1 **Title** Rooms without walls: Young children draw objects but not layouts

2

3 **Authors** Katelin Maguire^{1*}, and Moira R. Dillon¹

4

5 **Affiliations**

6 ¹Department of Psychology, New York University

7

8 *To whom correspondence should be addressed:

9 Katelin Maguire

10 Department of Psychology, New York University

11 6 Washington Place

12 New York, NY 10003

13 USA

14 **Abstract**

15 Drawing is an epitome of uniquely human expression, with few limits beyond those of
16 our perceptual and motor systems and the cultures in and for which we draw. The present study
17 suggests a previously unrecognized yet early emerging cognitive constraint on human drawing
18 rooted in the basic processes of navigation that humans share with other animals and evidenced
19 in the untutored drawings of young children. Following a preregistered design and analysis, 64 4-
20 year-old children either sat in a colorful “fort” or looked at a small “toy” version of the fort and
21 were asked to draw exactly what they saw. Children’s drawings often omitted the walls
22 composing the fort’s layout but included the corresponding object-part information for the toy.
23 Symbolic representations of space in children’s untutored drawings may thus privilege small-
24 scale objects, which elicit explicit attention, over large and fixed layout geometry, which is used
25 automatically for navigation.

As a form of human expression, drawing may seem limited only to that which we can see, whether in the world or in the mind's eye. Sure, our limited perceptual and motor systems must constrain our drawing in some ways, especially in children, and so do trends or traditions of culture and history (see Nadal & Chatterjee, 2018). But under these constraints, when asked to draw what we see, we should be otherwise free to do so. The present study posits instead a previously unrecognized yet early emerging cognitive constraint on human drawing. Here, we suggest that a distinction within human intuitive geometries—one for large-scale and fixed layouts and one for small-scale object shapes and features—leads to the production of drawings that prioritize objects. Phylogenetically ancient processes used automatically for navigation and those that allow for explicit attention to objects may thus constrain uniquely human drawing.

Humans and other animals navigate the spatial world in surprisingly similar ways (see Cheng & Newcombe, 2005 and Spelke & Lee, 2012 for reviews). One way, which appears to unfold automatically, is by evaluating their egocentric distances and directions to the fixed boundary surfaces in the environment (Dilks, Julian, Kubilius, Spelke & Kanwisher, 2011; Epstein, Patai, Julian, & Spiers, 2017; Hartley, Lever, Burgess, & O'Keefe, 2014; Lee, Sovrano, & Spelke, 2012; O'Keefe & Burgess, 1996; Persichetti & Dilks, 2016; Wills, Cacucci, Burgess, & O'Keefe, 2010). A seminal study by Cheng & Gallistel (1984), for example, found that rats disoriented in a rectangular environment regain their heading by using the geometry of the environment's boundaries: They recognize and search at a correct corner target location or its geometrically equivalent, diagonal opposite. Without training, moreover, rats fail to integrate landmark cues (e.g., a patterned wall) into their search behavior even though such cues break the room's geometric symmetry and therefore disambiguate the target's location (Julian, Keinath, Muzzio, & Epstein, 2015). Zebrafish (Lee, Vallortigara, Flore, Spelke, & Sovrano, 2013), ants

(Wystrach & Beugnon, 2009), bees (Lee, & Vallortigara, 2015), and control-reared animals of other species, like chicks and fish (Brown, Spetch, & Hurd, 2007; Chiandetti & Vallortigara, 2010), exhibit untutored search patterns similar to those of rats in reorientation tasks, suggesting that the automatic navigation of layouts by their surface boundary geometry is present across phylogeny. Young children also show such performance during navigation. A seminal study by Hermer & Spelke (1994), for example, found that young children succeed in using geometry to search at the correct and geometrically equivalent targets in a symmetrical, all white rectangular room during reorientation. Like rats and other animals, moreover, they also ignore a symmetry-breaking landmark, like a colored wall. Finally, while human adults, unlike human children and other animals, use both layout geometry and landmarks when reorienting, their use of layout geometry is automatic while their use of landmarks is explicit: When a colored wall is present, they report only their use of that landmark to reorient; when there is no colored wall, they report guessing randomly despite their non-random behavior (Hermer & Spelke, 1996).

While humans and other animals appear to navigate automatically by the geometry of the fixed layout, human adults, children, and trained animals can also navigate by isolated, small-scale objects with distinctive shapes or surface features. In human adults and rats, this object-based navigation is neurally and cognitively dissociated from boundary-based navigation and requires reinforcement learning, rather than occurring automatically (Barry & Muller, 2011; Doeller & Burgess, 2008; Doeller, King, & Burgess, 2008). Young children can use patterned or colored walls during reorientation when those features are direct cues for where to search or are highly salient, allowing for an easily learned association between those features and a target location (Learmonth, Newcombe, & Huttenlocher, 2001; Learmonth, Nadel, and Newcombe, 2002; Shusterman, Lee, & Spelke, 2011; Twyman, Friedman, & Spetch, 2007). And so for both

ROOMS WITHOUT WALLS

humans and other animals alike, while navigation by layout geometry unfolds automatically, navigation by object shape or featural information requires explicit attention.

