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Science with Duplo: Multilevel goal management in preschoolers' toy house constructions

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ABSTRACT

Executing goal-directed action sequences is fundamental to our behavior. Planning and controlling these action sequences improves greatly over the preschool years. In this study, we examined preschoolers' ability to plan action sequences. A total of 69 3- to 5-year-olds were assessed on an action sequence planning task with a hierarchical goal structure and on several executive function tasks. Planning abilities improved with age. Improvements in inhibition were related to avoidance of actions irrelevant to the goal hierarchy. Updating skill appears to be associated with executing actions relevant to different subgoals. Using optical motion capture, we showed that children who followed the subgoals displayed less movement with their nonreaching hand within a subgoal. This effect was enhanced in children with better inhibitory skills, suggesting that such skills allow greater focus on executing the current subgoal. Thus, we provide evidence that structuring of subgoals in action sequence planning emerges during the preschool years and that improvements in performance in action sequence planning are related to executive functions.

Introduction

Action planning is indispensable in our daily functioning. Planning and selecting an action or action sequence successfully involves taking into account task demands or constraints from the environ-

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ment. Actions are required to be planned ahead and should be adjusted with respect to these demands (Gottwald et al., 2017; von Hofsten, 1993, 2004). We constantly plan action sequences consisting of multiple levels of goals that are all set within a goal hierarchy (Rosenbaum, Cohen, Jax, Weiss, & van der Wel, 2007) such as making a sandwich and following our bedtime routine. Even something as simple as making a cup of coffee comprises a hierarchical goal structure. The main goal of obtaining a cup of coffee consists of several subgoals such as adding the sugar, which in turn consists of several action steps such as picking up the sugar package. Depending on the action sequence, action steps may need to be selected in a specific order. Furthermore, the executor needs to maintain the main goal of the hierarchy throughout the task while keeping track of which subgoal and which action steps have already been executed and which should be executed next (Botvinick, 2008; Cooper, Ruh, & Mareschal, 2014; Cooper & Shallice, 2000, 2006; Miller, Galanter, & Pribram, 1960). These goal hierarchies are the foundation of everyday goal-directed action sequences (Cooper et al., 2014).

Imitation studies have shown that memorization for the exact order of action steps in an action sequence is of low cognitive priority in both children (Loucks & Price, 2019) and adults (Loucks, Blakley, & Price, 2020). Instead, memory for action sequences seems to be led by hierarchical goal structure already early in life (Flynn & Whiten, 2008; Loucks & Meltzoff, 2013; Loucks, Mutschler, & Meltzoff, 2017; Whiten, Flynn, Brown, & Lee, 2006), possibly because planning action sequences according to a hierarchical goal structure decreases cognitive load.

In adults, action selection within a goal hierarchy is slowed down at decision boundary points (also called "branch points"), where a switch from one subgoal to another is required (Arnold, Wing, & Rotshtein, 2017; Ruh, Cooper, & Mareschal, 2010). Ruh et al. (2010) used a computer-based task in which adults needed to make tea or coffee (Experiment 1) or created a fertilizer for an artificial plant (Experiment 2). Actions were slowed down at branch points, for example, when a switch from adding sugar needed to be made to adding milk. Similarly, Arnold et al. (2017)[7] showed that action selection was slowed down at decision boundary points when building Lego walls. Selecting the next action at these branch points in hierarchical planning is thought to require cognitive control; the resulting increased cognitive load is reflected in increased selection time (Ruh et al., 2010). These markers of hierarchical action planning can potentially be investigated using motion capture techniques. Indeed, motion capture can be used to reveal the temporal progression of decisions, which would otherwise remain concealed from the human eye (Freeman, Dale, & Farmer, 2011; Song & Nakayama, 2009). Reaching kinematics are influenced by dynamic decision processes that occur in parallel in both lower-level processing (Song & Nakayama, 2006, 2008; Spivey, Grosjean, & Knoblich, 2005; Welsh & Elliott, 2005) and higher-level processing (Dale, Roche, Snyder, & McCall, 2008; McKinstry, Dale, & Spivey, 2008). Recently, some developmental studies have demonstrated the promising prospect of using motion capture to record children's reaching to investigate online decision-making processes (Erb, Moher, Song, & Sobel, 2017, 2018). Thus, the current study used motion capture to investigate the development of hierarchical action sequence planning in preschool children.

Recent studies have revealed that 5-year-olds are able to align their planning and execution of action sequences according to goals at both superordinate and lower levels of the goal hierarchy (Freier, Cooper, & Mareschal, 2017; Yanaoka & Saito, 2017, 2019). In contrast, 3- and 4-year-olds have difficulties in following the main goal in the goal hierarchy while executing an action sequence (Freier et al., 2017; Yanaoka & Saito, 2017, 2019). For example, in Freier et al. (2017), preschoolers were instructed to follow two levels of goals in their coloring of farm animals. Here, children needed to color the animals following an arrow below the animals indicating the order of coloring as the lower goal. The higher goal was to use each of three colors equally often. Both 3- and 5-year-olds showed good abilities to access the goal at the lowest level of this goal hierarchy and to execute their actions accordingly. However, only 5-year-olds were able to accommodate their actions according to the highest goal (Freier et al., 2017). Similarly, 5-year-olds were able to control their action execution based on the main goal in a doll-dressing task, whereas 4-year-olds may set subgoals rather than maintaining the main goal (Yanaoka & Saito, 2017). Furthermore, 5-year-olds showed more errors after disruptions in the middle of a subtask than after disruptions at the end of a subtask while executing a familiar action sequence (Yanaoka & Saito, 2019), a pattern that is also found in adults' execution of action sequences (Botvinick & Bylsma, 2005). In contrast, 4-year-olds were sensitive to both types of interruptions, providing evidence for developmental differences in action sequence representations

(Yanaoka & Saito, 2019). Children with better shifting skills also showed a more adult-like pattern in errors after disruptions, indicating a relationship between these action sequence representations and executive functions (EFs) (Yanaoka & Saito, 2019). Finally, young preschoolers often show *goal neglect* in that they fail to execute the task according to the main goal despite showing understanding and remembering this goal (Marcovitch, Boseovski, & Knapp, 2007; Marcovitch, Boseovski, Knapp, & Kane, 2010).

