The Development and Assessment of Cross-Sectioning Ability in Young Children

Kristin R. Ratliff (krratliff@uchicago.edu)
Department of Psychology, 5848 S. University Ave.
Chicago, IL 60637 USA

Charlotte R. McGinnis (cmcginnis@uchicago.edu)
Department of Psychology, 5848 S. University Ave.
Chicago, IL 60637 USA

Susan C. Levine (s-levine@uchicago.edu)
Department of Psychology, 5848 S. University Ave.
Chicago, IL 60637 USA

Abstract

In two experiments, we investigated the development of cross-sectioning ability using either three-dimensional (3D) or two-dimensional (2D) stimuli. Three to 9 year old children visualized cross-sections of either real 3D geometric shapes (Experiment 1) or 2D photographs of the shapes (Experiment 2). Performance on the 3D task was also analyzed to determine to what extent cross-sectioning ability is related to performance on more widely used spatial tasks including mental rotation and the water-level task. We found that performance on the cross-sectioning and mental rotation tasks were significantly correlated, and the 2D and 3D tasks were both successful in assessing cross-sectioning ability in young children. As expected, we also found a significant increase in cross-sectioning performance across age groups.

Key Words: spatial development; cross-section; education.

Introduction

Spatial ability is important for success across a variety of academic subjects, particularly in the science, technology, engineering, and mathematics (STEM) disciplines. Spatial ability is also related to choosing technological and science-related careers and predicts the choice of math and science as college majors (Shea, Lubinski, & Benbow, 2001), as suggested by the fact that individual differences across verbal, quantitative, and spatial abilities at age 13 were predictive of educational and vocational group membership 20 years later. However, despite the importance of spatial ability, spatial training is not a regular part of school curricula and there are no national or state standards for spatial intelligence. Consequently, many students have difficulty with spatial tasks and lack the opportunity to improve their spatial reasoning skills.

Spatial ability can refer to a wide range of skills, some of which focus on how individuals perceive and act on objects in space while others focus on how individuals orient and navigate within space. One category of spatial ability of particular interest is spatial visualization, or the ability to understand, mentally encode, and manipulate 3D forms (Carroll, 1993; Hegarty & Waller, 2004).

Cross-sectioning, also referred to as "penetrative" thinking (Kali & Orion, 1996) is a particular spatial visualization skill that involves inferring a 2D representation of a 3D structure, and vice versa (Cohen & Hegarty, 2007). This imaginary slicing of a 3D object to a 2D plane is an essential skill for many of the sciences, ranging from anatomical cross-sections in biology and neuroscience to cross-sections of landforms in geology (Cohen & Hegarty, 2008). Conversely, in order to understand what is under a microscope, students must also be able to mentally reconstruct a 3D object from a given 2D image.

Spatial visualization requires performing multistep manipulations of spatial representations, such as a paper-folding task that requires the ability to work quickly, rotate figures, and keep track of multiple operations. This is thought to be distinct from other spatial tasks such as spatial perception and mental rotation (Linn & Petersen, 1985). For example, the water-level task, which requires subjects to draw a horizontal line in a tilted bottle where they believe the water level would be, is categorized as a spatial perception task because it requires determining spatial relationships with respect to a given frame of reference. Linn and Petersen define mental rotation as a Gestalt-like analogue process that involves accurately mentally rotating a 2D or 3D figure. However, the development of cross-sectioning ability has not been compared to these other measures of spatial ability, in part because of a lack of adequate measures and the unknown age at which this ability emerges. Thus, we do not know whether it is more related to spatial visualization, spatial perception, or mental rotation.

Cross-Sectioning Ability of Young Children

There is disagreement about the age at which children are able to reason about cross-sections of 3D objects. In contrast to Piaget and Inhelder's (1956) view that children should have achieved mastery of geometric sectioning by 12 years old, many studies have found that spatial visualization involving cross-sections does not develop until the teenage years. For example, most students do not accurately predict the appearance of a geometric plane intersecting a simple cone or sphere until sometime between the ages of 11 and 15 (Russell-Gebbett 1984, 1985), while even students in grades 8, 10, and 12 have difficulty accurately choosing a cross-section of simple geometric line drawings (Boe, 1968; Davis, 1973).

The difficulty older children and adolescents have with these assessments may be in the presentation of the test items themselves rather than a lack of underlying cognitive processes supporting cross-sectioning skills. Assessments involving cross-sections are often based on 2D diagrams and complex figures that represent 3D objects. Although these have been shown to successfully measure spatial visualizations of cross-sections among adults (e.g., Santa Barbara Solids Test, Cohen & Hegarty, 2007) and adolescents (e.g., Mental Cutting Test "Schnitte," Quaiser-Pohl, 2003), these assessments are too advanced for use with younger children.