Young children's untutored, symbol-guided navigation also suggests an automatic use of boundary layout information and an attention-based use of object shape information (Dillon, Huang, & Spelke, 2013; Dillon & Spelke 2015, 2017). For example, Dillon & Spelke (2017) presented different groups of 4-year-old children with perspectival line drawings of just the layout of a rectangular room (i.e., its walls, floor, and ceiling) or just the distinctly shaped objects in the room (i.e., a table, chairs, and trash bins) and asked children to find locations that were either in a clear position relative to the room's walls or very close to an object of a particular shape in the room. Children searched more effectively at wall targets using the layout-only drawings and object targets using the object-only drawings. They nevertheless judged that the object-only drawings were better and more informative depictions of both kinds of targets, suggesting, like the adults in reorientation tasks, explicit attention to and use of object shape information, not layout geometry, during their symbol-guided navigation. Indeed, objects elicit attention in many everyday contexts (see Scholl, 2001 for a review), and heightened attention to objects as individuals as opposed to mere spatial extents is present from infancy (e.g., Feigenson & Carey 2005; Feigenson, Carey, & Hauser, 2002). Moreover, objects serve as the referents for infants' earliest symbolic learning: language. Infants first learn the names for objects (Gentner, 1982; Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976), and they use language to generalize object categories based on shape and function from as early as 6 months of age (Fulkerson & Waxman, 2007; Futó, Téglás, Csibra, & Gergely, 2010).

Drawings are physical, visuospatial geometries mostly on flat surfaces (Gombrich, 2000), but they are also symbolic; they can entail reference, representation, communication, and

intention (DeLoache, 2004; Callaghan & Corbit, 2015). Prior work on children's drawing suggests that children tend to draw mostly objects, even when conveying layout information (Machón, 2013; Villarroel & Ortega, 2017). Nevertheless, in such studies, children were presented either with only objects to draw (e.g., Bremner & Batten, 1991) or with object and layout information that differed in other visual features, such as shape, complexity, and texture (e.g., Kriendel & Intraub, 2017). Children's object-focused drawings in prior studies may thus have been the result of basic differences in the stimuli. The present study therefore presents different groups of 4-year-old children with either a colorful "fort," with layout and object information matching in shape and complexity, or a small "toy," matching the fort exactly but at 1/20 the size. In both conditions, children were asked to draw exactly what they saw. By measuring the number of walls and objects that children draw in the fort and comparing those counts to the number of the corresponding object-part configurations of the toy, we evaluate whether children preferentially draw objects over layouts based on differences in spatial category alone.

Methods

Participants

The sample size was chosen in advance of data collection, was based on pilot data in which patterns of responding were consistent across small numbers of children, and was preregistered on the Open Science Framework (OSF). Data collection stopped when the preregistered number of participants was determined to meet the inclusion criteria. Participants were recruited from New York City area, and the use of human participants for this study was approved by the Institutional Review Board on the Use of Human Subjects at New York University.

ROOMS WITHOUT WALLS

Sixty-four four-year old children participated. After the design and analysis plan were preregistered for the first condition, 32 children completed four drawings of a small “fort” arranged in different ways ($M_{\text{age}} = 4.50$, range = 4.03 - 4.99; 15 females). One additional child participated but did not meet our preregistered inclusion criteria because of experimenter error during data collection. The data from this first condition were analyzed, and prior to data collection with the second set of 32 participants, a second design and analysis plan were preregistered. This group of 32 children drew a small “toy” version of the fort, arranged in exactly the same ways ($M_{\text{age}} = 4.49$, range = 4.02 - 4.98; 21 females). No additional children were excluded.

Fort Condition, Materials and Procedures

Children were presented with four configurations of a colorful “fort” (**Fig. 1**). Two configurations included two rectangular side walls (5’6” x 7’) and one rectangular back wall (5’6” x 5’3”), with one rectangular object (2’ x 1’6”) in front of each wall. Two configurations included an additional fourth wall (5’6” x 3’6”), orthogonally bisecting the back wall, with one rectangular object in front of each side wall and one on either side of the bisecting wall. One 3-wall and one 4-wall configuration also included circular decals placed in the center of each wall (diameter = 0.875”) and object (diameter = 0.25”). Fort configurations were presented in a semi-counterbalanced order to children: Configurations with or without decals were always paired, but order was otherwise fully counterbalanced. The exterior room in which the fort was set up was covered with opaque white fabric to block any of its salient attributes. In addition, a white drop ceiling was installed to cover all but a plain, circular central light fixture. Two cameras were mounted above the door.

ROOMS WITHOUT WALLS

Fig. 1. Photographs of the context and configurations in the fort (top row) and toy (bottom row) conditions. A sample set of one child's drawings from each condition are included below each set of photographs to illustrate the study's main finding that children tend to leave out large, fixed layout information in their drawings but include all shape-defining features of objects in their drawings.