Imitation studies have provided further evidence for an improvement in action sequence planning in preschoolers. Toddlers in their second year of life are able to imitate simple action sequences consisting of two or three action steps (Bauer & Hertsgaard, 1993; Bauer & Mandler, 1989, 1992; Bauer & Shore, 1987; Bauer & Thal, 1990). Hierarchy goal structures are already important for action sequence imitation early during the preschool years. Three-year-olds' imitation of intact goal sequences did not differ from their imitation of interleaved sequences, indicating that their representations for these two action displays are similar (Loucks & Meltzoff, 2013; Loucks et al., 2017). The ability to follow hierarchical goal structures in the imitation of action sequences increased from 3 to 5 years of age (Flynn & Whiten, 2008). Furthermore, younger children were more likely to reenact an action irrelevant to the hierarchical goal structure of the sequence than older children (Freier, Cooper, & Mareschal, 2015). In sum, imitation studies have demonstrated fledging hierarchical goal representation in 3-year-olds (Loucks & Meltzoff, 2013; Loucks et al., 2017; Whiten et al., 2006), but this hierarchical goal representation or the ability to plan actions appropriately is still developing over the preschool period (Flynn & Whiten, 2008; Freier et al., 2015; Yanaoka & Saito, 2019). This finding is consistent with the idea of graded goal representations, suggesting that representations gradually become stronger over development (Munakata, 2001).

In summary, the planning and control of action sequences develops throughout the preschool years. Five-year-olds are able to accommodate their action sequence execution based on the structure of goal hierarchy, as are adults, whereas 3- and 4-year-olds experience problems in maintaining the highest level goal (Freier et al., 2017; Yanaoka & Saito, 2017, 2019). However, it remains unclear what drives the improvements in the control of action sequences over early childhood. Many putative factors have been proposed. For example, it has been suggested that working memory, set shifting, and especially inhibition could underlie complex planning (McCormack & Atance, 2011). These three abilities are commonly considered to be the core aspects of EFs. EFs are the cognitive control processes that regulate a person's goal-directed behavior (Barkley, 2012; Miyake & Friedman, 2012). Planning is often considered as a more complex and higher-level EF that is likely to be dependent on all three core aspects of EFs (McCormack & Atance, 2011; Miyake & Friedman, 2012). Importantly, working memory, set shifting, and inhibition all are skills that improve enormously over the preschool years (Anderson & Reidy, 2012; Diamond, 2013; Garon, Bryson, & Smith, 2008). Furthermore, EFs during infancy and childhood are linked to motor planning (Gottwald, Achermann, Marciszko, Lindskog, & Gredebäck, 2016; Pennequin, Sorel, & Fontaine, 2010) and motor behavior (Livesey, Keen, Rouse, & White, 2006). Therefore, improvements in these core components of EFs may be related to improvements in the planning and control of action sequences during the preschool years.

In the current study, we asked two questions. First, how does the development of complex planning during the preschool years relate to the development of preschoolers' EFs? Second, are there dynamic markers of hierarchical planning in their action sequences when preschoolers are engaged in a complex goal-directed task? To investigate this, we designed a new and fun planning task using Duplo blocks. Children needed to build a house using Duplo blocks following a demonstration video. The Duplo house could be built in different ways, enabling us to investigate whether children plan their actions according to the hierarchical goal structure and whether they are motivated to follow the hierarchical goal structure of a more knowledgeable adult. We expected that children with better EF skills would be better on the planning task (McCormack & Atance, 2011). Furthermore, we predicted that in children with adult levels of proficiency, action planning would be slowed down at branch points where a switch from one subgoal to another is required (Arnold et al., 2017; Ruh et al., 2010). We looked for these markers of hierarchical action planning in children's reaching movements because reaching kinematics is already affected during infancy by what to do next with an object (Chen, Keen, Rosander, & von Hofsten, 2010; Claxton, Keen, & McCarty, 2003) and is adjusted to the difficulty of the next successive action (Gottwald et al., 2017). Therefore, we expected children to adjust their reaching at the ‘‘more difficult” branch points.

Method

Participants

In total, 25 3-year-olds (*M* = 39.24 months, *SD* = 3.36; 10 girls), 24 4-year-olds (*M* = 50.71 months, *SD* = 2.79; 10 girls), and 20 5-year-olds (*M* = 63.05 months, *SD* = 2.19; 10 girls) were tested in this study. Participants were drawn from a population of typically developing children. Caregivers gave written informed consent, and children gave verbal assent. More detailed information about the participants is available in Supplementary data.

Procedure

Children were presented with four tasks in the following order: planning task, inhibition task, set shifting task and working memory task. Children were praised for their performance and given a sticker as a reward after each task. All procedures were approved by the local ethics committee.

Planning task

Children were asked to wear cycling gloves with distinct small plastic plates of reflective markers on both hands (Fig. 1). The marker of interest was located on the knuckle of children’s middle finger (third metacarpal). Movements were recorded at 100 Hz using a three-dimensional (3D) optical motion capture system (Vicon, Yarnton, UK) with six near-infrared cameras positioned around the table. The task was filmed using a synchronized video camera at 50 Hz to record children’s behavior.

The action sequence task involved constructing a Duplo house with a hierarchical goal structure for a Duplo man. Children were instructed to pay close attention to a movie of an adult building the house so that they could build it the exact same way (Fig. 2B). On average, children saw the instruction movie 1.88 times (*SD* = 0.96, range = 1–6) before confirming that they were ready to move on. It was checked whether children knew the goal of the task (build a house) and the action sequence subgoal colors (yellow wall, followed by blue wall, followed by green roof). If children answered incorrectly, the experimenter discussed the movies anew.

