Young Children’s Perception of Diagrammatic Representations

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Abstract

Diagrams and pictorial representations are common in children's lives and require abstraction away from visual perception. In three experiments, we investigated 4- to 8-year-olds' comprehension of such representations. In Experiment 1 ($N = 80$), children were shown photographs of geometric objects and asked to choose the corresponding line drawing from among sets of four, or vice versa. Results showed considerable developmental progression, especially around age 6. Experiment 2 ($N = 16$) ruled out that 4-year-olds' difficulties were due to problems with the visual matching task itself. Experiment 3 ($N = 32$) showed comparable performance for matching diagrams to 3D objects rather than to photographs. Findings suggest increasing understanding of diagrammatic representations around the time of school entry.

Keywords: cognitive development, spatial cognition, diagram, line drawing, two-dimensional representation, three-dimensional, pictorial depth

Young Children's Perception of Diagrammatic Representations

From very early on, children experience two-dimensional (2D) representations of three-dimensional (3D) objects and spaces. For example, looking at picture books together is a very common kind of parent-child interaction in western cultures. Later on, pictures and diagrams are frequently used in school. Furthermore, developmental research and assessments often require 3D spatial reasoning based on 2D line drawings (e.g., mental rotation, paper folding, surface development). Thus, understanding when and how young children understand such abstract 2D representations has theoretical, methodological, and applied importance.

Whereas photographs (and realistic drawings) depict a scene as an observer would see it from one particular perspective, schematic diagrams abstract away from specific viewpoints and rich visual detail, using commonly accepted conventions and techniques for how to deal with the third dimension when trying to represent 3D objects on a flat surface. Such conventions are necessary in order to use these representations as a communicative tool and to avoid ambiguity and misinterpretations. For example, Hagen (1974) pointed out that outline drawings preserve information for the boundaries and edges of objects. The lines typically indicate discontinuities or contrast changes in the optic layout due to changes in color, shadows, slant, or texture of surfaces, which is fundamental to perception of surface forms. However, Hagen raised the question of whether a line drawn on a paper necessarily gives rise to the perception of such a change, and whether it provides a sufficient source of information for naive observers or young children. The understanding and application of such conventions may require experience (for a review, see Miller, 1973). However, empirical work on this issue has been mixed.

A number of studies of early pictorial competence, beginning with the pioneering work of Julian Hochberg (Hochberg & Brooks, 1962), have suggested that the recognition of 2D depictions of familiar objects appears very early. Rose (1977) showed that 6-month-old infants are able to detect a change in dimensionality and transfer information from objects to photos or vice-versa. In studies by DeLoache and colleagues (for an overview, see DeLoache, Pierroutsakos, & Uttal, 2003), 9-month-old infants showed manual exploration behavior toward highly realistic photographs of familiar objects, suggesting that they recognized the objects. By about 2½ years of age, toddlers can use information from a photograph (DeLoache, 1991) or a line drawing (DeLoache & Burns, 1994) to find a hidden object in a real room. But although these findings seem to provide evidence for a comprehension of the representational function of 2D images at a very early age, in these search tasks, children may be able to use a salient feature of the scene present in both the 2D image and 3D environment to guide their search (e.g., 'under the chair'). Thus, this research does not directly address the issue of whether young children can use metric information provided by 2D images, or what Downs (1985) referred to as the ability to establish *geometric* correspondence between the depiction and its referent. In fact, when 2.5-year-olds were asked to place a puppet on one of three identical chairs as indicated on a map (Winkler-Rhoades, Carey, & Spelke, 2013), they were able to differentiate the middle chair based on topological information ('between the other two'), but they failed to differentiate the outer chairs based on their relative distance from the middle chair.

Extracting fine-grained metric spatial information from representations seems to be difficult for preschoolers and even young children (Liben & Downs, 1993; Liben & Yekel, 1996). In a study of object recognition, Leighty, Menzel, and Fragaszy (2008) showed that it was not until 4 years of age that children gained reliable knowledge of object structure from 2D displays, even though the stimuli were highly realistic and dynamic video presentations. Other research focusing on children's understanding of spatial relations depicted in 2D displays has used reconstruction tasks, in which children were asked to align an array of 3D objects to match a photograph. For example, Brown (1969) showed that at age 6, children preserved the rough positions of a depicted array of objects, but it was not until age 8 that they reconstructed the depth dimension in a systematic manner. A subsequent study (Jahoda & McGurk, 1974) showed that children below the age of 8 years had difficulties systematically aligning an array of 3D objects to match the array shown in a photograph, in a way that would preserve the size of the depicted objects as well as their spatial relations. Overall, these studies suggest that it is not until around the age of 8 years that children develop an understanding of metric spatial information depicted in photographs.