Children entered the fort with two experimenters (one primary experimenter and one coder) and sat on a black "X" on the floor, 6" from the fort's opening. Children first completed a practice trial in which they were asked to use a pencil and 8.5" x 11" piece of white paper to draw everything that they saw (after Lewis, Russell, & Berridge, 1993), but nothing more, from a 8.5" x 11" laminated piece of paper, which depicted 16 colorful forms of various shapes and sizes arranged in a quasi-symmetrical layout (for practice trial picture and full experimental script, see **SM**). When children indicated that they had completed their drawing, they received instructive feedback: The experimenter went through every element in the practice trial picture and asked children to point to that element in their own drawing. If an element was missing, the experimenter asked children to add it to their drawing, reiterating that children should draw

ROOMS WITHOUT WALLS

157 everything that they saw. If there were extra elements, the experimenter reiterated to children
158 that they should only draw what they saw and nothing more.

159 The first test trial began immediately after the practice trial. The experimenter waved
160 their hand across the space and said, “See how we’re in this super cool fort? I’m going to give
161 you another piece of paper, and your job is to draw exactly what you see.” Children were given a
162 clipboard with an 8.5” x 11” sheet of white paper and a pencil to complete their drawing. As in
163 the practice trial, children were asked to indicate when they were done, and there was no time
164 limit. Unlike the practice trial, children received no informative feedback.

165 After children indicated that the drawing was complete, the coder took a photograph of
166 the drawing with an iPad and followed a preregistered coding procedure. In this procedure, the
167 experimenter first asked children to point to each individual element in their drawing, and the
168 coder outlined each element on the corresponding iPad photograph with a stylus. If there were
169 isolated lines or closed shapes that children did not point out, the experimenter asked, “Is there
170 anything else?” If children did not indicate any further elements, the experimenter pointed to the
171 missing element(s), saying, “Is this something else?” If children indicated that the missing
172 element was not an element or was a mistake, the element was not outlined or included as part of
173 the final drawing. Second, the experimenter asked children to identify each of the outlined
174 elements by touching them in the fort. To do so, the experimenter touched one element directly
175 on the drawing and asked, “Can you go touch it to show me what you drew?” The experimenter
176 repeated this procedure for each outlined element. The coder recorded the element in the fort that
177 children touched by annotating the photograph (see **SM** for the full set of coded drawings). If
178 children at that point indicated that an element they had already individuated was a mistake, that
179 element was coded as having an indeterminate referent. If children wanted to add something to

their drawing after the coding had begun, they were allowed to, but such elements were not coded. After this procedure, children exited the testing space, and the room was re-configured for the next test trial. This procedure was repeated for the next three test trials.

Toy Condition, Materials and Procedures

The toy condition closely mimicked the fort condition in materials and procedures. We created a 3D-printed, plastic scale model of the fort at 1/20 the size, matching the fort exactly in color and configuration (**Fig. 1**). While all the parts of the toy were now “objects,” and the toy was always described as a toy (never as, e.g., a “model fort”), for ease of comparison, we refer in this paper to the parts of the toy that correspond to the walls of the fort as “walls” and the parts of the toy that correspond to the objects in the fort as “objects.”

Children entered the testing room with two experimenters (one primary experimenter and one coder) and sat in a child-sized chair at a small table. The experimenter sat at the table, orthogonal to children, and the coder stood behind children to one side. The toy was on top of the table, positioned at children’s eye level and was covered with opaque white fabric as children entered and left the room so that they did not see the toy from an overhead perspective. The table, as well as the side walls of the room, were also covered with opaque white fabric to cover any of the exterior room’s salient features. One camera was placed behind children and one was placed next to the experimenter.

Children completed the same practice trial as in the fort condition and then moved on to the test trials, which were presented in the same semi-counterbalanced order as the fort condition. The experimenter waved their hand in front of the toy and said, “Do you see this super cool toy? I’m going to give you another piece of paper, and your job is to draw exactly what you see.” As in the fort condition, the coder and experimenter followed the preregistered coding

procedure. The only difference between the conditions was that children used a long plastic pointer, instead of their hands, to indicate the identity of each element of their picture since the setup was small.

Analysis

All of our analyses were specified prior to data collection and preregistered on OSF with one change: We had initially specified some models with random-effects slopes as well as random-effects intercepts (see **SM**); however, several of these models failed to converge, and so we dropped all random-effects slopes from all analyses. We defined two primary dependent variables. First, we enumerated the number of spatial elements that children drew according to four categories: walls; objects; wall decals; or object decals. The relative counts of each element were analyzed with mixed-model Poisson regressions. There were three additional categories of elements, which were coded but not included in the analysis: miscellaneous elements in the room (e.g., door handle); miscellaneous elements not in the room (e.g., ice cream cone); and elements with an indeterminate referent (e.g., scribbles). Second, we measured the geometric richness of the spatial elements by evaluating each element's dimensionality (one-, two-, or three-dimensional; see **SM** for details). These dimensionality categories were analyzed with mixed-model ordinal logistic regressions.