One factor impacting success when measuring other spatial skills in young children has been using more familiar, salient, and concrete stimuli. For example, tasks have used pictures of humans and animals to successfully measure mental rotation ability in young children (Quaiser-Pohl, 2003; Wiedenbauer & Janesen-Osmann, 2008). Similarly, by using basic 2D geometric shapes, Levine and colleagues (1999) were able to successfully assess mental transformation ability in preschool children.

In the present study, we created a new method for assessing cross-sectioning skills in young children by using brightly colored foam shapes as the stimuli. We contrasted this 3D method with a 2D method using photographs of the actual shapes. Thus, we aimed to successfully measure children's cross-sectioning skills to determine a) how cross-sectioning skills develop between the ages of 3 and 9 years, b) the association between cross-sectioning skills and other spatial reasoning tasks, and c) how the method of assessment impacts performance.

We expected that using salient and familiar objects, such as the foam shapes, would make the task accessible for preschool to early elementary children. We also predicted that there would be an increase in spatial ability across the age range. We explored the relation between cross sectioning and two other measures of spatial ability that would engage similar yet categorically distinct spatial operations (see Linn & Petersen, 1985): mental rotation and the water-level task. We predicted that cross-sectioning would correlate with these more established measures of spatial reasoning but that the strength of the correlations would vary depending on the spatial processes required. Specifically, given that cross-sectioning involves manipulating mental images and possibly rotation, we predicted that performance on the cross-sectioning tasks would be significantly correlated with performance on a mental rotation task. However, as the water-level task has been shown to demonstrate distinctly different spatial operations from spatial visualization tasks (see meta-analysis by Linn & Petersen, 1985), we expected this task might not correlate as strongly with cross-sectioning as mental rotation.

Additionally, spatial ability has been shown to develop even through early adolescence (Vasta & Liben, 1996). Therefore, we expected to find an effect of age such that performance on cross-sectioning improves over time. Interestingly, using 3D objects adds complexity, which some researchers have shown negatively impacts performance on mental rotation tasks (e.g. Rosser, 1980). Since cross-sectioning ability involves the interface of 2D and 3D representations we might expect that this task would be more difficult for young children because of the increased complexity of the stimuli. Consequently, in Experiment 2 we contrasted the presentation of the stimuli between actual three-dimensional geometric shapes (3D) and photographs of the real shapes (2D). Our expectation was that young children would be more successful when they were presented with problems involving cross-sections of actual 3D objects than when these same cross-sectioning problems were presented as photographs on a computer screen.

Experiment 1

In this study, we developed an assessment of cross-sectioning ability to determine if this task was suitable for young children. Experiment 1 used real objects (e.g., geometric foam shapes) and compared performance on the 3D cross-sectioning task to performance on two other standard measures of spatial ability (mental rotation and the water-level task) to determine the trajectory of cross-sectioning development during the early elementary years in relation to other spatial skills.

Method

Participants. Fifty-one elementary students (17 boys, 34 girls) ranging in age from 5 years 0 months to 9 years 0 months (M=7.35 years, SD=1.16), were recruited from the Chicago area. Participants were compensated $10 for their time and travel and were also given a t-shirt for participating. We constructed four age groups from the data collected: 5 year olds (n=8, M=5.58 years, SD=0.32), 6 year olds (n=11, M=6.43 years, SD=0.31), 7 year olds (n=16, M=7.32 years, SD=0.32), and 8 to 9 year olds (n=8, M=8.69 years, SD=0.27).

Apparatus and materials. Stimuli for the cross-sectioning task consisted of six solid foam geometric shapes. Each solid had a base edge length or diameter of 7cm and a height of either 7cm (sphere, pyramid) or 14cm (cone, cylinder, rectangular prism, triangular prism).

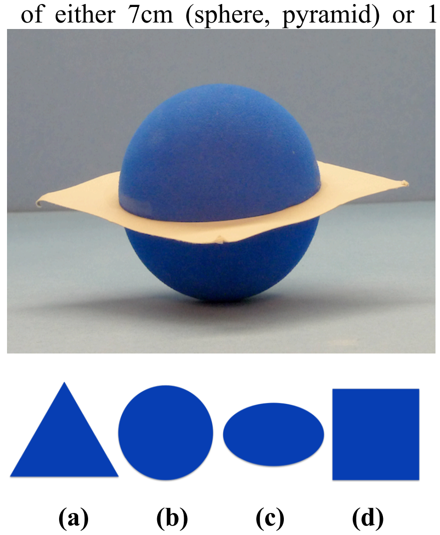

Figure 1. The sample cross-sectioning item, showing a sphere bisected by an intersecting plane. Participants were asked to choose among four options to identify the resulting cross-section.