However, surprisingly few studies have investigated young children's understanding of more schematic 2D representations, such as line drawings and diagrams. Such representations might be easier to interpret than photos or video, because they highlight the boundaries and edges and thus focus attention to spatial information that is fundamental to perception of object structure. Alternatively, the greater degree of abstraction might add to the difficulty of interpreting the representations, by decreasing familiarity and possibly omitting crucial information. One line of research on outline drawings has focused on the development of image completion or the question of how children interpret overlapping, embedded, or fragmented contours (for an overview, see Hagen, 1974), which is specifically interesting in the context of the development of object recognition. Other studies have investigated whether children incorporate depth cues or preserve spatial relations when asked to *produce* their own drawings of objects or scenes (e.g., Ebersbach & Hagedorn, 2011; Ebersbach, Stiehler, & Asmus, 2011; for a literature review up to 1989, see Nicholls & Kennedy, 1992). These studies have shown a very protracted developmental trajectory, extending up to the age of 12 (Cox, 1986; Mitchelmore, 1978).

However, paradigms that require drawings or active productions probably underestimate children's understanding of 2D representations. Piaget, Inhelder and Szeminska (1948/1973) pointed out that it is one thing for children to *perceive* whether a copy corresponds to a model (which according to them is already possible around age 4), but another thing to *construct* a copy that conserves the spatial relations, and yet a different thing to be able to exactly *measure* the spatial relations. Furthermore, in the wake of Luquet's pioneering work (1927/2001), biases for drawing objects in canonical orientations, mixing points of view, or for drawing occluded objects and features that the children know to exist, have been repeatedly shown to affect young children's drawings (e.g., Davis, 1985; Freeman, & Janikoun, 1972; Piaget & Inhelder, 1948/1956; Picard & Durand, 2005; Willats, 1977). These difficulties young children exhibit when attempting to *produce* depth in 2D line drawings are hardly surprising, considering that it took human adults millennia to come up with systematic ways to draw in perspective.

But do children also have trouble *perceiving* the third dimension in 2D line drawings, or can we assume that they process stimuli presented in two and three dimensions in a similar way? So far, these questions have not been clearly answered. In the present study, we therefore used a choice task to investigate 4- to 8-year-olds' ability to interpret 2D diagrams and match them to photographs or 3D objects. In Experiment 1, we investigated the development of children's understanding of diagrams across multiple age groups using a single paradigm, in which children were asked to match line drawings with photographs. We presented single or combined objects, because performance might be better with single objects than with displays that present more features if children compare the representations party by part. In contrast, if children compare the whole objects, complexity should have little or no effect. Furthermore, we manipulated the direction of the comparison, in order to find out whether abstracting away information from one photograph, and matching it to multiple line drawings, is easier than the opposite task. According to Kaminski and Sloutsky (2009), concreteness of a stimulus (i.e., how much information it communicates) may impede detecting structural or proportional relations, by distracting attention from relevant relational information. Moreover, there seems to be an asymmetry, in that transfer from more abstract to more concrete is greater than the reverse (Sloutsky, Kaminski, & Heckler, 2005). Similar asymmetry effects have been found in object naming tasks (e.g., Son, Smith, & Goldstone, 2008), indicating that shape information is generalized more easily from simple to complex instances than in the opposite direction, perhaps because simple instances direct attention to the relevant properties for transfer. Based on these findings, one might expect that performance in the present task would be better when children have to compare an abstract line drawing to more concrete photographs than the reverse. We also investigated possible sex differences on this task, based on previous research showing sex differences in spatial skills (e.g., Linn & Peterson, 1985; Voyer, Voyer, & Bryden, 1995) and in children's drawings of complex diagrams (Huguet & Régner, 2009) and cubes (Lange-Küttner & Ebersbach, 2013).

Experiment 2 was designed to elucidate what kind of cognitive demands might account for young children's difficulties with metric spatial mapping tasks. Such tasks presumably involve several cognitive steps: First, the spatial relations in the displays have to be encoded, including their metric properties, such as the lengths of edges, and the distance between edges and corners. Second, this information has to be mentally moved and brought into alignment with the to-be-compared representation (cf. Piaget et al., 1948/1973) in a way that preserves distances and lengths. Third, the representations have to be compared, which poses an additional challenge when the two representations use different formats. In Experiment 2, we tested whether young children's difficulties in our tasks were specifically due to the contrast in formats between line drawings and photographs, or whether they had difficulties with encoding and displacing the spatial information per se. Therefore, the target object and choice alternatives were presented in the same format, such that no translation between diagrams and photographs was necessary.

Whereas the first two experiments presented 2D depictions in different representational formats (diagrams and photographs), in Experiment 3 we tested whether performance would be comparable if children had to match line drawings to real 3D objects. In this case, the comparison step involves an understanding of how a 3D object can be rendered onto a flat surface. Experiment 3 also tested children's understanding of more complex diagrams of objects, which are often used in research on spatial abilities.