Our data coding was also preregistered. The live-coding procedure, detailed above, was our primary coding scheme. However, we also implemented two additional coding schemes to evaluate the reliability of our results. First, a second coder used the experimental videos to recode 25% of children's drawings from each condition for their spatial element counts. Our planned model for calculating coder reliability was misspecified (see **SM**), and so we calculated the reliability of the count data using a measure of intraclass correlation (see Shrout & Fleiss,

1979). The coding reliability for both conditions was high (fort: $ICC(1,1) = .97$, 95% CI [.96, .98]; toy: $ICC(1,1) = .89$, 95% CI [.85, .92]). Second, two hypothesis-blind coders also coded the drawings (coder 1 did all of the drawings; coder 2 did 25%). These blind coders used photographs of the fort and toy from children's seated perspective to make their best guess as to the identity of each spatial element in the original drawings. The planned analyses were repeated on the entire set of blind coder 1's drawings, and the count reliability analysis evaluated how well blind coder 2's coding predicted blind coder 1's. The results from this analysis are convergent with the results in the main text, and so we report them in the **SM**.

Results

Fort Condition

Our primary analysis examined the number of spatial elements that children drew. A mixed-model Poisson regression with spatial element (wall or object) and configuration (each of the four configurations, see **Fig. 1**) included as predictor variables and participant included as a random-effects intercept revealed main effects of both spatial element (Wald Test, $\chi^2(1) = 45.90$, $p < .001$) and configuration (Wald Test, $\chi^2(3) = 12.31$, $p = .006$). As predicted, in the fort condition children drew significantly more objects ($M = 3.39$, $SEM = 0.20$) than walls ($M = 1.99$, $SEM = 0.15$; **Fig. 2**), and children varied their drawings based on the number of spatial elements present in each configuration (configurations included 6, 8, 12, or 16 total elements, see **Fig. 1**). A second mixed-model Poisson regression with spatial element (wall, object, wall decal, or object decal) included as a predictor variable and participant included as a random-effects intercept, but considering only the two configurations that included decals (see **Fig. 1**), again revealed a main effect of spatial element (Wald Test, $\chi^2(3) = 27.37$, $p < .001$). Planned Holm-

ROOMS WITHOUT WALLS

corrected pairwise contrasts also revealed that children drew significantly more objects than walls (**Fig. 2**).

Fig. 2. Spatial element counts as predicted by the model in the fort (top) and toy (bottom) conditions. Across all configurations in **Fig. 1**, children drew more objects than walls in the fort, but not for the toy (left column). In configurations with surface decals, children drew more objects than other spatial elements in the fort but appeared to draw the larger spatial elements more frequently for the toy (right column). Planned Holm-corrected pairwise contrasts, *** $p < .001$, ** $p < .01$, * $p < .05$, † $p < .1$. Error bars display the standard error of the model fits.

We then measured the geometric richness of the spatial elements by evaluating their dimensionality. A mixed-model ordinal logistic regression with spatial element (wall or object) and configuration (each of the four configurations, see **Fig. 1**) included as predictor variables and participant included as a random-effects intercept revealed that children drew objects with more

geometric richness than walls. The odds of children's drawing objects with greater dimensionality were 269.88% more likely than the odds of children's drawing walls with greater dimensionality (95% CI = [112.31, 544.41], $p < .001$, **Fig. S1**). For the two configurations with decals, the odds of children's drawing objects with greater dimensionality were 222.97% more likely than the odds of children's drawing walls with greater dimensionality (95% CI = [46.63, 611.36], planned Holm-corrected pairwise contrast, $p = .004$, **Fig. S1; Table S1A**).

Toy Condition

As in the fort condition, our primary analysis examined the number of spatial elements that children drew using mixed-model Poisson regressions. In the first regression exploring wall and object counts across all four configurations, we again found main effects of both spatial element (Wald Test, $\chi^2(1) = 4.45$, $p = .035$) and configuration (Wald Test, $\chi^2(3) = 12.41$, $p = .006$). While we had predicted no difference in the spatial element count, children showed the opposite pattern in the toy condition compared to the fort condition: Children drew more walls ($M = 3.39$, $SEM = 0.12$) than objects ($M = 2.92$, $SEM = 0.13$; **Fig. 2**). In the regression considering the rooms with all four element types, we again found a main effect of spatial element (Wald Test, $\chi^2(3) = 25.93$, $p < .001$), and planned Holm-corrected pairwise contrasts also revealed that children drew more walls than objects (**Fig. 2**). Indeed, while children clearly drew more objects than walls in the fort condition, their drawing counts in the toy condition may have reflected the relative sizes of each of the element types. That said, in the analysis of the configurations without decals and the analysis of the blind-coded data, the greater counts for walls versus objects was less consistent than in the main analysis (see **SM**), so this size-based result may be weak.

We then again measured the geometric richness of the spatial elements by evaluating their dimensionality. Unexpectedly, children drew objects with more geometric richness than walls, as in the fort condition. The odds of children's drawing objects with greater dimensionality were 1823.50% more likely than the odds of children's drawing walls with greater dimensionality (95% CI = [981.51, 3321.01], $p < .001$, **Fig. S1**). This effect persisted when just examining the two configurations with decals: The odds of children's drawing objects with greater dimensionality were 897.33% more likely than the odds of children's drawing walls with greater dimensionality (95% CI = [445.68, 1722.80], planned Holm-corrected pairwise contrast, $p < .001$, **Fig. S1, Table S1B**). This unexpected result may have been due to a more general challenge that children face when capturing the concavity formed by both the fort's and object's walls.

