et al., 2012; Cecchi, Serio, Del Maestro, Laschi, & Dario, 2010). For example, Campolo, Laschi, Keller, and Guglielmelli (2007) developed instrumented toys (e.g., a ball, babies rattle, toy blocks) that were equipped with kinematic (via triaxial accelerometer, triaxial magnetometer, and triaxial gyroscope) and fingertip force sensors (Quantum Tunneling Composites) capable of accurately and quantitatively measuring manual function and motor development during a block rotation and fitting task in normally developing toddlers between 12 and 36 months of age. Given the effects of object familiarity on the interplay between the habitual and goal-directed systems, as well as the fact that investigating motor behavior at multiple levels may provide a more thorough understanding of motor control processes, researchers should utilize nonobtrusive instrumented technologies fitted with highly accurate sensors to measure detailed aspects of motor behavior in developing populations.

References

- Allievi, A. G., Arichi, T., Gordon, A. L., & Burdet, E. (2014). Technology-aided assessment of sensorimotor function in early infancy. *Frontiers in Neurology*, *5*, 197.
- Balleine, B. W., & Dickinson, A. (1998). Goal-directed instrumental action: Contingency and incentive learning and their cortical substrates. *Neuropharmacology*, *37*, 407–419. [http://dx.doi.org/10.1016/S0028-3908\(98\)00033-1](http://dx.doi.org/10.1016/S0028-3908(98)00033-1)
- Barrett, T. M., Davis, E. F., & Needham, A. (2007). Learning about tools in infancy. *Developmental Psychology*, *43*, 352–368. <http://dx.doi.org/10.1037/0012-1649.43.2.352>
- Campolo, D., Laschi, C., Keller, F., & Guglielmelli, E. (2007). A mechatronic platform for early diagnosis of neurodevelopmental disorders. *Advanced Robotics*, *21*, 1131–1150. <http://dx.doi.org/10.1163/156855307781389392>
- Campolo, D., Taffoni, F., Formica, D., Iverson, J., Sparaci, L., Keller, F., & Guglielmelli, E. (2012). Embedding inertial-magnetic sensors in everyday objects: Assessing spatial cognition in children. *Journal of Integrative Neuroscience*, *11*, 103–116. <http://dx.doi.org/10.1142/S0219635212500070>
- Cecchi, F., Serio, S. M., Del Maestro, M., Laschi, C., & Dario, P. (2010). Design and development of sensorized toys for monitoring infants' grasping actions. *Biomedical Robotics and Biomechanics*, *2010*, 247–252. <http://dx.doi.org/10.1109/BIOROB.2010.5627725>
- Creem, S. H., & Proffitt, D. R. (2001). Grasping objects by their handles: A necessary interaction between cognition and action. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 218–228. <http://dx.doi.org/10.1037/0096-1523.27.1.218>
- Daw, N. D., Niv, Y., & Dayan, P. (2005). Uncertainty-based competition between prefrontal and dorsolateral striatal systems for behavioral control. *Nature Neuroscience*, *8*, 1704–1711. <http://dx.doi.org/10.1038/nn1560>
- Dickinson, A., & Balleine, B. (2002). *The role of learning in the operation of motivational systems*. Stevens' handbook of experimental psychology. New York, NY: Wiley.
- Gentilucci, M. (2002). Object motor representation and reaching-grasping control. *Neuropsychologia*, *40*, 1139–1153. [http://dx.doi.org/10.1016/S0028-3932\(01\)00233-0](http://dx.doi.org/10.1016/S0028-3932(01)00233-0)
- Herbert, O., & Butz, M. V. (2011). Habitual and goal-directed factors in (everyday) object handling. *Experimental Brain Research*, *213*, 371–382. <http://dx.doi.org/10.1007/s00221-011-2787-8>
- Hughes, C. M. L., Haddad, J. M., Franz, E. A., Zelaznik, H. N., & Ryu, J. H. (2011). Physically coupling two objects in a bimanual task alters kinematics but not end-state comfort. *Experimental Brain Research*, *211*, 219–229. <http://dx.doi.org/10.1007/s00221-011-2673-4>
- Hughes, C. M. L., Seegelke, C., & Schack, T. (2012a). The influence of initial and final precision on motor planning: Individual differences in end-state comfort during unimanual grasping and placing. *Journal of Motor Behavior*, *44*, 195–201. <http://dx.doi.org/10.1080/00222895.2012.672483>
- Hughes, C. M. L., Seegelke, C., Spiegel, M. A., Oehmichen, C., Hammes, J., & Schack, T. (2012b). Corrections in grasp posture in response to modifications of action goals. *PLoS ONE*, *7*, e43015. <http://dx.doi.org/10.1371/journal.pone.0043015>
- Jeannerod, M. (1981). Intersegmental coordination during reaching at natural visual objects. *Attention and performance IX*, *9*, 153–168.
- Jeannerod, M. (1984). The timing of natural prehension movements. *Journal of Motor Behavior*, *16*, 235–254.
- Keen, R. (2011). The development of problem solving in young children: A critical cognitive skill. *Annual Review of Psychology*, *62*, 1–21. <http://dx.doi.org/10.1146/annurev.psych.031809.130730>
- Logan, S. W., & Fischman, M. G. (2011). The relationship between end-state comfort effects and memory performance in serial and free recall. *Acta Psychologica*, *137*, 292–299. <http://dx.doi.org/10.1016/j.actpsy.2011.03.009>
- Manoel, E. J., & Moreira, C. R. P. (2005). Planning manipulative hand movements: Do young children show the end-state comfort effect? *Journal of Human Movement Studies*, *49*, 93–114.
- Marteniuk, R. G., MacKenzie, C. L., Jeannerod, M., Athenes, S., & Dugas, C. (1987). Constraints on human arm movement trajectories. *Canadian Journal of Psychology*, *41*, 365–378. <http://dx.doi.org/10.1037/h0084157>
- McCarty, M. E., Clifton, R. K., & Collard, R. R. (2001). The beginnings of tool use by infants and toddlers. *Infancy*, *2*, 233–256. http://dx.doi.org/10.1207/S15327078IN0202_8
- Napier, J. R. (1956). The prehensile movements of the human hand. *The Journal of Bone and Joint Surgery*, *38*, 902–913.
- Rosenbaum, D. A., Chapman, K. M., Weigelt, M., Weiss, D. J., & van der Wel, R. (2012). Cognition, action, and object manipulation. *Psychological Bulletin*, *138*, 924–946. <http://dx.doi.org/10.1037/a0027839>
- Rosenbaum, D. A., Marchak, F., Barnes, H. J., Vaughan, J., Slotta, J. D., & Jorgensen, M. J. (1990). Constraints for action selection: Overhand versus underhand grips. In M. Jeannerod (Ed.), *Attention and performance XIII* (pp. 321–342). Hillsdale, NJ: Erlbaum.