Blocks necessary for building the house were stored in boxes that were mechanically wired to open when children pressed a start button. This was introduced to ensure that each reach movement began

Fig. 1. A participant wearing the motion capture gloves with the two distinct plates of optical markers for the left and right hands.

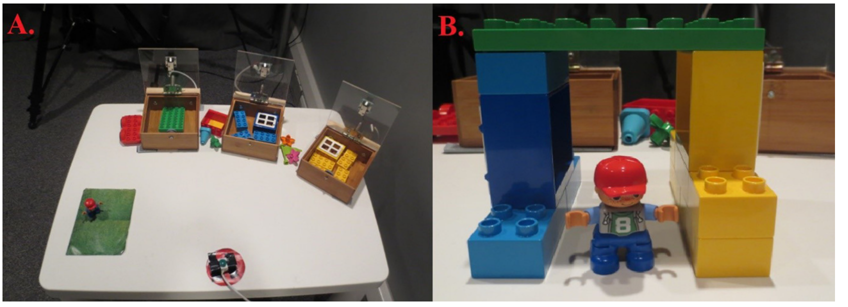

Fig. 2. (A) The setup of the planning task. Pressing the small green button opens the boxes. Each action step started with pressing the button to open the boxes to grasp a block. (B) The house as it should be built according to the instruction movie. The main goal was to build a house, which consisted of several subgoals such as to build the blue or yellow wall, each of which in turn consisted of several action steps.

from the same location. Boxes were manually closed by the experimenter after each reach and grasp of a block. Each box contained the blocks of one color required to complete one subgoal (Fig. 2A). Several additional distractor blocks were placed randomly between the boxes. Children were instructed to first build the house before playing with other fun blocks. The experimenter encouraged children to build using the Duplo blocks provided but never mentioned the goal or subgoals of the task or answered any questions from children related to the task. The task was considered complete when children indicated that their house was finished. Children were asked what they had built and whether it was the same one as they had seen in the movie.

Examples of children's action sequences and corresponding houses are provided in Supplementary data. Three main behaviors of the planning task were coded: whether children were able to complete the main goal, whether children followed the subgoal order, and whether children used distractors in their building. The start and end of each reaching movement was coded as well. These action steps were divided into branch points (*between* subgoal steps) and *within* subgoal steps. Further details of the data analysis are provided in Supplementary data.

EF tasks

All EF tasks were programmed using PsychoPy coder interface (Version 3.0.2; Peirce, 2008) and were played on a normal laptop with two smiley stickers on the spacebar to indicate the response button.

Inhibition. Inhibition was assessed using the BAT task, a child-friendly version of the go/no-go task (Fig. 3) (Drechsler, Rizzo, & Steinhausen, 2010; Kaller, Rahm, Spreer, Mader, & Unterrainer, 2008; Sobeh & Spijkers, 2013). Children were told a story in which there was a small town that had problems with vampires and were asked to be the monster hunters.

Children were instructed to press the space bar if they saw a bat, because bats can change into vampires, but not when they saw a cat, because cats are good. Children needed to press the space bar as quickly as possible for the bat (go trials) but not for the cat (no-go trials). The task started with 2 practice trials (one cat and one bat). Before the start of the experiment, children were asked what they needed to do when they saw a bat and what they needed to do when they saw a cat. They were always initially presented with 5 go trials to ensure that the go response was the prepotent response. The remaining trials occurred in a random order. The majority of the trials (74%, 26 of 35 total trials) were go trials. Children had 2 s to respond before the image disappeared from the screen and the next trial started after an interstimulus interval of 1 s. The total number of errors (misses and false alarms) divided by the number of trials was taken as the inhibition score.

Set shifting. Set shifting was measured using an adapted shifting task. Here, children always saw two pictures at the same time on the laptop screen: either a sun or a moon, and a fish or a fox (Fig. 4). Half

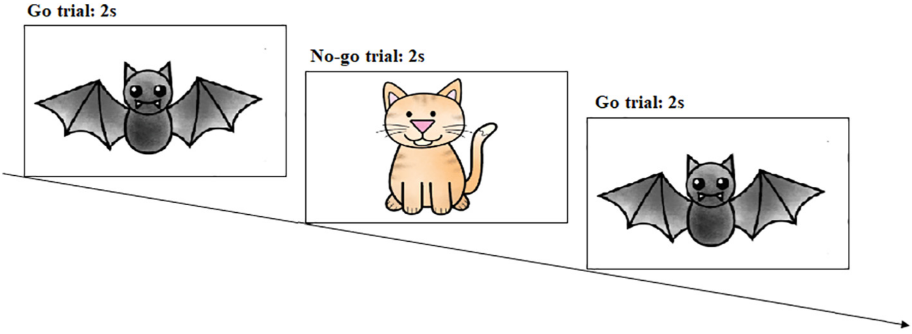

Fig. 3. Example trials of the BAT inhibition task. Children were required to push the space bar whenever a bat appeared but not whenever a cat appeared.

of the children first played the moon game, and the other half of the children first played the fish game. Order was assigned randomly based on participant number. Children were told, "We are playing the moon [or fish] game. The moon [or fish] game is really fun and really easy. If you see a moon [or fish] on the screen, you press between the smileys—but only if you see a moon [or fish]. If you see anything else, no pressing." This was followed by 3 practice trials (2 pressing trials and 1 no-pressing trial). The experimenter then said, "Let's play the moon [or fish] game." In each game, 60% of the trials were go trials (i.e. requiring a button press). There were extra conflict trials (in which children did not need to respond before the rule change) compared with other types of trials.