Comparing the Fort and Toy Conditions

To directly examine the differences in children's drawings across the two conditions, we conducted the same mixed-model regressions as above, but with condition as an additional predictor variable. First, for element count, including walls and objects across all four configurations, we found main effects both of spatial element (children drew more objects than walls; Wald Test, $\chi^2(1) = 8.55$, $p = .003$) and of condition (children drew more elements in the toy condition versus the fort condition; Wald Test, $\chi^2(1) = 7.44$, $p = .006$). Critically, these results were further characterized by a significant spatial element by condition interaction (Wald Test, $\chi^2(1) = 41.44$, $p < .001$): Children drew significantly more walls than objects in the toy versus fort condition. Planned Holm-corrected pairwise contrasts revealed that children did not draw significantly more objects in the toy versus fort condition ($p = .082$), but they did draw significantly more walls in the toy versus fort condition ($p < .001$). The second regression,

ROOMS WITHOUT WALLS

examining element counts in the two configurations with four spatial elements also revealed main effects of both spatial element (Wald Test, $\chi^2(3) = 20.06$, $p < .001$) and condition (Wald Test, $\chi^2(1) = 6.76$, $p = .009$) as well as an interaction between these variables (Wald Test, $\chi^2(3) = 33.06$, $p < .001$). Again, planned Holm-corrected pairwise contrasts revealed that children did not draw significantly more objects in the toy versus fort condition ($p = .187$), but they did draw significantly more walls in the toy versus fort condition ($p < .001$).

Finally, a mixed-model ordinal logistic regression examining element dimensionality for walls and objects across all four configurations revealed that, across conditions, children drew objects with more geometric richness than walls. The odds of children's drawing objects with greater dimensionality were 210.74% more likely than the odds of children's drawing walls with greater dimensionality (95% CI = [105.93, 368.91], $p < .001$). Children also drew elements with greater dimensionality in the fort versus toy condition. The odds of children's drawing elements with greater dimensionality in the fort condition were 76.58% more likely than the odds of children's drawing elements with greater dimensionality in the toy condition (95% CI = [65.31, 84.19], $p < .001$). The model also revealed a significant element type by condition interaction: the odds of children drawing objects versus walls with greater dimensionality in the toy condition was 126.62% more likely than the odds of children drawing objects versus walls with greater dimensionality in the fort condition (95% CI = [32.26, 288.32], $p = .003$). The model including all four element types across two configurations was convergent with these results: The odds of children's drawing objects with greater dimensionality were 183.17% more likely than the odds of children's drawing walls with greater dimensionality (Planned Holm-corrected pairwise contrast, 95% CI = [50.60, 432.44], $p = .001$), and the odds of children's drawing elements with greater dimensionality in the fort condition were 82.79% more likely than the odds

of children's drawing elements with greater dimensionality in the toy condition (95% CI = [69.86, 90.18], $p < .001$). The model also revealed a significant element type by condition interaction: the odds of children drawing objects versus walls with greater dimensionality in the toy condition was 186.88% more likely than the odds of children drawing objects versus walls with greater dimensionality in the fort condition (Planned Holm-corrected pairwise contrast comparing walls and objects in the fort and toy conditions, 95% CI = [26.28, 551.73], $p = .035$).

Discussion

Using stimuli matched on shape and complexity, we compared in young children's drawings the frequency of large, fixed layout information and small, manipulable object information. When drawing a layout, children merely juxtaposed objects and surface features and omitted environmental boundaries. When drawing an equally complex object, in contrast, children captured all of the elements, including those in the background. These findings are the first to show that the untutored drawings of young children clearly prioritize objects over layouts.

Why do children draw objects but not layouts? We suggest that basic differences in the way that not only children, but also adults and non-human animals, attend to layouts and objects for everyday navigation might constrain human drawing. While humans and other animals use layout information automatically to determine their position in space, they must attend to and learn associations between their position in space relative to distinct landmark objects (e.g., Doeller & Burgess, 2008; Doeller et al., 2008). For humans uniquely, the same dissociation of automaticity and attention to layouts and objects is evident in symbol-guided navigation (e.g., Dillon & Spelke, 2017) and language (e.g., Grimm, 1975). Because drawings, like language, are symbolic, intentional, and communicative (see Callaghan & Corbit, 2015), they may therefore

prioritize those elements in the environment that draw our explicit attention. These constraints might be especially evident in young children's drawings, before children have been affected by their culture's artistic traditions (such as instruction to draw or trends in drawing horizon lines; Nand, Masuda, Senzaki, & Ishii, 2014).

Such a general hypothesis for constraints on human drawing should thus extend beyond layouts and objects to other aspects of everyday life. For example, are we more likely to pay attention to people than objects, and so depict people more often in our drawings? Or, are objects more likely to be drawn because we use drawings to communicate to people about the properties and functions of objects? Future studies varying the content of drawing subject matter while matching other variables like visual complexity may begin to address these questions. Moreover, varying the communicative intent of drawings, including what information is important to the purpose of the drawing (e.g., to show someone *where* something is or *what* something does), may shed light on what attentional hierarchies are present in everyday life and translate to our picture-making.