Experiment 1

Method

Participants. Participants were 80 children, with 16 children (8 boys and 8 girls) in each of the following age groups: 4-year-olds (mean age = 4;4 [years; months], range = 4;0 – 4;11); 5-year-olds (mean age = 5;5, range = 5;0 – 5;9); 6-year-olds (mean age = 6;5, range = 6;0 – 6;11); 7-year-olds (mean age = 7;6, range = 7;1 – 7;11); 8-year-olds (mean age = 8;8, range = 8;1 – 9;0). One additional 5-year-old was excluded because she failed the practice trial and then chose the same location on eight consecutive trials. In this and the following experiments, participants were predominantly white, from middle class backgrounds, and recruited from suburban areas of a large US city.

Stimuli. Stimuli were color printouts that were presented in transparent document pockets in a binder. They showed color photographs of geometric objects and line drawings that were created by tracing the borders and edges of the geometric objects with a black solid line. The target stimulus (e.g., a photograph) was centered in the upper part of the letter-sized paper (21.6 cm x 27.9 cm) presented in landscape orientation; four choice alternatives (e.g., four line drawings) were shown below it, aligned horizontally with equal spacing between them (for examples see Figure 1). One of the choice alternatives matched the target object and three were foils that were created by changing the shapes (pyramid vs. cone; sphere vs. hemisphere) or proportions of the depicted objects (short vs. long cylinders; cubes vs. cuboids). Stimuli were either single geometric objects (e.g., purple cone), or combined objects that consisted of two geometric forms of different colors (e.g., yellow cone on top of a blue cylinder).

Procedure & Design. Participants were tested in a laboratory room. Children were first shown a picture of a house and a boy who drew the same house on a piece of paper. Children were told that this was Timmy who liked to draw things, so that his drawings would look exactly like the real thing, except for color as he only used a pencil to draw. Children were then presented with a practice trial, in which a ball was placed on the upper part of the paper, and children were instructed to help decide which one of four line drawings was Timmy's best drawing of the ball.

In subsequent test trials, no real objects were presented. On half of the test trials, children were presented with a photograph as the target stimulus and asked to choose which one of four line drawings best matched the photograph (photo-to-drawings). On the other half of the trials, task direction was reversed, such that children saw a line drawing as target stimulus at the top of the page and were asked to choose the best matching photograph among four alternatives (drawing-to-photos). Additionally, item complexity was varied by presenting single geometric objects or combined objects. Each combination of complexity and direction was repeated 6 times with different objects, amounting to 24 test trials. Trials were blocked and presented in the following order: single photo-to-drawings, combined photo-to-drawings, single drawing-to-photos, combined drawing-to-photos. For half of the boys and girls, trial order was reversed to counterbalance for fatigue or learning effects.

Results

The test showed excellent internal consistency, with a Guttman’s split-half coefficient of .85 (i.e., the correlation between trials analogous in terms of complexity and task direction, but with different objects).

A repeated measures analysis of variance (ANOVA) was performed, with age (4) and sex (2) as between-subjects variables, direction (photo-to-drawing vs. drawing-to-photo) and complexity (single vs. combined objects) as within-subject variables, and number of correct choices as dependent variable. Results showed considerable developmental progression, $F(4, 70) = 10.75$, $p < .001$, $\eta^2 = .38$ (see Table 1), with overall accuracy increasing from 60% to 86% between ages 4 to 8. Post hoc tests (Sidak-corrected here, and throughout) indicated significant increases in correct responses from 4 to 6 years and older, and from 5 to 7 years and older (all *p*s $< .05$), whereas after 6 years, age groups did not differ significantly (all *p*s $> .14$). The ANOVA further yielded a significant main effect of task direction, $F(1, 70) = 5.90$, $p < .05$, $\eta^2 = .08$, which was qualified by an interaction of age and task direction, $F(4, 70) = 3.00$, $p < .05$, $\eta^2 = .15$. Post hoc tests showed that this interaction was mainly driven by 4-year-olds, who performed better when they were asked to compare one diagram to a choice of four photographs, as opposed to comparing one photograph to a choice of four diagrams ($p < .01$; see Figure 2). For all other age groups, performance was not significantly affected by task direction (all *p*s $> .09$).

Item complexity did not affect performance (all *F*s < 2.78, all *p*s >.10) and there were no sex differences (all *F*s < 1.82, all *p*s >.18).

On the individual level, we analyzed how many children of each age group performed significantly above chance level (i.e., solved more than 10 out of 24 trials correctly, Binomial Test, $p < .05$). Three 4-year-olds performed at chance level, whereas all of the older children performed above chance.

A closer analysis of children's responses revealed that on average, they chose the correct alternative in 73 % of the cases. Foils that were created by altering the proportions were chosen in 16 % of the cases, and foils that were created by changing the shapes in 11 % of the cases On an individual level, 47 children chose the proportional foils on the majority of the trials, 20 children chose the shape foils most often, and 13 children chose the two foil types equally often. The proportional foils were chosen most often by significantly more children than the shape foils, χ^2 (df = 1) = 10.88, $p < .001$, and this preference for the proportional foil type was not affected by age, χ^2 (df = 4) = 3.75, $p = .44$.