After the first 20 trials in the moon (or fish) game, the experimenter said, "Now forget about the moon [or fish] game. We are going to play a more fun game. We are going to play the fish [or moon] game." The experimenter continued to repeat exactly the same instructions as in the previous game. Each block consisted of 20 trials presented in a random order. Children were reminded using an auditory cue ("We are playing the moon/fish game" or "Only press if you see a moon/fish") every 4 trials, which was indicated by only showing a moon/fish surrounded by a red square. Children had 3 s to respond before the current trial disappeared from the screen and the next trial started after an interstimulus interval of 1 s. The pre-shift and post-shift error rates of the shifting task were calculated. The error rate was the number of misses and false alarms divided by the number of trials. The shift effect error rate, the set shift score, was calculated by subtracting the pre-shift error rate from the post-shift error rate.

Working memory. Working memory was measured using an auditory reverse digit span task (Carlson, Moses, & Breton, 2002; Marcovitch et al., 2010). Children were presented on the laptop screen with a bunny named Fluffy who always said things backward (Fig. 5). They were then asked to repeat the list of numbers that Fluffy said in the correct order. Children heard the following instructions: "This is Fluffy, and Fluffy is a bit of a silly bunny because he says things backward. Do you want to hear?" Fluffy then said, "Carrots like I." The experimenter then said, "That is silly. Fluffy meant to say 'I like carrots,' but because he said things the other way around, he said 'Carrot like I.' Now Fluffy is going to say some numbers, and I want you to say them the other way around to me." The experimenter then did the first one as an example. There were three sets of two, three, and four numbers, and children were reminded that Fluffy says things the other way around at each trial. After hearing the numbers, the experimenter asked children "What did Fluffy say?" and then "Fluffy says things the other way around, so what did Fluffy mean to say?" The next trial started manually after children had answered

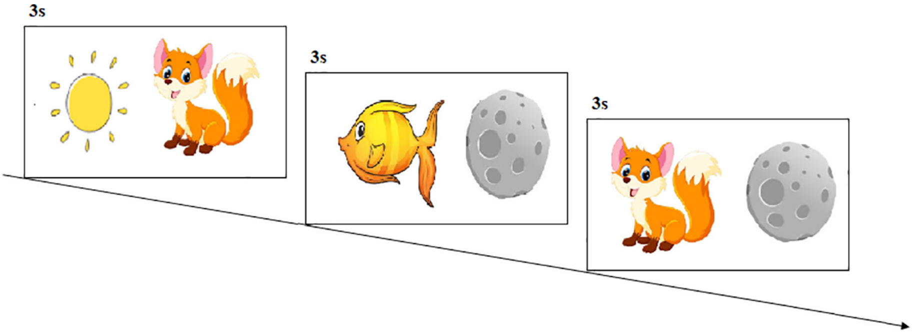

Fig. 4. An example of 3 trials in the moon game. The fish game looked the same except that children needed to respond whenever they saw a fish.

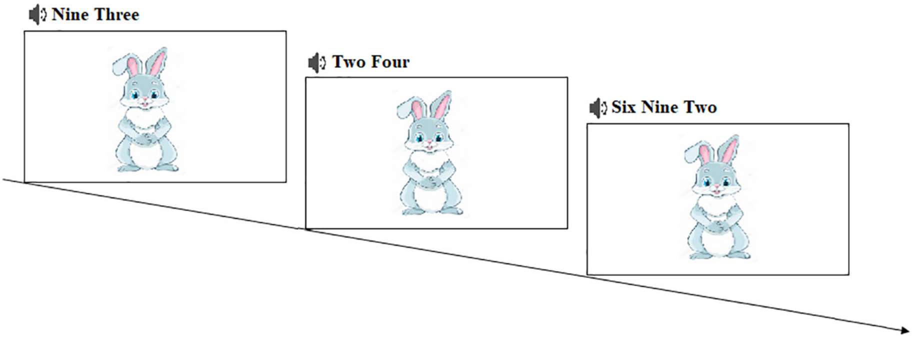

Fig. 5. Example of 3 trials of the working memory task. Children were required to repeat the numbers that Fluffy said in the opposite order.

what Fluffy said in the current trial. The average proportion correct across every set of items (two, three, and four) was coded respective of serial order (updating) and irrespective of serial order (working memory).[1] The scores were then averaged to create one average score on updating and one average score on working memory for each child.

Results

Not all children successfully provided data for all tasks. One 3-year-old and one 4-year-old provided no motion capture data because they were unwilling to wear the motion capture gloves. Two 4-year-olds had no data for the planning task, including the motion capture. Four 3-year-olds and one 4-year-old had no data for the working memory task. Analyses were implemented in RStudio (Version 1.2.1335). We controlled for multiple comparisons for each hypothesis using a separated Benjamini–Hochberg procedure (Benjamini & Hochberg, 1995). Raw *p* values are reported, but conclusions about significance effects are based on this procedure.

[1] The working memory score is calculated exactly as described in Marcovitch et al. (2010) and reflects how many digits children can successfully keep in their working memory. The updating score is an addition to the original procedure reflecting whether children are able to update the digit list in the right order in their working memory, that is, say the list of numbers backward. Previous studies have recommended that forward and backward digit span scores should not be combined because there is evidence indicating that these processes are distinct (Reynolds, 1997; Rosenthal, Riccio, Gsanger, & Jarratt, 2006).