Another possibility for why young children draw objects but not layouts is that drawing layouts and objects may pose unique geometric challenges. In particular, the geometry of a scene's layout may be more difficult to draw than the shapes of objects. Automatic navigation by layouts tends to rely on the distances and directions of boundary surfaces (e.g., Julian, Keinath, Marhcette, & Epstein, 2018; Lee et al., 2012), while recognition of objects tends to rely on the relative lengths and angles that define object-shape (e.g., Biederman & Cooper 1991; Smith, 2009). Drawing distance or depth information on a 2D surface in general may be difficult, as perhaps exemplified in the present study by children's tendency to depict the walls of the fort and the corresponding object-parts of the toy using only single lines. Since distance information

ROOMS WITHOUT WALLS

is primarily for boundary-based navigation but not object recognition, the difficulty in capturing boundary distance as a particular shape on a 2D surface may lead children to omit it in drawings. In contrast, since the very same shape information is attended to and used both to recognize objects in everyday life and to draw them on a 2D surface (Fan, Yamins, & Turk-Browne, 2018; Sayim & Cavanaugh, 2011), children instead may prioritize object depictions in drawings and even convey the layout of a scene by merely juxtaposing objects in drawings. Indeed, while by age three to four years children can capture object shape information in their drawings (e.g., Cox, 2005; Drake & Winner, 2012), children have difficulty incorporating receding depth information into their drawings through early adolescence (e.g., Freeman, 1980; Willats, 1995). Because object-focused drawings do nevertheless give a reasonable sense of the general arrangement of most layouts, future studies could examine how helpful the inclusion of layout geometry is to the purpose or aesthetics of a drawing. Future studies might also explore whether there are differences in the difficulty of drawing the depth information that describes layouts versus objects or whether, if children are asked to reconstruct 3D models instead of 2D drawings, they still leave out the walls of layouts.

While drawing may seem like an epitome of relatively unconstrained human expression, especially in young children, the present study has revealed a clear, early emerging cognitive constraint on drawing. Drawings may prioritize a layout's small-scale objects, which elicit explicit attention, over large-scale and fixed layout geometry, which is used automatically for navigation. Phylogenetically ancient cognitive domains for interacting with layouts and objects, as well as other shared or uniquely human cognitive domains for attending to the actions, goals, and emotions of people and animals, may thus universally shape our art. To better understand an

individual's artistic development or even the history of art, we must better understand the cognitive constraints and attentional hierarchies that frame human drawings.

Author Contributions

M.R.D. conceived of and designed the study. M.R.D.'s lab collected the data. K.M. analyzed the data. K.M. and M.R.D. wrote the paper.

Open Practices Statement

As specified in the text, the design, protocol, and analysis plan for this study were preregistered prior to data collection on the Open Science Framework. The procedural materials, data, and analysis code are publicly accessible at: osf.io/5wng2

Acknowledgments

This work was supported by a National Science Foundation CAREER Award (DRL-1845924; to M.R.D.) and by a Jacobs Foundation Early Career Fellowship (to M.R.D.). We thank the families who participated, O. Garcia, H. Huey, N. Loncar, and D. Dayal for assistance with data collection, and E. Spelke, B. Reilly, B. Landau, and M. Rhodes for suggestions on the manuscript.

References

- Barry, J., & Muller, R. (2011). Updating the hippocampal representation of space: place cell firing fields are controlled by a novel spatial stimulus. *Hippocampus*, 21(5), 481-494.
- Biederman, I., & Cooper, E. E. (1991). Evidence for complete translational and reflectional invariance in visual object priming. *Perception*, 20(5), 585-593.
- Bremner, J. G., & Batten, A. (1991). Sensitivity to viewpoint in children's drawings of objects and relations between objects. *Journal of Experimental Child Psychology*, 52(3), 375-394.
- Brown, A. A., Spetch, M. L., & Hurd, P. L. (2007). Growing in circles: Rearing environment alters spatial navigation in fish. *Psychological Science*, 18(7), 569-573.
- Callaghan, T., & Corbit, J. (2015). The development of symbolic representation. In L. S. Liben & U. Müller (Eds.) *Cognitive processes*. Volume 2 of the *Handbook of child psychology and developmental science* (7th ed.; pp. 250-295). Editor-in-chief: R. M. Lerner. Wiley.
- Cheng, K. & Gallistel, C. R. (1984). Testing the geometric power of an animal's spatial representation. In H. L. Roitblat, T. G. Bever & H. S. Terrace (Eds.) *Animal Cognition*. (pp. 409-423). Lawrence Erlbaum Associates.
- Cheng, K., & Newcombe, N. S. (2005). Is there a geometric module for spatial orientation? Squaring theory and evidence. *Psychonomic Bulletin & Review*, 12(1), 1-23.
- Chiandetti, C., & Vallortigara, G. (2010). Experience and geometry: controlled-rearing studies with chicks. *Animal cognition*, 13(3), 463-470.
- Coles, R., Sartor, M. (1992). *Their eyes meeting the world: The drawings and paintings of children*. Boston, MA: Houghton Mifflin.
- Cox, M. (2005). *The pictorial world of the child*. Cambridge: Cambridge University Press.