To create the 12 test items, each shape was bisected with an intersecting plane of sturdy, gray stock paper (see Figure 1).

Design and Procedures.

Participants were tested on three spatial reasoning tasks in a set order: cross-sectioning, mental rotation, and the water-level task. All participants were tested individually in a laboratory at the University of Chicago.

Participants first completed a cross-sectioning task adapted from Piaget and Inhelder (1956) and Boe (1968). In this task, children were presented with one sample item and twelve test items composed of familiar, colorful 3D foam shapes that were cross-sectioned by an intersecting plane. A sphere was used as the sample item and five different shapes (a cone, cylinder, pyramid, rectangular prism, and triangular prism) were used to construct the test items. Each shape was used twice, with one test item depicting a cut along the horizontal axis and the other along the vertical axis. An additional horizontal cut cone and vertical cut rectangular prism of different colors were used to complete the 12 test items.

The experimenter first showed each solid foam shape to the child, rotating the object so they could view all sides of the object, and then identified it (e.g. "This is a cylinder") in order to familiarize the child with the stimuli. Next, the experimenter showed the sample item. A sphere was bisected with a piece of sturdy stock paper between the two halves demonstrating where and how the object had been cut (see Figure 1). The participant was told to imagine what the inside of the sphere would look like if we were to pull it apart at the cut point. The experimenter stated that the cut side would be flat and may make a shape that is different than the shape of the whole object that we see. The participants were then asked to point to the resulting cross-section shape from an array of four 2D shape choices. All shapes were cut either symmetrically (i.e., along the center) or asymmetrically along the longitudinal or horizontal axis. The stimuli were shown to the participants from one of two orientations: half of the participants viewed the objects so that they were looking at the intersecting plane from an approximate 90 degree angle (e.g., the plane of the paper was parallel to the ground such that the edges were more visible, see Figure 1) and the other half viewed the intersecting plane face-on (e.g., the paper was perpendicular to the ground such that the surface around was fully visible).

Participants also completed the Primary Mental Abilities (PMA) spatial relations test (Thurstone & Thurstone, 1963), where they were asked to pick from a four-choice array the shape that would make a square if it were put together with the target shape. Participants were instructed that this task was like a puzzle where shapes could be rotated to fit but could not be flipped over.

Then, participants performed the water-level task adapted from Piaget and Inhelder (1956). In this task, participants were presented with a line drawing of a half-full bottle of water. They were then given four pictures of empty bottles tilted upright, to the left or to the right, 30°, 45°, and 60° from horizontal. Participants were asked to draw the resulting water line if the bottle was half full and was tilted.

The cross-sectioning and mental rotation tasks were scored such that each participant received an accuracy score (e.g., mean proportion correct), whereas the water-level task measured the angular disparity from 0 degrees (e.g., mean error). First, we present our analysis on the cross-sectioning task as a new method to assess spatial visualization skill in young children. Then, we compare performance across the three tests.

Results

Table 1 presents the mean performance for each spatial task by age group. Note, for the cross-sectioning task, there was no significant difference based on the viewing orientation of the test items (90 degrees: n=26, M=.69, SD=.21; facing: n=25, M=.76, SD=.18). Thus, we collapsed across this factor in our analysis.

For the cross-sectioning task, a 2x4 ANOVA (gender by age group) revealed a significant effect of age group, $F(3,43)=7.98$, $p<.001$, but no effect of gender, $F(1,43)=0.07$, $p=.79$, and no interaction, $F(3,43)=1.79$, $p=.16$. Specifically, cross-sectioning performance significantly improved at each age compared to the last, except for between ages 6 and 7 years (all p's < .02, using Bonferroni adjustment). This reflects a developmental trend, such that participants improve with age, starting at 5 years old, and attain very good performance on this task (88% correct) around 8 years of age.

We conducted an item analysis to determine item difficulty. The most difficult test items across the entire sample were generally those where the cross-section resulted in a different shape from the whole, which we call

Table 1. Mean performance on spatial tasks by age group.

