Constraints and Development in Children's Block Construction

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Abstract

Block construction tasks are highly complex, yet even young children engage in these tasks in both informal and formal learning settings. In this paper, we ask whether the specific paths through which children build a structure are unique to the individual, or alternatively, constrained by similar principles across individuals and over age. Our results show that although children between 4 and 8 make frequent errors in copying model constructions, there is a striking amount of consistency in specific attributes of their paths of construction, and this consistency mirrors that of adults. The build paths suggest that although children sometimes build inefficiently, they tend to build layer-by-layer, consistent with a role for intuitive physics that enables the creation of stable structures.

Keywords: skilled action; spatial skills; spatial cognition; development; block copying; intuitive physics

Introduction

Block play is an accessible activity for young children, and has been prominent both in informal and formal educational settings for hundreds of years (Hewitt, 2001). The relevance of block construction as an indicator of overall cognitive growth is well-known, as it relates to performance on other spatial tasks, such as mental rotation (Brosnan, 1998; Caldera et al., 1999), as well as skill in math and science (Casey, Andrews, Schindler, Kersh, Samper, & Copley, 2008; Nath & Szücs, 2014; Richardson, Hunt, & Richardson, 2014). However, our understanding of the principles underlying children's block-building skills is quite limited. In part, this is due to both the complexity of the task, and limitations in the measurement of block-building skill used to evaluate children's proficiency.

Even the apparently simple task of copying an existing structure is remarkably complex, utilizing both domain relevant information (e.g. the spatial relationships among blocks), as well as general cognitive skills (Cortesa, Jones, Hager, Khudanpur, Shelton, & Landau, 2017; Landau & Hoffman, 2012). For example, the builder must be able to represent the global spatial configuration of the model, use selective attention to segment the model into individual blocks, and deploy working memory as building unfolds, checking back to ensure that the copy accurately represents the spatial relationships among the component blocks (Ballard, Heyhoe, Pook, & Rao, 1997; Landau & Hoffman, 2012). Copying a block construction is also likely to engage the builder's understanding of intuitive physics, which could guide the construction of a connected, and gravitationally stable/balanced model. Previous research indicates that both adults and children use intuitive physics to judge whether a large block structure is likely to fall when it moves (Fischer, Mikhael, Tenenbaum, & Kanwisher, 2016; Kamps, Julian, Battaglia, Landau, Kanwisher, & Dilks, 2017). Consistent with this approach, computational models of instructions for how to assemble a block structure emphasize the effects of gravity, with optimal instructions guiding the builder to build from the bottom layer upwards, avoiding block placements that are unsupported from below (Zhang et al., 2016).

As we mentioned, our understanding of how children manage this complex task has been limited by the tools available to analyze their performance. Although block construction skills have been studied for over 85 years (Bailey, 1933), the field has largely focused on accuracy of the end-product. Some studies have characterized the types and numbers of errors during a block copying task (Brosnan, 1998; Schatz, Ballantyne, & Trauner, 2000; Verdine, Golinkoff, Hirsh-Pasek, & Newcombe, 2017), and others examined actions of assembly and disassembly (Kamii, Miyakawa, & Kato, 2004). However, we know of no studies that have characterized children's entire construction path, from beginning to end, in a precise, quantifiable way.

In a recent study, we developed a novel representation and annotation method that provides unprecedented detail about the step-by-step nature of adults' behavior on a block copying task (Cortesa et al., 2017). In that study, a sample of 27 adults constructed copies of block models, and their construction behaviors were annotated utilizing a detailed step-by-step description, in which sequential actions, or block placements, result in intermediate assembly states, culminating in a final state which replicates the model. One of our key findings was that adult behavior is highly constrained, with full construction paths remarkably similar across individuals and target models. Despite individual variability, participants' paths were strikingly constrained, such that only a small portion of all possible correct actions actually were carried out. In addition, we found that adults were highly consistent in their approach, relying on layer-by-layer building patterns. Relying on layered construction might allow adults to move accurately and efficiently through the construction process. For example, layered constructions can be executed with one hand without relocating placed blocks, while building from the top down requires the builder to lift previously constructed pieces to place additions underneath.