- Seegelke, C., Hughes, C. M. L., Knoblauch, A., & Schack, T. (2013). Grasp posture planning during multi-segment object manipulation tasks—Interaction between cognitive and biomechanical factors. *Acta Psychologica, 144*, 513–521. <http://dx.doi.org/10.1016/j.actpsy.2013.09.002>
- Seegelke, C., Hughes, C. M. L., Knoblauch, A., & Schack, T. (2015). The influence of reducing intermediate target constraints on grasp posture planning during a three-segment object manipulation task. *Experimental Brain Research, 233*, 529–538. <http://dx.doi.org/10.1007/s00221-014-4133-4>
- Seegelke, C., Hughes, C. M. L., & Schack, T. (2011). An investigation into manual asymmetries in grasp behavior and kinematics during an object manipulation task. *Experimental Brain Research, 215*, 65–75. <http://dx.doi.org/10.1007/s00221-011-2872-z>
- Stöckel, T., & Hughes, C. M. L. (2015). The relation between measures of cognitive and motor functioning in 5- to 6-year-old children. *Psychological Research*. Advance online publication. <http://dx.doi.org/10.1007/s00426-015-0662-0>
- Stöckel, T., Hughes, C. M. L., & Schack, T. (2012). Representation of grasp postures and anticipatory motor planning in children. *Psychological Research, 76*, 768–776. <http://dx.doi.org/10.1007/s00426-011-0387-7>
- Thibaut, J. P., & Toussaint, L. (2010). Developing motor planning over ages. *Journal of Experimental Child Psychology, 105*, 116–129. <http://dx.doi.org/10.1016/j.jecp.2009.10.003>
- van Elk, M., Viswanathan, S., van Schie, H. T., Bekkering, H., & Grafton, S. T. (2012). Pouring or chilling a bottle of wine: An fMRI study on the prospective planning of object-directed actions. *Experimental Brain Research, 218*, 189–200. <http://dx.doi.org/10.1007/s00221-012-3016-9>
- Weigelt, M., Rosenbaum, D. A., Huelshorst, S., & Schack, T. (2009). Moving and memorizing: Motor planning modulates the recency effect in serial and free recall. *Acta Psychologica, 132*, 68–79. <http://dx.doi.org/10.1016/j.actpsy.2009.06.005>
- Weigelt, M., & Schack, T. (2010). The development of end-state comfort planning in preschool children. *Experimental Psychology, 57*, 476–482. <http://dx.doi.org/10.1027/1618-3169/a000059>
- Wunsch, K., Henning, A., Aschersleben, G., & Weigelt, M. (2013). A systematic review of the end-state comfort effect in normally developing children and in children with developmental disorders. *Journal of Motor Learning and Development, 1*, 59–76.

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