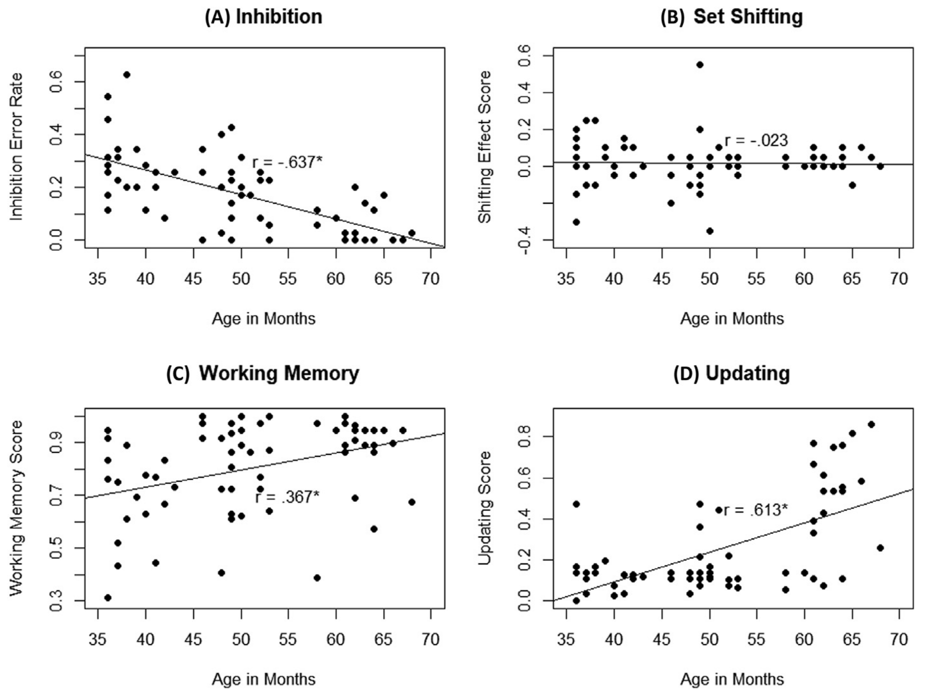

Fig. 6. The scores for participants on the executive function tasks. An asterisk (*) represents a significant correlation at $p < .016$.

EFs tasks

To investigate the validity of the EFs tasks, we correlated the score on each of these tasks with the participant's age in months (Fig. 6). We expected performance to improve with age.

Inhibition error rate correlated negatively with age in months, $r(69) = -.637$, $p < .001$. Older children had a lower error rate in the inhibition task compared with younger children, indicating that they were better at the inhibition task. The shifting effect score did not correlate with age in months, $r(69) = -.023$, $p = .853$. This reflects a lack of task sensitivity, suggesting that this task might not be an appropriate task for investigating set shifting in this age group. The working memory score (correct items irrespective of order) on the digit span task correlated significantly with age in months, $r(64) = .367$, $p = .003$. Older children had a higher working memory score than younger children. Finally, the updating score (correct items respective of order) on the backward digit span task correlated significantly with age in months, $r(64) = .613$, $p < .001$. Older children had a higher updating score than younger children.

Completing the main goal score

To investigate whether age and EFs task scores were predictors of whether children were able to keep track of the main goal (i.e., build a house), we used a binary logistic regression with main goal score as the dependent variable [1 = keep track of main goal, 0 = failed to keep track of main goal] and age in months and EFs task scores as predictors. We report the results using the sample with data for all tasks ($N = 62$).[2]

[2] Five children had missing data for the working memory and updating scores. Including these in the binary logistics models with the dependent variable main goal score and predictors of inhibition, shifting, and age did not change the results.

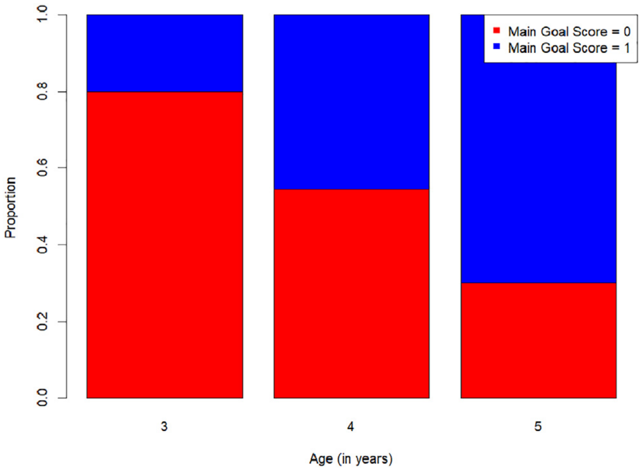

Fig. 7. The proportions of 3-, 4-, and 5-year-olds who were able to keep track of the main goal (blue) in the planning task or who were unable to keep track of the main goal (red).

This analysis showed that age is a significant predictor of performance, $\chi^2(1) = 7.099$, $p = .008$, Nagelkerke $R^2 = .144$. The 5-year-olds were more likely to keep track of the main goal successfully in the planning task than the 3-year-olds (Fig. 7).

None of the EFs scores added anything significant over and above the variance explained by age in months [inhibition score: $\chi^2(1) = 0.011$, $p = .916$; shifting score: $\chi^2(1) = 2.168$, $p = .141$; updating score: $\chi^2(1) = 1.385$, $p = .239$; working memory score: $\chi^2(1) = 0.328$, $p = .567$].

Following the subgoals

To investigate whether age and EFs task scores were predictors of children's ability to follow the subgoals, we used a binary logistic regression with subgoal score as the dependent variable [1 = perfect subgoalers with two color switches, 0 = imperfect subgoalers with more than two color switches] and age in months and EFs task scores as predictors. We report the results using the sample with data for all tasks ($N = 62$).[3]

Updating score was the strongest predictor despite not reaching significance after controlling for multiple testing, $\chi^2(1) = 4.122$, $p = .042$, Nagelkerke $R^2 = .086$. The Bayes factor provided weak evidence for this model ($BF_{10} = 1.352$). The other scores did not improve the model [age in months: $\chi^2(1) = 0.914$, $p = .339$; inhibition score: $\chi^2(1) = 1.033$, $p = .309$; shifting score: $\chi^2(1) = 1.110$, $p = .292$; working memory score: $\chi^2(1) = 0.732$, $p = .392$]. Children who were perfect subgoal followers ($M = 0.30$, $SD = 0.28$) had a higher average updating score than children who were imperfect subgoal followers ($M = 0.19$, $SD = 0.20$).

Distractibility during planning

To investigate whether age and EFs task scores were predictors of children's distractibility, we used a binary logistic regression with distractor score as the dependent variable [0 = no distractors used in building, 1 = distractor(s) used in building] and age in months and EFs task scores as predictors. We report the results using the sample with data for all tasks ($N = 62$).[4]

[3] Five children had missing data for the working memory and updating scores.