Do children's complete build paths exhibit some of the same characteristics as those of adults? We asked young children to carry out block construction tasks using Duplo^{TM} blocks to copy the same target models as we used in our study of adults. It is possible that adults' highly selective choice of paths, including their efficient, layered construction patterns only emerge after years of carrying out skilled action tasks (including block building). Moreover, given the complexity of the task, we might expect young children to be less efficient than adults, taking more steps to completion and making more errors, especially given their limitations in metacognition, executive function, and working memory, and fewer years of formal education (Alloway, Gathercole, Kirkwood, & Elliott, 2009; Goswami, 2008; Zelazo, 2008). We also might expect children to utilize highly variable ad hoc solutions, such that each child executes the block copying task in a unique way, or they may generate homogenous responses that are distinct from adults', such as building from left to right or top to bottom. On the other hand, it is also possible that consistency across individuals is driven by universal underlying functional knowledge such as an understanding of intuitive physics, which emerge early in development and persist throughout adulthood. In this case, children's knowledge might lead them to create highly constrained paths, selecting only a select few of all possible correct build paths, and perhaps building layer-by-layer, as we observed in our adult data. A large amount of overlap between adult and child construction patterns would provide support for this second possibility.

Method

Participants

Thirty-four children participated in this experiment, aged 4-8 years, (*M* = 6.72 years, *SD* = 1.68), 22 females. A university ethical review board approved all study procedures, and participants and their legal guardians provided informed assent and consent, respectively.

Materials

Participants were asked to copy six different block models consisting of 4, 6, or 8 blocks. Each participant copied each of the six models in randomized order, but always began with the two smallest models (models 1 and 2). One model of each size was symmetrical along a vertical axis, and one was asymmetrical (Figure 1).

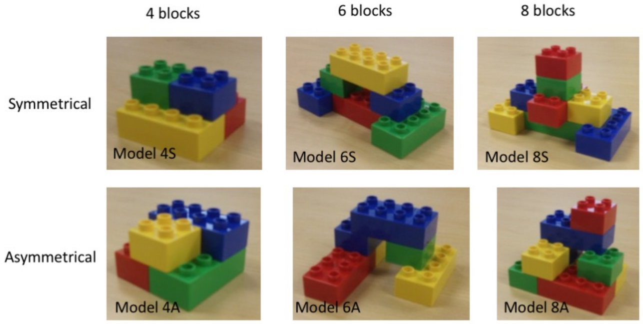

Figure 1: Block models are named for the number of blocks they contain, and their structural symmetry, S for structurally symmetric models, and A for asymmetric models. Models 4S and 4A contain four blocks, 6S and 6A contain six blocks, and 8S and 8A contain 8 blocks.

We mounted a PrimeSense Carmine RGBD camera in an overhead configuration to record participants' behaviors as they carried out the construction task, at a rate of 30 frames per second. All videos were coded using our annotation interface. The coder viewed the video recording frame-by-frame on a desk-top computer.

Procedures

First, the experimenter provided a simple model of two blocks, and children were asked to "make a tower that looks just like mine" using another set of the same two blocks. They were allowed to repeat the practice trial until they successfully replicated the model. The experimenter pointed out how the two structures were the same because the shapes and colors were in the same locations. Next, the experimenter presented each of the models (Fig 1), first placing it on the table in a standardized orientation so that the greatest number of model surfaces were visible to the participant. Then, the experimenter placed a rectangular basket on the table which contained the corresponding loose blocks. Participants were asked to "make one that looks just like" the model provided. If, after the first time the child indicated he/she had finished, the copy was not an accurate replication of the model, the experimenter provided general feedback that the copy and the model did not match, and ask the participant to try once more.