Discussion

Results showed considerable developmental improvement in the ability to match photographs and line drawings between 4 and 8 years, with 4-year-olds performing at chance level, and a most prominent improvement occurring around age 6. The finding that item complexity did not affect performance suggests that children of all ages compared the stimuli as a whole rather than part by part. The fact that there was no interaction with age, suggests that there were no significant age differences in strategy use.

However, results showed a significant interaction of age and task direction. This was mainly driven by the fact that 4-year-olds performed better when they were asked to match one diagram to a choice of four photographs, as compared to when they were asked to match one photograph to a choice of four diagrams. These results are in line with asymmetric effects shown in previous studies on relational matching (e.g., Sloutsky et al, 2005) and object naming (Son, et al., 2008), suggesting that a transfer from abstract to concrete is easier than the reverse. Abstraction (i.e., the subtraction of information) may be harder than the filling in (i.e., the addition of information), due to automated mechanisms of object completion (e.g., Kellman, Spelke, & Short, 1986) or the development of inhibitory control processes (for a review, see Zelazo, & Müller, 2011). Furthermore, seeing only one drawing at the top of the page may have directed our youngest children's attention toward the relevant spatial structure of the object, whereas rich visual information in the photo stimuli may have distracted them from the relevant structural information. Alternatively, it is possible that the youngest age group encountered difficulties when having to differentiate choice alternatives showing multiple line drawings.

Finally, an analysis of foil types suggested that there were no age differences in whether children preferred proportionally distorted foils or foils showing wrong shapes. In all age groups, more children chose proportionally distorted foils rather than shape foils on the majority of the trials, suggesting that all children had larger difficulties with comparing the lengths and distances, rather than the objects' shapes. For example, when the target stimulus showed a cylinder (Figure 1, top row), children had more difficulties rejecting a shorter or thinner cylinder than a semi cylinder.

Experiment 2

The comparison of photographs to line drawings in Experiment 1 appeared to be quite challenging for 4-year-olds. However, young children's low performance could have also been due to difficulties with (a) encoding the images and their metric properties, or (b) an inability to mentally move the target object down on the page to map it onto the choice alternatives (or vice versa), in order to align it with the to-be-compared representation while preserving metric properties. Another reason for 4-year-olds' low performance could be that they (c) had difficulties understanding the task instructions. Experiment 2 was designed to test these alternative interpretations. Another group of 4-year-olds was tested with a similar task, except that the target object at the top of the page was now in the same format as the choice alternatives below (matching photo-to-photos or drawing-to-drawings). If the translation between formats was responsible for the low performance of the youngest age group in Experiment 1, we expected better performance in Experiment 2, where no such translation was necessary. If, however, the low performance in Experiment 1 was a result of a basic inability to (a) encode and (b) mentally displace the target object, or (c) understand the task instructions, we expected a similarly low performance in Experiment 2.

Method

Participants. Participants were 16 children at the age of 4 years (mean age = 4;6, range = 4;1 – 4;10, 8 boys and 8 girls), who had not participated in Experiment 1.

Stimuli, Procedure & Design. Similar stimuli as in Experiment 1 were used, but instead of presenting photographs that had to be matched with line drawings (or vice versa), target stimuli and choice arrays were of the same format. Thus, on one half of the trials, the target stimulus and the choice arrays were photographs (photo-to-photos); on the other half of the trials, the target stimulus and the choice arrays were line drawings (drawing-to-drawings). To make the stimuli more comparable between the two conditions, and in order to avoid that the task could be solved based on color matching, the photographs were presented in gray scale.

The procedure and the design were identical to Experiment 1, except that children were instructed to choose the alternative that would best match the image presented on the top of the page.

Results

A repeated measures analysis of variance (ANOVA) was performed, with experiment (2) and sex (2) as between-subjects variables, choice array (photos vs. drawings) and complexity (single vs. combined objects) as within-subject variables, and number of correct choices as dependent variable. Crucially, the analysis yielded a significant effect of experiment, $F(1, 28) = 28.10$, $p < .001$, $\eta^2 = .50$, showing that 4-year-olds in Experiment 2, in which no transformation was necessary, performed much better than the 4-year-olds in Experiment 1. The analysis also yielded a significant effect of choice array, $F(1, 28) = 7.31$, $p < .05$, $\eta^2 = .21$, with 4-year-olds performing at lower levels when the choice alternatives consisted of four line drawings, compared to when choice alternatives were photographs. There were no other significant effects or interactions (all Fs < 3.51, all ps > .07).

The 4-year-olds in Experiment 2 showed a mean accuracy of 88% ($SD = 9.7$), which did not differ from the mean accuracy of the oldest age group (8-year-olds) in Experiment 1, $t(30) = -.57$, $p < .58$, $d = 0.20$. Furthermore, all children performed above chance on the individual level (Binomial Test, $p < .05$).