[4] Five children had missing data for the working memory and updating scores. Including these in the binary logistics models with the dependent variable distractor score and predictors of inhibition, shifting, and age did not change the results.

Inhibition score (total error rate) was a significant predictor, $\chi^2(1) = 7.179$, $p = .007$, Nagelkerke $R^2 = .175$. Only updating score as predictor in combination with inhibition score improved the model despite not reaching significance after controlling for multiple testing, $\chi^2(1) = 3.885$, $p = .049$, Nagelkerke $R^2 = .261$. The Bayes factors provided substantial evidence for the model with inhibition as predictor ($BF_{10} = 7.619$) and substantial evidence for the model with both inhibition and updating as predictors ($BF_{10} = 4.243$).

The other scores did not significantly improve the model [shifting: $\chi^2(1) = 1.149$, $p = .284$; working memory score: $\chi^2(1) = 0.363$, $p = .547$; age in months: $\chi^2(1) = 0.961$, $p = .327$]. Children who were not distracted during the planning task ($M = 0.15$, $SD = 0.15$) had a lower error rate on the inhibition task compared with children who were distracted ($M = 0.27$, $SD = 0.12$). Furthermore, children who were not distracted during the planning task ($M = 0.29$, $SD = 0.24$) had a higher updating score compared with children who were distracted ($M = 0.11$, $SD = 0.05$).

Associations between different behavioral planning measures

To investigate the association among the main goal score reflecting maintenance of the main goal, the subgoaler score reflecting following the subgoals, and the distractor score reflecting distractibility during planning, three Fisher's exact tests were executed.

There was a significant association between the main goal score and the subgoal score (odds ratio = 4.222, $p = .007$), between the subgoal score and the distractor score (odds ratio = 26.971, $p < .001$),[5] and between the main goal score and the distractor score (odds ratio = .0186, $p = .030$).

Kinematics of action planning

In this section, we discuss the kinematic variables of lingering time and nonreaching hand movement. Pause time before pressing the button (and after moving back from the previous action) showed no evidence of hierarchical planning and is reported in Supplementary data.

Lingering time

Lingering time (in frames) was the number of frames that participants waited to move to reach for a block after they had pressed the start button. This was calculated as the number of frames between the start frame of pressing the button and the movement onset, as described in Supplementary data. One outlier with a score 3 times the standard deviation above the mean was removed. All dependent variables were checked for normal distribution and homogeneity of variance. Nonparametric tests are reported if these assumptions were violated.

A nonparametric related-sample Wilcoxon signed rank test showed a higher lingering time at branch points ($M = 57.78$ frames, $SD = 47.16$, $Mdn = 39.00$ frames) compared with within subgoal steps ($M = 43.68$ frames, $SD = 47.51$, $Mdn = 33.10$ frames) ($z = -4.091$, $p < .001$, $r = -.520$). To investigate possible effects between different groups, separate tests were conducted comparing the difference score (i.e., lingering time at branch points minus lingering time at within subgoal steps) between age groups, main goal score, and subgoal score.

A one-way analysis of variance (ANOVA) with difference score of lingering as the dependent variable and age group as the between-participant factor showed no significant effect of age on the difference between lingering time in branch point and within subgoal steps, $F(2, 59) = 0.714$, $p = .494$ (Fig. 8A).

A nonparametric independent-sample Mann–Whitney U test with difference score of lingering as the dependent variable and main goal score as the between-participant factor showed no significant effect of main goal on the difference in lingering time in branch point and within subgoal steps ($z = -1.116$, $p = .264$) (Fig. 8B).

[5] There were no children with a subgoal score of 0 (perfect subgoalers) and a distractor score of 1 (distracted during planning). Therefore, the odds ratio was calculated as infinite. The odds ratio here was calculated by filling this cell with a score of 0.60 and therefore underestimates the actual odds ratio.

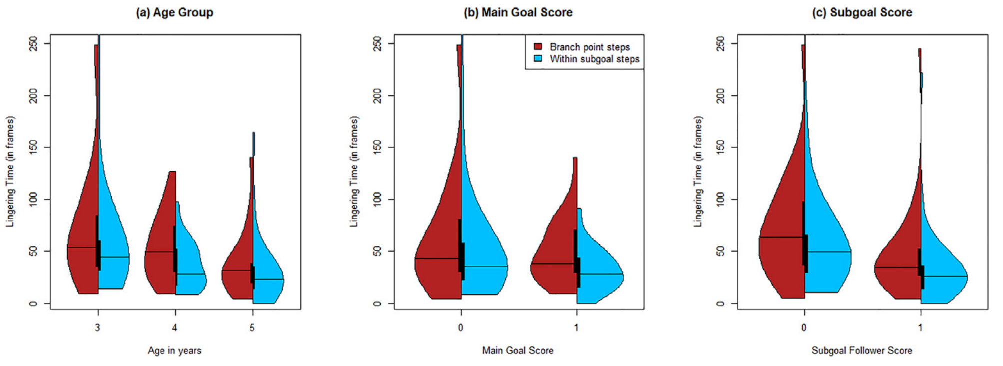

Fig. 8. Violin plots of lingering time (in frames) for the different age groups (A), the different main goal scores (B), and the different subgoal scores (C) for both within subgoal steps (blue) and branch points (or between subgoal steps) (red). The line represents the median value for each group.

An independent-sample *t* test with the difference score of lingering as the dependent variable and subgoal score as the between-participant factor showed no significant effect of subgoal score on the difference in lingering time in branch point and within subgoal steps, $t(60) = 0.957$, $p = .342$ (Fig. 8C).

Nonreaching hand movement

This variable reflected a measure of the amount of movement children made with their nonreaching hand. The mean velocity (in mm/frame) between 2 s before and 2 s after the button press was used as this measure, as described in Supplementary data. One outlier with a score 3 times the standard deviation above the mean was removed. All dependent variables were checked for normal distribution and homogeneity of variance. Nonparametric tests are reported if the assumptions were violated.