Data Analysis

We followed the same procedures as in Cortesa et al. (2017) to characterize the children's full construction path. This includes characterizing each block placement, the resulting intermediate assembly states, and how they culminate in a final state. To do this, each video was annotated using a custom designed computer interface (described in Cortesa et al., 2017), in which the annotator defines a series of *actions*, such as placing a block onto or removing a block from the copy. The set of ordered actions result in a series of *states* which emerge over time, each of which are a specific set of block attachments present in the copy at a single time. We refer to the ordered sequence of actions and states over time as a *construction path*, shown in Figure 2. All construction paths begin at a null state where no blocks are connected, and end with the final construction declared to be complete by the participant. Video data for nine paths, from seven different children, were lost due to camera malfunction during the video recording, or incomplete video data (such as when children moved the blocks out of the video recording area). A total sample of 195 videos were analyzed from our sample of 34 participants, annotated by four researchers, each of whom annotated a subset of the videos.

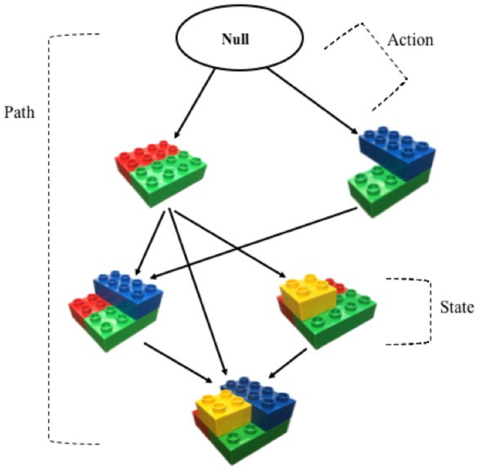

Figure 2: Illustration of *states*, (images of blocks), *actions* (directed arrows), and *construction paths* (a set of actions and states that leads from the initial null state to the final state).

In order to assess the structure of paths for each of our six models, we computed several outcome variables to summarize the types of paths traversed by each participant. First, to assess procedural efficiency of the construction controlling for model size, we computed the *number of excess actions* taken to complete a copy construction. We assume that a procedurally efficient building process would result in the fewest number of excess steps. Excess actions are defined as the total number of actions in a path minus the minimum number of actions needed to complete the model (where n is the number of blocks in the model, and n-1 is the minimum actions). Second, our observations of adults suggested that layering was a prominent strategy. Therefore, we computed a measure of *layer-by-layer construction*, the proportion of states in a given path that were consistent with such construction. A state was considered consistent with a layer-by-layer strategy if no blocks were placed on any layer before the preceding layer was correctly and completely constructed. Finally, we computed the *speed of copy construction*, controlling for the number of actions in a path. To do this, we computed an average of all action durations, measured in seconds from the point at which the participant released the previous block until the point at which they let go after placing (or removing) a block in their copy. These outcome measures were assessed using Pearson's correlations and repeated measures ANOVAs.

Results

Most children successfully completed a correct copy of each of the models, but they were not perfect (90% accuracy across all children and models). Based on the measures of overall copy accuracy, model 6A was the most challenging, with only 67% of all copies completed correctly, while models 4S, 4A, and 6S were the easiest, with 97% final accuracy.

One of the benefits of our detailed coding method is that we can examine children's performance beyond simple measures of overall accuracy to examine systematic patterns of building throughout the entire block construction paths. First, we examine the types of intermediate states created by children compared to adults on a similar task.

Intermediate States

We examined the types and numbers of different states that children created along their construction paths. There is a finite enumerable number of possible correct states that replicate a part or whole of each of the models. For example, model 4A has 14 possible correct states that could be created by children as they carry out their copy. In fact, when the children in our study copied model 4A, they generated only five unique correct states. The distribution of correct states closely aligns with the number and type of correct states observed in our previous studies of adult participants (Cortesa et al., 2017). In those studies, a sample of 27 adults also generated five correct states, with 4/5 states (80%) overlap between the child and adult samples, shown here in Figure 3.