- 444 DeLoache, J. S. (2004). Becoming symbol-minded. *Trends in Cognitive Sciences*, 8(2), 66-70.
- 445 Dilks, D. D., Julian, J. B., Kubilius, J., Spelke, E. S., & Kanwisher, N. (2011). Mirror-image
446 sensitivity and invariance in object and scene processing pathways. *The Journal of*
447 *Neuroscience*, 31(31), 11305-11312.
- 448 Dillon, M. R., Huang, Y., & Spelke, E. S. (2013). Core foundations of abstract
449 geometry. *Proceedings of the National Academy of Sciences*, 110(35), 14191-14195.
- 450 Dillon, M. R., & Spelke, E. S. (2015). Core geometry in perspective. *Developmental Science*,
451 18(6), 894–908.
- 452 Dillon, M. R., & Spelke, E. S. (2017). Young children’s use of surface and object information in
453 drawings of everyday scenes. *Child Development*, 88(5), 1701-1715.
- 454 Doeller, C. F., & Burgess, N. (2008). Distinct error-correcting and incidental learning of location
455 relative to landmarks and boundaries. *Proceedings of the National Academy of*
456 *Sciences*, 105(15), 5909-5914.
- 457 Doeller, C. F., King, J. A., & Burgess, N. (2008). Parallel striatal and hippocampal systems for
458 landmarks and boundaries in spatial memory. *Proceedings of the National Academy of*
459 *Sciences*, 105(15), 5915-5920.
- 460 Drake, J. E., & Winner, E. (2012). Children gifted in drawing: The incidence of precocious
461 realism. *Gifted Education International*, 29(2), 125-139.
- 462 Epstein, R. A., Patai, E. Z., Julian, J. B., & Spiers, H. J. (2017). The cognitive map in humans:
463 spatial navigation and beyond. *Nature Neuroscience*, 20(11), 1504.
- 464 Fan, J. E., Yamins, D. L., & Turk-Browne, N. B. (2018). Common object representations for
465 visual production and recognition. *Cognitive Science*, 42(8), 2670-2698.

- 466 Feigenson, L. & Carey, S. (2005). On the limits of infants' quantification of small object arrays.
467 *Cognition*, 97, 295-313.
- 468 Feigenson, L., Carey, S., & Hauser, M. (2002). The representations underlying infants' choice of
469 more: Object files versus analog magnitudes. *Psychological science*, 13(2), 150-156.
- 470 Freeman, N. (1980). *Strategies of representation in young children: Analysis of spatial skills and*
471 *drawing processes*. London: Academic Press.
- 472 Fulkerson, A. L., & Waxman, S. R. (2007). Words (but not tones) facilitate object categorization:
473 Evidence from 6- and 12-month-olds. *Cognition*, 105(1), 218-228.
- 474 Futó, J., Téglás, E., Csibra, G., & Gergely, G. (2010). Communicative function demonstration
475 induces kind-based artifact representation in preverbal infants. *Cognition*, 117(1), 1-8.
- 476 Gentner, D. (1982). Why nouns are learned before verbs: Linguistic relativity versus natural
477 partitioning. In S. A. Kuczaj (Ed.), *Language development: Language, thought, and*
478 *culture* (Vol. 2, pp. 301-334). Hillsdale, NJ: Erlbaum.
- 479 Gombrich, E. H. (2000). *Art and illusion: A study in the psychology of pictorial representation*
480 (Vol. 5). Princeton, NJ: Princeton University Press.
- 481 Grimm, H. (1975). On the child's acquisition of semantic structure underlying the wordfield of
482 prepositions. *Language and Speech*, 18, 97-119.
- 483 Hartley, T., Lever, C., Burgess, N., & O'Keefe, J. (2014). Space in the brain: how the
484 hippocampal formation supports spatial cognition. *Philosophical Transactions of the*
485 *Royal Society B*, 369, 20120510.
- 486 Hermer, L., & Spelke, E. S. (1994). A geometric process for spatial reorientation in young
487 children. *Nature*, 370(6484), 57.

ROOMS WITHOUT WALLS

- 488 Hermer, L., & Spelke, E. (1996). Modularity and development: The case of spatial
489 reorientation. *Cognition*, 61(3), 195-232.
- 490 Julian, J. B., Keinath, A. T., Marchette, S. A., and Epstein, R. A. (2018). The Neurocognitive
491 Basis of Spatial Reorientation. *Current Biology*, 28, R1059–R1073.
- 492 Julian, J. B., Keinath, A. T., Muzzio, I. A., & Epstein, R. A. (2015). Place recognition and
493 heading retrieval are mediated by dissociable cognitive systems in mice. *Proceedings of*
494 *the National Academy of Sciences*, 112(20), 6503-6508.
- 495 Kreindel, E., & Intraub, H. (2017). Anticipatory scene representation in preschool children's
496 recall and recognition memory. *Developmental Science*, 20(5), e12444.
- 497 Learmonth, A. E., Nadel, L., & Newcombe, N. S. (2002). Children's use of landmarks:
498 Implications for modularity theory. *Psychological Science*, 13(4), 337-341.
- 499 Learmonth, A. E., Newcombe, N. S., & Huttenlocher, J. (2001). Toddlers' use of metric
500 information and landmarks to reorient. *Journal of Experimental Child Psychology*, 80(3),
501 225-244.
- 502 Lee, S. A., Sovrano, V. A., & Spelke, E. S. (2012). Navigation as a source of geometric
503 knowledge: Young children's use of length, angle, distance, and direction in a
504 reorientation task. *Cognition*, 123(1), 144-161.
- 505 Lee, S. A., & Vallortigara, G. (2015). Bumblebees spontaneously map location of conspecific
506 using geometry and features. *Learning and Motivation*, 50, 32-38
- 507 Lee, S. A., Vallortigara, G., Flore, M., Spelke, E. S., & Sovrano, V. A. (2013). Navigation by
508 environmental geometry: the use of zebrafish as a model. *Journal of Experimental*
509 *Biology*, 216(19), 3693-3699.