A nonparametric related-sample Wilcoxon signed rank test showed that children had a higher mean velocity of nonreaching hand at branch points ($M = 0.94$ mm/frame, $SD = 0.63$, $Mdn = 0.86$ mm/frame) compared with within subgoal steps ($M = 0.78$ mm/frame, $SD = 0.61$, $Mdn = 0.63$ mm/frame) ($z = -2.430$, $p = .015$, $r = -.316$). To investigate possible effects between different groups, separate tests were conducted comparing the difference score (i.e. velocity at branch points minus velocity at within subgoal steps) between age groups, main goal score, and subgoal score.

A nonparametric independent-sample Kruskal–Wallis test with the difference in velocity of nonreaching hand as the dependent variable and age as the independent variable showed a significant effect of age group on difference in velocity between branch point and within subgoal steps, ($\chi^2(2) = 8.954$, $p = .011$, $\epsilon^2 = .154$). Only the contrast between 3-year-olds and 5-year-olds is significant ($z = -3.349$, $p = .002$, Bonferroni corrected) in pairwise Mann–Whitney *U* tests. The 5-year-olds have a higher difference in velocity in nonreaching hand ($M = 0.37$ mm/frame, $SD = 0.43$, $Mdn = 0.44$ mm/frame) compared with the 3-year-olds ($M = 0.01$ mm/frame, $SD = 0.35$, $Mdn = -0.01$ mm/frame) (Fig. 9A).

An independent-sample *t* test with difference score of velocity of nonreaching hand as the dependent variable and main goal score as the between-participant factor showed no significant effect of main goal on the difference in velocity in branch point and within subgoal steps, $t(57) = -0.881$, $p = .382$ (Fig. 9B).

An independent-sample *t* test with difference score of velocity of nonreaching hand as the dependent variable and subgoal score as the between-participant factor showed that the difference was higher for the group that managed to follow the subgoal structure ($M = 0.26$ mm/frame, $SD = 0.43$) compared with the group that did not ($M = 0.00$ mm/frame, $SD = 0.52$), $t(57) = -2.068$, $p = .043$, Cohen's $d = -0.548$ (Fig. 9C) despite reaching nonsignificance after correction for multiple comparisons. The Bayes factor ($BF_{10} = 1.550$) provided weak evidence for this effect.

In summary, the mean velocity of the nonreaching hand was a marker of hierarchical planning only in older children, with that velocity being significantly greater at branch points in those who managed to follow the subgoal structure.

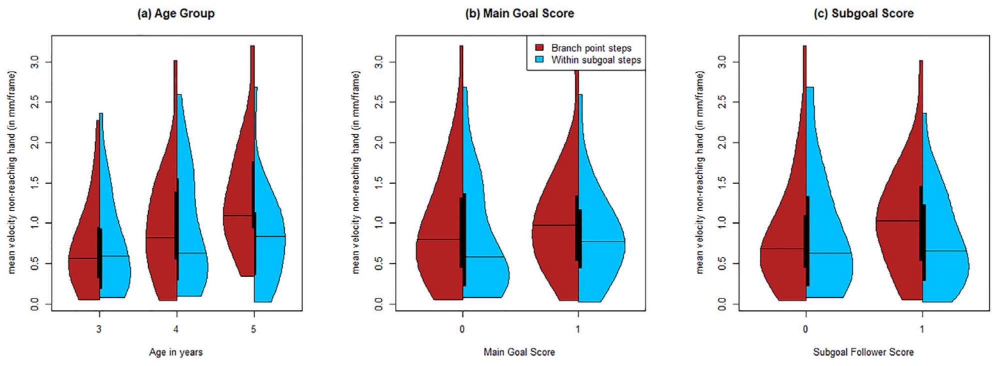

Fig. 9. Violin plots of velocity of the nonreaching hand (in mm/frame) for the different age groups (A), the different main goal scores (B), and the different subgoal scores (C) for both within subgoal steps (blue) and branch points (or between subgoal steps) (red). The line represents the median value for each group.

Relationship between kinematics and EFs scores

To investigate the potential relationship between the dynamic markers of motion capture and EFs, we correlated the EFs task scores with the kinematic scores. A kinematic score was calculated as the score on the between subgoal steps (branch points) minus the score on the within subgoal steps. Differences between the classes of steps reflected evidence of hierarchical planning of action sequences for those participants. This was done for the kinematic measures of lingering and mean velocity of nonreaching hand. For each of the difference scores, one outlier with a difference score 3 times the standard deviation above the mean was removed. Nonparametric Spearman correlations were used for the lingering difference score because its distribution deviated significantly from a normal distribution ($W = .957$, $p = .029$).

Lingering time did not correlate with the inhibition error rate, $r_s(62) = .021$, $p = .869$, the shifting effect score, $r_s(62) = -.184$, $p = .153$, the working memory score, $r_s(57) = -.071$, $p = .599$, or the updating score, $r_s(57) = -.126$, $p = .351$. However, the nonreaching hand movement difference score correlated significantly with the inhibition error rate, $r(59) = -.329$, $p = .011$. This indicated that children who were better at inhibition (i.e. lower error rate) showed a bigger difference in their nonreaching hand movement at branch points compared with within subgoal steps. This difference score did not correlate with the shifting effect score, $r(59) = -.174$, $p = .187$, the working memory score, $r(54) = .072$, $p = .604$, or the updating score, $r(54) = .179$, $p = .194$.

Discussion

The planning and execution of complex action sequences with a hierarchical goal structure improves over the preschool years (Freier et al., 2017; Yanaoka & Saito, 2017, 2019). In this study, we examined preschoolers' action sequence planning abilities, such as maintaining the key goal, following the subgoals in execution and avoiding actions irrelevant to the goal hierarchy. We investigated the potential relationship between improvements in planning abilities and EFs. Furthermore, we investigated whether we could find dynamic markers of hierarchical planning in preschoolers' reaching using motion capture.