This pattern holds for larger models as well. For example, for model 6S, there are 79 possible correct states, but adults created only 17 of 79, while children created 29 of 79. Figure 3 also shows that both children and adults follow two primary construction paths. Nearly all participant actions started with the bottom layer of the structure, by connecting the red and green rectangles, and then moved to the top layer, reaching the correct final construction. Overall, a large majority of children followed the same few modal construction paths, even within the limited number of observed states. To illustrate, we examined the states in the single most common construction path for each of the six models, not including the final state which was common across builders. All of the most common paths follow layer-by-layer construction and represent over 56% of all the data for that model, (4S: 78.6%, 4A: 79.8%, 6S: 60.9%, 6A: 60.0%, 8S: 57.8%, 8A: 56.1%). If children were constructing randomly, the states in any single construction path would represent only about 15% of the data as a conservative estimate for the smallest models. In addition, children's most common paths match closely with the most common paths for adults; 25 of 30 states along the modal paths overlap across the present study's sample and the adult sample from a previous study.

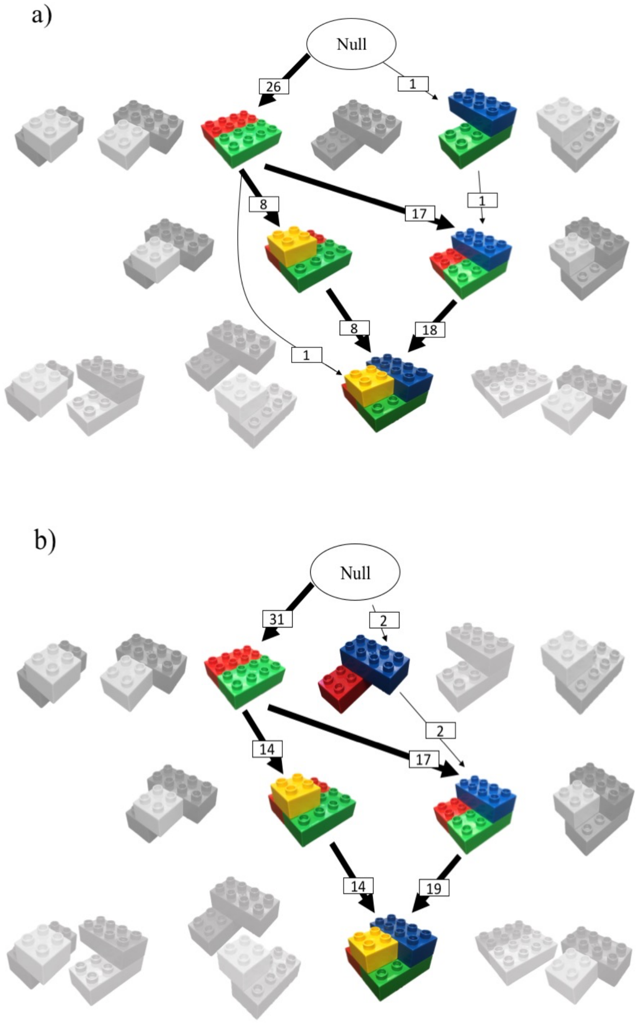

Figure 3: Correct states visited for model 4A. Panel a: Correct states visited by 27 adults from Cortesa et al., 2017 compared with Panel b, a sample of 33 children from the current study. Observed states are shown as colored images. Possible correct states that were *not* observed are shown in greyscale. Actions are drawn as arrows numbered to indicate the number of individuals who executed that action. Both adults and children created similar sets of construction paths, representing only a small portion of all possible correct construction paths. In both groups, the large majority of participants tend to follow only two primary construction paths, which follow a layer-by-layer construction pattern.

Figure 3 illustrates the large amount of overlap in the construction behavior of adults and children. However, it does not show the errors committed by either group. For model 4A, adults generated only one incorrect state (which was visited by only one individual), while the children generated 10 unique incorrect states, which were visited 26 times by 11 different individuals.

Path Characteristics Across Development

Next, we characterize how path type changes across development. We examined our three outcome variables 1) the number of excess actions, as an indicator of procedural efficiency, 2) the proportion of each path that follows a bottom-up layer-by-layer construction pattern, as an indicator of whether children seemed to rely on intuitive physics during their construction, and 3) the average action duration of each path, as an indicator of movement fluency and temporal efficiency. Table 1 presents descriptive statistics for each of our outcome variables for each model.