ROOMS WITHOUT WALLS

- 510 Lewis, C., Russell, C., & Berridge, D. (1993). When is a mug not a mug? Effects of content,
511 naming, and instructions on children's drawings. *Journal of Experimental Child*
512 *Psychology*, 56(3), 291-302.
- 513 Machón, A. (2013). Children's drawings: The genesis and nature of graphic representation. A
514 developmental study. Madrid: Fibulas Publishers.
- 515 Nand, K., Masuda, T., Senzaki, S., & Ishii, K. (2014). Examining cultural drifts in artworks
516 through history and development: cultural comparisons between Japanese and western
517 landscape paintings and drawings. *Frontiers in Psychology*, 5, 1041.
- 518 Nadal, M., & Chatterjee, A. (2018). Neuroaesthetics and art's diversity and universality. *Wiley*
519 *Interdisciplinary Reviews: Cognitive Science*, e1487.
- 520 O'Keefe, J., & Burgess, N. (1996). Geometric determinants of the place fields of hippocampal
521 neurons. *Nature*, 381(6581), 425-428.
- 522 Persichetti, A. S., & Dilks, D. D. (2016). Perceived egocentric distance sensitivity and invariance
523 across scene-selective cortex. *Cortex*, 77, 155-163.
- 524 Pinna, B. (2003) Why are paintings painted as they are? The place of children's drawings in
525 vision and art. *Art & Perception*, 1(1-2), 75-104.
- 526 Rosch, E., Mervis, C. B., Gray, W. D., Johnson, D. M., & Boyes-Braem, P. (1976). Basic objects
527 in natural categories. *Cognitive Psychology*, 8(3), 382-439.
- 528 Sayim, B., & Cavanagh, P. (2011). What Line Drawings Reveal About the Visual
529 Brain. *Frontiers in Human Neuroscience*, 5, 118.
- 530 Scholl, B. J. (2001). Objects and attention: The state of the art. *Cognition*, 80(1-2), 1-46.
- 531 Shrout, P. E., & Fleiss, J. L. (1979). Intraclass correlations: uses in assessing rater reliability.
532 *Psychological Bulletin*, 86(2), 420.

- 533 Shusterman, A., Lee, S. A., & Spelke, E. S. (2011). Cognitive effects of language on human
534 navigation. *Cognition*, 120(2), 186-201.
- 535 Smith, L. B. (2009). From fragments to geometric shape: Changes in visual object recognition
536 between 18 and 24 months. *Current Directions in Psychological Science*, 18(5), 290-294.
- 537 Spelke, E. S., & Lee, S. A. (2012). Core systems of geometry in animal minds. *Philosophical
538 Transactions of the Royal Society B: Biological Sciences*, 367(1603), 2784-2793.
- 539 Twyman, A., Friedman, A., & Spetch, M. L. (2007). Penetrating the geometric module:
540 Catalyzing children's use of landmarks. *Developmental Psychology*, 43(6), 1523.
- 541 Villarroel, J. D., & Ortega, O. S. (2017). A study regarding the spontaneous use of geometric
542 shapes in young children's drawings. *Educational Studies in Mathematics*, 94(1), 85-95.
- 543 Fulkerson, A. L., & Waxman, S. R. (2007). Words (but not tones) facilitate object categorization:
544 Evidence from 6-and 12-month-olds. *Cognition*, 105(1), 218-228.
- 545 Willats, J. (1995). An information-processing approach to drawing development. In C. Lange-
546 Kuttner, & G. V. Thomas (Eds.), *Drawing and looking: theoretical approaches to
547 pictorial representation in children* (pp. 27–43). New York, NY: Harvester Wheatsheaf.
- 548 Wills, T. J., Cacucci, F., Burgess, N. & O'Keefe, J. (2010) Development of the hippocampal
549 cognitive map in preweanling rats. *Science*, 328, 1573-1576.
- 550 Wystrach, A., & Beugnon, G. (2009). Ants learn geometry and features. *Current Biology*, 19(1),
551 61-66.
- 552 Xiao, J., Ehinger, K. A., Hays, J., Torralba, A., & Oliva, A. (2016). Sun database: Exploring a
553 large collection of scene categories. *International Journal of Computer Vision*, 119(1), 3-
554 22.
- 555