Discussion

Experiment 2 showed that when no transformation between line drawings and photographs was necessary, and the target stimulus merely had to be matched with the identical choice alternative, 4-year-olds performed significantly better than in Experiment 1 where a translation between formats was necessary. Moreover, 4-year-olds performed better in

Experiment 2 even though the stimuli were presented in gray scale (to avoid matching on the basis of color information in the photo-to-photo condition). These findings ruled out the possibility that 4-year-olds' difficulties in Experiment 1 were due to (a) encoding, (b) mentally displacing the items to align them with the choice alternatives, or (c) trouble understanding the task instructions per se. Thus, they supported the hypothesis that the need for a translation between formats caused 4-year-olds' low performance in Experiment 1.

In Experiment 2, children performed better if they saw photos as compared to drawings. This finding suggests that 4-year-olds' low performance in the photo-to-drawings conditions of Experiment 1 had less to do with the object shown at the top of the page, but was likely due to the format of the choice array (i.e., having to differentiate multiple line drawings).

The fact that young children's performance in Experiment 2 was significantly better than in Experiment 1 is somewhat surprising, considering that both photographs and line drawings are in fact 2D representations. Thus, one could think that a transformation in Experiment 1 would have been very easy, given that no projection of a 3D object on a 2D space was necessary. However, the much greater difficulties of young children in Experiment 1 as compared to Experiment 2 suggest that the transformation between line drawings and photographs presents a major cognitive challenge that is unrelated to this issue.

Experiment 3

Considering that transformations between 2D representations of different formats is challenging for young children, the question arises whether matching real 3D objects to line drawings would be harder or easier than matching 2D photographs to line drawings. On the one hand, it is possible that the task is easier with photographs, as they are already 2D, and the task of projecting the 3D structure onto the flat surface of the paper is already done. Furthermore, the line drawings were created by tracing the photographs, and therefore the viewing angle and size of the images were exactly the same, whereas the viewing angle and (retinal) size of a real 3D object can vary when the observer moves. On the other hand, one could also hypothesize that children have less difficulty with the real 3D objects, as they are more natural, offer richer visual cues (stereopsis, motion parallax), and their 3D structure is easier to encode (e.g., through systematic perspective changes caused by slight movement of the observer, Gibson, 1966). Therefore, in Experiment 3 we investigated whether performance would be different if real 3D objects were presented instead of photographs, which had to be matched to line drawings. Performance with 3D stimuli was compared within participants to performance with 2D drawings and photographs that were similar to the ones used in Experiment 1, except that only single objects were presented in all of these cases.

A second objective of Experiment 3 was to test whether children would show similar performance with more complex stimuli (see Figure 1, bottom row), similar to the ones typically used in mental rotation studies (e.g., Shepard & Metzler, 1971). Stimulus complexity had no significant effect on performance in Experiment 1. However, perhaps this non-effect was due to the manipulation not being strong enough and the complex objects not being spatially complex enough. Thus, in Experiment 3, even more complex objects consisting of multiple cubes were presented, again in two task directions from drawing to photos or vice versa. Children at the age of 4 and 5 years were tested, because the range of these age groups' accuracies in Experiment 1 did not exceed 88 %, so that no ceiling-effects were to be expected.

Method

Participants. Participants were 16 children at the age of 4 years (mean age = 4;4, range = 4;0 – 4;9, 8 boys and 8 girls) and 16 children at the age of 5 years (mean age = 5;6, range = 5;0 – 5;10, 8 boys and 8 girls), who had not participated in Experiments 1 or 2.

Stimuli, Procedure, & Design. In Experiment 3 five different stimulus types were presented. The first two types presented drawings or photographs of simple geometric solids, similar to Experiment 1 (single photo-to-drawings; single drawing-to-photos). A third stimulus type showed real 3D objects in the upper half of the paper (i.e., instead of and at the same position where the corresponding photographs were presented in the photo-to-drawings format), and had to be compared to four line drawings in the lower half of the paper (real object-to-drawings). Two further stimulus types presented objects that were more complex than the ones used in Experiment 1. They consisted of three or four identical cubes in varying configurations, similar to the stimulus material typically used in mental rotation tasks (e.g., Shepard & Metzler, 1971). Again, these cube-figures were presented in the photo-to-drawings and the drawing-to-photos conditions. Each of the five stimulus types was presented with different objects five times in a row, amounting to 25 test trials. Again, stimulus types were blocked, and order of presentation was reversed for half of the boys and girls.

Results

An ANOVA was carried out with stimulus type (single photo-to-drawings; single drawing-to-photos; real objects-to-drawings; cube photo-to-drawings; cube drawing-to-photos) as within-subject variable, sex and age as between-subjects variables, and number of correct choices as dependent variable. The analysis yielded significant effects of stimulus type, $F(4, 112) = 4.81$, $p < .01$, $\eta^2 = .15$, and age, $F(1, 28) = 14.03$, $p < .01$, $\eta^2 = .33$, but no other effects (all Fs <

1.91, all *p*s > .17). Post hoc tests indicated that the effect of stimulus type was mainly driven by about 15% lower performance in the photo-to-drawings format (68% correct, *SD* = 20.2), as compared to real object-to-drawings (83% correct, *SD* = 16.9, $p < .01$) and as compared to cube drawing-to-photos (83% correct, *SD* = 13.4, $p < .001$). There were no significant differences involving the drawing-to-photos (79% correct, *SD* = 20.0) and the cube photo-to-drawings format (76% correct, *SD* = 23.5), *p*s >.18.