Table 1: Descriptive statistics for path-level outcome variables for each of the six block models. (*M* (*SD*)).

Model	Excess Actions	Layer strategy (%)	Ave. Action Duration (sec)
4S	1.88 (4.27)	85.54 (21.54)	2.92 (1.38)
4A	1.52 (2.29)	87.41 (18.68)	2.91 (1.24)
6S	2.85 (5.64)	71.63 (35.37)	3.25 (1.33)
6A	7.33 (9.90)	53.11 (27.31)	3.75 (1.38)
8S	2.06 (3.52)	63.61 (36.43)	3.34 (0.96)
8A	5.06 (7.96)	64.71 (33.95)	4.14 (1.74)

In order to assess the relationships among our outcome variables of interest, we conducted a Pearson's correlation among them, reported here in Table 2. Correlations between the path-level outcome variables show that those paths that follow a layer-by-layer construction strategy have fewer excess actions, and have faster actions on average. Similarly, those paths that have fewer excess actions also tend to have faster actions on average. Each of these outcomes may be meaningfully related to a larger construct of construction efficiency.

Table 2: Correlations between path-level outcome variables (*r* (*p*)).

	Excess Actions	Ave. Action Duration
Ave. Action Duration	0.20 (.004)	
Layer Strategy %	-0.62 (<.001)	-0.19 (.007)

Because of the high correlations among our outcome variables of interest, we chose to examine three independent repeated measures ANOVA models, one for each outcome of interest. Each ANOVA includes within-subject variables of model size and symmetry, as well between-subjects variables of participant age and gender.

Model 1: Excess Actions. We explored the number of excess actions as an indicator of construction procedural efficiency. Although most children successfully completed the task, they took much longer construction paths, which contain more excess actions, compared to adults. The previous study reported that adults averaged fewer than one excess action per construction (Cortesa et al., 2017), whereas children in the present study executed over three excess actions per construction (M = 3.37, SD = 6.34), when averaged across all models and children. For children, task 6A was the most challenging, with only 30% of participants executing this copy without committing errors, or undoing and redoing their actions resulting in excess steps. Even for the simplest models, 4S and 4A respectively, only 71% and 64% of children executed their copy with no excess actions.

We found that model size influenced procedural efficiency, $F(2,66) = 6.72, p = .002$. The smallest 4-block models tended to elicit paths with fewer excess actions compared to the 6-block models, which had paths containing the most excess actions, $t(1,66) = -3.66$, $p < .001$. In addition, symmetric models showed fewer excess actions than asymmetrical models $F(1,33) = 8.47, p = .006$. An interaction of model size and symmetry, $F(2,57) = 3.36$, $p = .042$, indicated that the larger asymmetric models, 6A and 8A, showed more excess actions than either of the 4-block models, or the symmetric 6- and 8- block models. The larger asymmetric models, particularly model 6A, showed the most excess actions (see Table 1), indicating that children found this model particularly challenging to copy correctly. In addition, we found a main effect of age, $F(1,155) = 33.60$, $p < .001$, such that for each additional year in age, the number of excess actions in a path is expected to decrease by -0.87 actions. In other words, for every additional year in age, participants needed nearly one fewer action, on average, to successfully copy the model. There were no effects of participant gender on the number of excess actions in their construction paths.

Model 2: Layer Strategy. Next, we examined the proportion of each path that follows a layering strategy. We found that model size affected the degree to which participants used steps consistent with layer-by-layer constructions, $F(2,66) = 15.06$, $p < .001$, such that smaller models tended to have greater amounts of layering patterns compared to 6-block and 8-block models, $t(1,66) = 4.93$, $p < .001$, and $t(1,66) = 4.51, p < .001$. This may be an artifact of the more limited set of construction options available for smaller models compared to larger ones. In addition, we found a main effect of age, $F(1,154) = 4.95$, $p = .028$. As children age, they increase their use of layering strategy.