Results showed that older children were more often successful at executing their actions to accomplish the main goal compared with younger children. Children who followed the subgoal structure of the goal hierarchy had better updating skills than children who mixed up the action steps. Good updating skills appeared to be beneficial, possibly because they support the ability to maintain which subgoal and action steps have been executed and which subgoal or action step should be executed next. Moreover, children with better inhibition were less likely to be distracted when executing their action sequences. Good inhibitory skills are essential to overcome distractors or avoid executing actions irrelevant to hierarchical goal structure. There was weak evidence that updating skills are also important for avoiding distractors in action sequence planning. Our results continue to highlight the importance of EFs in the development of action sequence planning (McCormack & Atance, 2011; Yanaoka & Saito, 2017, 2019).

The kinematic data revealed evidence of structuring of subgoals in the kinematic profiles of action sequences. The velocity profiles of the nonreaching hand reflected this structuring of subgoals, especially in those older children who followed the subgoal order. There was some evidence for an effect of whether children are able to follow the subgoal order on the difference between movement at branch points and within subgoal steps in the nonreaching hand. This effect was somewhat masked by the high variability in movement observed within groups. Inspection of the video data revealed that this effect was explained by increased task focus while executing actions within a subgoal, resulting in a relative freezing of the nonreaching hand during completion of the subgoal (i.e., all actions within a subgoal, e.g., all yellow blocks on the wall). Conversely, the nonreaching hand relaxed at branch points (resulting in more movement) when taking time to plan and explore the next subgoal action sequence. The difference in movement of the nonreaching hand observed between branch points and within subgoal steps was also related to individual differences in inhibition. Children with better inhibitory skills showed less nonreaching hand movement during subgoal action steps, suggesting a greater ability to focus on executing the current subgoal and decreased susceptibility to distraction.

During infancy, there is a gradual decrease in movements of nonacting hand or limb during unimanual actions such as reaching (D'Souza, Cowie, Karmiloff-Smith, & Bremner, 2017). Examples of these visible movements in children's nonreaching hand were wiggling and twisting. These extraneous nonacting limb movements might further decrease from toddlerhood to childhood, resulting in small movements only visible by fine-grained techniques such as motion capture. Moreover, these small movements in the nonacting hand might decrease while children are concentrating on executing their actions, helping children to improve cognitive focus on executing these actions with the acting hand.

In contrast to our predictions, lingering time after pressing the start button did not show evidence of hierarchical planning. We had initially hypothesized that lingering time would reflect increased load when planning at a branch point (Arnold et al., 2017; Ruh et al., 2010). However, our results suggest that it reflects the fact that reaching toward a new box on a branch point compared with redoing an exact identical reach toward the same box as before (within subgoal steps) takes more time to plan before moving. This could indicate either that lingering time was insensitive to whether children followed the goal structure of the action sequence or that the effect of a new reaching location dominated the lingering results.

One limitation of the current study is that the shifting measure we used was insensitive to age. Consequently, we could not draw any conclusions about set shifting and its link to planning abilities. Furthermore, motivation of children to plan their actions according to the goal hierarchy in the planning task might have influenced our results. Perhaps some children were not motivated to execute the subgoals and the key goal but did nevertheless manage to keep track of these. Indeed, an important component of planning is motivation. Without motivation to reach a particular goal, planned actions are abandoned before the execution phase (Friedman, Scholnick, & Cocking, 1987). Therefore, future studies should investigate the link between motivation and planning during the preschool years further in order to understand whether young children are unable to plan action sequences or are simply unmotivated to execute action sequences.

Despite these limitations, this study provides new insights into the development of executing goal-directed action sequences. We are the first to use optical motion capture to investigate the development of hierarchical planning of action sequence in preschoolers, and we provide a marker of structuring sequences into subgoals that emerges over the preschool period. The results continue to argue for a tight coupling between embodied motor control and cognition (Freeman et al., 2011; Rakison & Woodward, 2008; Smith & Gasser, 2005; Song & Nakayama, 2009; Thelen et al., 1993). Furthermore, we created a fun planning task using Duplo blocks that was entertaining for young preschoolers and produced very low dropout rates. Duplo blocks can be useful and fun equipment for investigating action planning in young children.

Future research should extend these findings and investigate how young preschoolers plan action sequences with a different hierarchical task structure, for example, a more complex hierarchical goal structure including greater subgoal nesting, more subgoals, and longer action sequences. We anticipate that the ability to manage more complex hierarchical goal structures may emerge at older ages. Familiarity with the task equipment may also affect lingering time differences at branch points. Indeed, most children in our preschool sample were very familiar with Duplo blocks, perhaps requiring less planning at branch points than with less familiar equipment. Moreover, future research should extend these kinematic findings to older children and adults, investigating whether they freeze their nonreaching hand while focusing on executing a subgoal as well. In sum, kinematic analysis can provide a new window into the planning mind across all ages (Song & Nakayama, 2008).

Conclusions

We were able to show that maintaining the key goal when executing an action sequence improves with age. Inhibition skills are related to the ability to avoid the execution of actions irrelevant to the goal hierarchy. Furthermore, updating might be related to the ability to constrain the action steps in subgoals and follow these instead of mixing up the order of all action steps. The results are consistent with the suggestion that EFs could underlie complex planning (McCormack & Atance, 2011). Inhibition and updating are the key developmental factors linked to improvements in selection of actions and inhibition of distractors in action sequence planning.

Furthermore, we demonstrated that children freeze their nonreaching hand during execution of a subgoal when following the goal hierarchy in action sequence planning. This provides further evidence of maturation of hierarchical goal representation over the preschool years. Once again, the preschool years emerge as a critical period for the development and organization of effective and intelligent behaviors.

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Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jecp.2020.105067.

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Further reading

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