Closer examination of the photo-to-drawings trials further revealed that the low performance was mainly driven by one single trial, on which children performed far below average (4-year-olds: 47% lower accuracy; 5-year-olds: 21% lower accuracy than the average of all other photo-to-drawings trials). Apparently, this particular trial showing a triangular prism posed major difficulties, especially for the younger age group. Children predominantly chose the option that had all the correct lines but the wrong proportions, which seemed to be especially hard to recognize for a triangular object. Therefore, we carried out another analysis, in which we excluded this particular trial, which raised overall performance in the photo-to-drawings format by 7% (to 75%, *SD* = 21.1). In this analysis (otherwise identical to the above ANOVA) the effect of stimulus type was no longer significant, $F(1, 28) = 1.72$, $p = .15$, $\eta^2 = .06$. The age effect remained significant, $F(1, 28) = 11.84$, $p < .01$, $\eta^2 = .30$, with 5-year-olds outperforming 4-year-olds, and all other effects and interactions remained non-significant (all *F*s < 1.29, all *p*s > .26). All children performed above chance on the individual level (Binomial Test, $p < .05$).

Discussion

Results of Experiment 3 showed that stimulus type did not affect 4- and 5-year-olds' performance, if data from one particularly difficult trial was excluded. That is, there was no significant difference between conditions in which 2D representations showed single geometric solids or cube-figures in more complex spatial configurations. It also did not matter for children's performance whether they had to compare real 3D objects or photographs to line drawings. Thus, even though in the photo-to-drawings format target and choice stimuli were 2D and no dimensional transformation was necessary, performance was not higher than when the spatial structure of a 3D object had to be projected onto a flat surface. If anything performance was lower with photographs, if a particularly difficult outlier trial was not excluded from the data. These results suggest that transformations between different representational formats are difficult for young children, regardless of whether this transformation includes a dimensional change. The fact that presenting more complex cube-figures did not lead to lower performance indicates that children might have matched the objects as a whole, such that object-internal spatial complexity did not affect performance. Future research that assesses response time data (e.g., using a touch screen) could yield further insight into children's matching strategies.

General Discussion

Experiment 1 of the present study showed that children gain an increasing understanding of line drawings and diagrammatic representations between 4 and 8 years of age, with the most pronounced increase in performance between 5 and 6 years. Children at the age of 4 performed particularly poorly when they were asked to compare one photograph to a choice of four line drawings, rather than the opposite task direction. Experiment 2 demonstrated that the difficulties of the youngest children in Experiment 1 were not simply due to encoding and mentally displacing the images or understanding task instructions, but were specifically due to the transformation between line diagrams and photographs. Experiment 3 showed that children performed comparably with real 3D objects as with photographs of the same objects, and with simple geometrical solids as with spatially more complex cube-figures.

The present results are in line with previous findings from reconstruction tasks that showed increases in children's performance between 3.5 and 8 years (Brown, 1969) and between 4 and 10 years of age (Jahoda & McGurk, 1974). However, while these previous studies showed no systematic reconstruction of spatial relations and metric features before the age of 8, the present study demonstrated a marked increase in performance around age 5 to 6. This suggests that children may be able to notice differences in spatial relations before they are able to produce them in a reconstruction task. However, it has to be noted that many 8-year-olds performed far from perfectly in the present task, suggesting that the interpretation of different representational formats of 3D objects still presents a challenge even at this age. In line with this result, Jahoda and McGurk showed that performance increased to near perfect performance after 8 years of age. This converging evidence for a relatively late development, along with 4-year-olds' difficulties in our task, is rather surprising, given that toddlers readily use information on photographs (DeLoache, 1991) or line drawings (DeLoache & Burns, 1994) to find an object in a real space.

What cognitive mechanisms could explain this surprisingly late development? The excellent performance in Experiment 2 suggests that encoding and displacing spatial information or understanding the instructions was not the problem, but that the difficulty lay in the comparison between different formats. Piaget and Inhelder (1948/1956) argued that young children are unable to coordinate multiple perspectives and lack the understanding of what they called *projective space*. Along these lines, a lack of an understanding of how a 3D image can be rendered onto a 2D surface might explain young children's difficulties in comparing the different object formats in the present task. In fact, a recent study of young children's understanding of perspectives that used a similar choice format (Frick, Möhring, & Newcombe, 2014), showed a similar improvement in performance around 6 years of age. However, the result that performance was comparable when photographs or real objects had to be matched to line drawings suggests that the development of what Piaget and Inhelder called projective space may not tell the whole story. In the case of the photographs, a projective transformation onto the flat surface of the paper is not necessary, as they are already 2D. If a projective transformation was the sole reason for children's difficulties, performance should have been better with photographs than with real 3D objects.