Model 3: Action Duration. Finally, we examined average action durations in order to assess participants' temporal efficiency. We found a main effect of model size, $F(2,66) = 8.22, p < .001$, such that smaller models tended to have faster actions compared to 6-block and 8-block models, $t(1,66) = -2.88$, $p = .005$, and $t(1,66) = -3.90$, $p < .001$, respectively. Also, a main effect of model symmetry, $F(1,33) = 5.53$, $p = .025$, shows that symmetric models had faster average action times than asymmetric models. A main effect of gender, $F(1,32) = 7.39$, $p = .011$, indicates that males have faster actions on average compared to females. There was also an effect of age, $F(1,154) = 8.09$, $p = .005$, such that for each additional year in age, average action timing is expected to decrease by approximately -0.34 seconds per action. Finally, an interaction of age and gender, $F(1,154) = 4.65$, $p = .033$ shows that the gender difference becomes smaller with increasing age.

Discussion

Our study illustrates the constraints and developmental changes in block construction between 4 and 8 years of age. Overall, children were quite accurate in their final versions of the target models. However, they also made many errors along their construction paths; errors were most pronounced among young children, and for the larger 6- and 8-block asymmetric models. Even when their final result was accurate 90% of the time, children produced more than three excess actions, on average, to reach that final correct state.

Despite these excess steps, children's actions were highly constrained, especially given the large number of construction paths possible for creating correct copies of the different models. Children's paths mapped closely onto those observed in adults in our previous studies (Cortesa et al., 2017). One prominent characteristic of both children's and adults' paths was the reliance on a bottom-to-top construction pattern that generates horizontal layers in sequence. This suggests that children and adults are both trying to create stable structures and may be using intuitive physics concepts such as balance and support to do so.

Although children achieved high levels of final accuracy, they make many errors along the way, resulting in more unique block states than a previous study found for adults who constructed the same models. While both children and adults build in accordance with physics principles of support and balance by starting their construction at the base and building upwards, children's behaviors may be disrupted by limitations in attention, working memory, or spatial representation which result in errors.

We also found that age plays a significant role in the structure of children's construction paths, with some aspects of block construction skills developing between the ages of 4 to 8 years. Specifically, layering strategy increased with age, which may indicate that as children age, they develop a more organized layer-by-layer strategy—perhaps with increased understanding of the role that layering plays in enhancing stability and efficiency in building, or as a result of increased experience with construction toys like blocks. On average children used fewer excess actions and executed actions more quickly with age. Parents of children in the present study indicated a wide range of experience and preferences for play with blocks or other construction toys, but all participants had at least some exposure to playing with blocks prior to enrollment in the study. As layering strategy increases, that organization may lead to an increase in accuracy and efficiency in their building behaviors. Future research should examine the role of experience in children's block construction.

It seems clear that model complexity, including model size and symmetry, affects the construction paths that children create. Overall, we found that asymmetric models, especially those larger models with 6- or 8-blocks elicited the greatest number of excess actions in their construction paths, as well as slower average action times, which may indicate that children find them to be the most difficult. This finding aligns with previous research, which indicates that children's performance replicating spatial patterns or constructions is facilitated by symmetry (Richardson et al., 2014). Children's gender largely did not affect the accuracy and efficiency of their construction behaviors. While we did find a gender difference in the average speed of construction actions, this gender difference was expected to decrease as children age.

In sum, we analyzed children's full construction paths as they copied block models. We found that children use only a small subset of the possible correct construction paths available for any given model, consistent with the same high degree of constraint on adults' construction paths. We also found significant increases in accuracy and efficiency between ages 4 and 8, reflected by fewer excess steps and increasing use of layering as children build their models. As children develop, their experiences may lead to greater reliance on layered construction patterns. These findings are consistent with the idea that construction behavior, irrespective of age, may be constrained by some functional strategies that reflect an understanding of intuitive physics. We hope that our findings provide a foundation for future explorations of the cognitive functions that support skilled action behaviors, and their relationship to these other important cognitive capacities, including the nuanced contributions of individual differences.

Acknowledgments

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