Another likely mechanism may be that the abstraction of information is hard for children. Even though photographs are technically 2D, they are rich in 3D cues (such as color, shades, and gradients) and evoke a strong 3D perceptual experience. Children may still have to abstract from and ignore this 3D information in order to find the matching line drawing. This interpretation is also supported by the finding that in Experiment 1, the youngest age group had particular problems with the task direction in which information had to be abstracted from one photograph to multiple line drawings. However, this asymmetry effect was not replicated in Experiment 3, and should therefore be interpreted with caution. Furthermore, based on results of Experiment 2, showing higher performance when no translation between formats was necessary, and lower performance with choice arrays of line drawings, we can conclude that young children's difficulties were likely due to (a) having to extract boundaries and translate contrast between surfaces into lines, and (b) having to differentiate multiple such line drawings.

Overall, the present research suggests a rather late development in the ability to interpret diagrammatic representations. These results have potential implications for thinking about the development of object perception, suggesting that boundary assignment and the detection of edges and contours, which have been implied as important mechanisms in the perception of 3D shape (Kellman & Arterberry, 2006), may not be fully developed even by school age. The present results may also inform theories regarding the development of children's drawing (e.g., Bremner, Morse, Hughes, & Andreasen, 2000; Cox, 1986; Davis, 1985; Ebersbach, et al., 2011; Ebersbach & Hagendorn, 2011; Freeman, & Janikoun, 1972; Mitchelmore, 1978; Nicholls & Kennedy, 1992; Piaget & Inhelder, 1948/1956; Picard & Durand, 2005; Willats, 1977, 1997), as they suggest that the difficulties young children have with producing or copying line drawings may already exist at the perceptual level.

A practical implication of the present findings is that educators and researchers should be cautious when presenting diagrams and line drawings to young children. Many psychological experiments are conducted with 2D stimuli, due to the ease of presentation and manipulation of stimulus forms. Some tests specifically require the participant to form a 3D mental representation of the 2D depiction to solve the task (e.g., mental rotation, paper folding, surface development). Pictorial representations are also an important means of communication in most cultures and play a major part in education. The fact that 4-year-olds performed close to chance level in the present task, and even 8-year-olds did not perform perfectly, cautions against the use of abstract line drawings with young children.

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Table 1

Mean accuracy (number of correct trials, percentage of correct trials with standard deviation and range) per age group in Experiment 1.

	Accuracy			
	Trials Correct	% Correct	% *SD*	% Range
4-year-olds	14.5	60	13.37	25 – 88
5-year-olds	15.0	63	13.35	46 – 88
6-year-olds	17.8	74	11.83	46 – 92
7-year-olds	19.1	79	13.40	46 – 96
8-year-olds	20.6	86	8.17	67 – 100

Figure Captions

Figure 1. Examples for stimuli in the drawing-to-photo (left column) and photo-to-drawing (right column) conditions, for single (top row) and combined (middle row) objects in Experiment 1, and for cube-figures in Experiment 3 (bottom row). Correct solutions are indicated by asterisks (not visible to participants).

Figure 2. Mean correct responses (in %) by age group, task direction, and object complexity in Experiment 1.

Figure 1

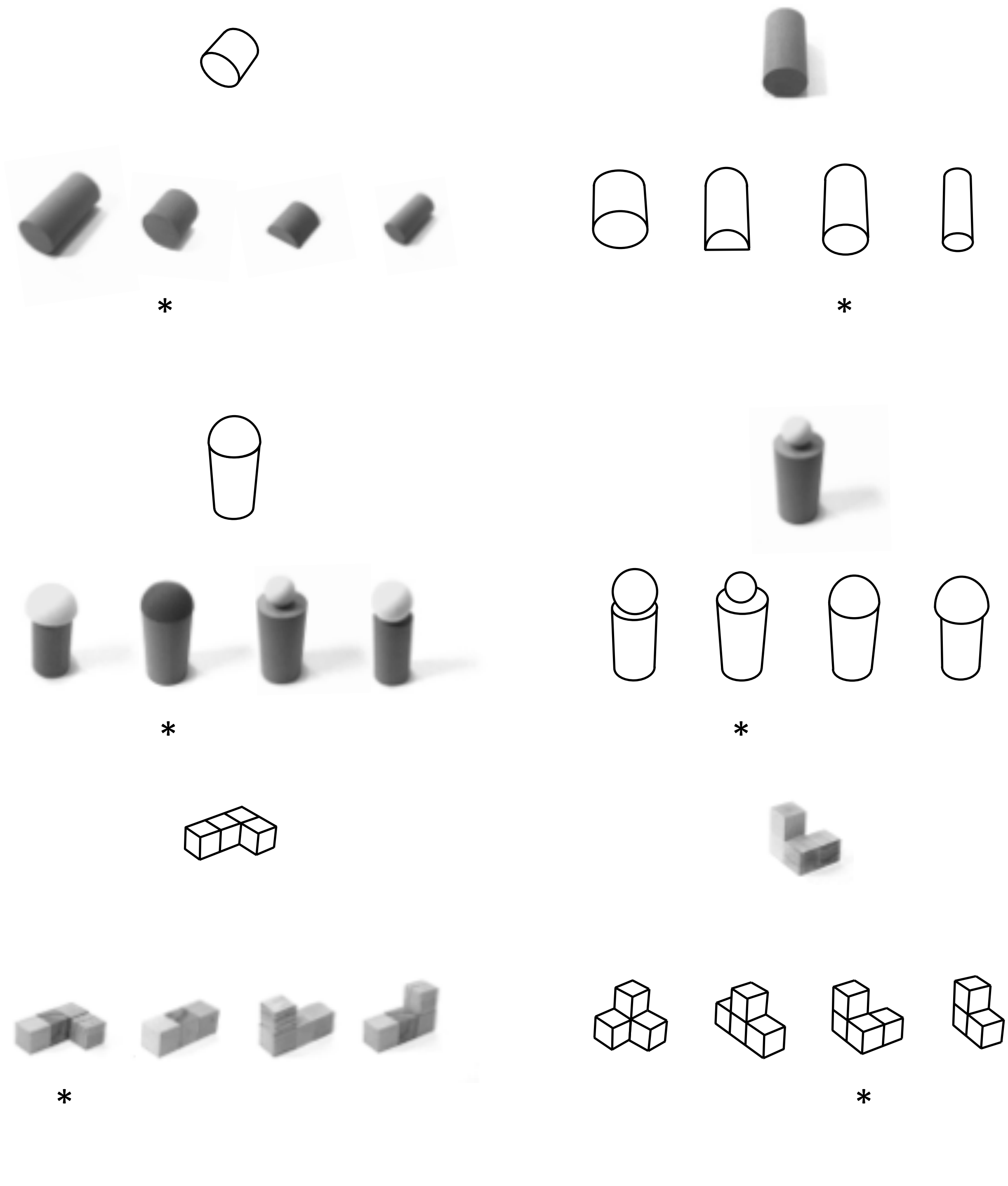
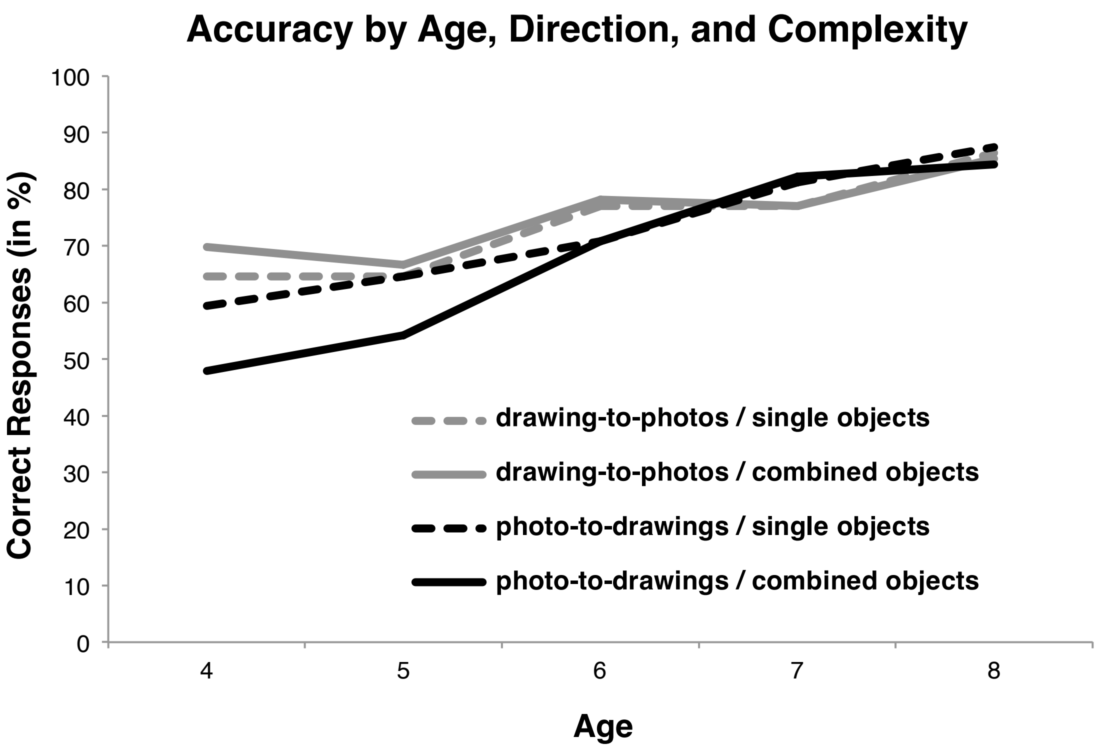


Figure 2


Accuracy by Age, Direction, and Complexity
Correct Responses (in %)
100
90
80
70
60
50
40
30
20
10
0
4
5
6
7
8
Age
drawing-to-photos / single objects
drawing-to-photos / combined objects
photo-to-drawings / single objects
photo-to-drawings / combined objects