Task	Age	M	SE	N
Cross-Sectioning				
(proportion correct)	5 yrs	0.53	0.07	8
	6 yrs	0.70	0.05	11
	7 yrs	0.72	0.04	16
	8-9 yrs	0.88	0.03	16
	Total	0.74	0.03	51
Mental Rotation				
(proportion correct)	5 yrs	0.34	0.06	8
	6 yrs	0.54	0.06	11
	7 yrs	0.50	0.03	16
	8-9 yrs	0.68	0.04	16
	Total	0.54	0.03	51
Water-Level				
(angular disparity)	5 yrs	172	5.5	8
	6 yrs	178	12	11
	7 yrs	167	15	16
	8-9 yrs	113	40	16
	Total	163	9.5	51

Table 2. Mean accuracy (standard error) of cross-section task items across the entire sample (N=51).

Item type	Item Shape	Cross-section	% correct
Congruent	Triangular Prism	Triangle	94
	Cylinder	Circle	92
	Rectangular Prism (2)	Rectangle	84
	Cone (2)	Triangle	78
	Pyramid	Triangle	59
		Total	81.4 (6.3)
Incongruent	Rectangular Prism	Square	84
	Cylinder	Rectangle	80
	Triangular Prism	Rectangle	49
	Cone	Circle	39
	Pyramid	Square	31
		Mean Total	56.6 (10.8)

incongruent cross-sections (Table 2). For example, performance on the pyramid cut horizontally to reveal a square cross-section was the most difficult item (31% accuracy rate overall). Conversely, shapes with congruent cuts were much easier for children to grasp (e.g., the pyramid cut vertically to reveal a triangle, 59% answered correctly). Overall, children scored significantly higher on the congruent items than the non-congruent items, $t(50)=3.72$, $p=.001$.

For the mental rotation and water-level tasks, we conducted an analysis of variance (ANOVA) with the mean proportion correct (or the mean deviation score in the case of the water level test) by gender and age group. We found a significant age group effect for the mental rotation task, $F(3,43)=8.26$, $p<.001$, and the water-level task, $F(3,43)=3.10$, $p = .04$.

The cross-sectioning and mental rotation tasks were significantly correlated across the entire sample, $r(49)=.47$, $p=.001$. However, when controlling for age (in months), a multiple regression model revealed that mental rotation score was not a significant predictor for cross-sectioning performance, $\beta = .23$, $p = .09$, $R^2 = .40$, $\Delta R^2 = .04$. Further, when collapsing across age groups, we found no significant correlation between cross-sectioning and water-level task performance, $r(49)=.20$, $p=.23$.

In summary, children successfully completed the cross-sectioning task, suggesting that children as young as 5 years old are capable of performing basic cross-sections given the appropriate stimuli. Further we found an increase in performance with age. Difficulty of test items generally represented two categories: congruent items were easier in that the cross-section resulted in a similar shape to the overall object, whereas incongruent items were harder due to the cross-section resulting in a different shape than the overall object. Positive correlations between the mental rotation and cross-sectioning tasks were present across the 5 to 8 year age range. However, when controlling for age, mental rotation was not a significant predictor of cross-sectioning performance, which suggests these tasks are not measuring *identical* skills but rather related spatial skills, particularly in children younger than 8 years old. Further, there was no significant correlation between performance on the cross-sectioning and water-level tasks. Thus, cross-sectioning ability is somewhat independent of both spatial perception and mental rotation. We are currently examining cross-sectioning performance in relation to another spatial visualization task using a paper folding task that is appropriate for young children.

Experiment 2

In order to examine the effects of presentation on cross-sectioning ability, we contrasted performance using 3D and 2D stimuli. Hence, half of the participants saw real three-dimensional geometric shapes (3D), while the other half of participants viewed 2D photographs of the shapes on a computer screen. We also investigated whether preschool children as young as 3 years old would succeed at the task. If successful, the cross-sectioning assessment would be useful in a variety of settings outside of a laboratory, as well as with a greater age range.

Method

Participants. Sixty-nine elementary students (37 boys, 32 girls) ranging in age from 3 years 1 month to 9 years 3 months (M=5.82 years, SD=1.66) were recruited as previously described and randomly assigned to two groups: 3D stimuli (19 boys, 16 girls; age, M=5.72 years, SD=1.67, range 3yrs1mos to 8yrs11mos) and 2D stimuli (19 boys, 16 girls; age, M=5.47 years, SD=1.74, range 3yrs1mos to 9yrs3mos).

Apparatus, Design and Procedures. All participants received the same familiarization and testing procedure for the cross-sectioning task only as described in Experiment 1. However, participants were randomly assigned to either the 3D or 2D stimuli group, which determined the type of objects they saw during the cross-sectioning test (either real 3D foam shapes used in Experiment 1 or 2D photographs of the shapes, see Figure 1). Additionally, as viewing orientation did not impact performance in Experiment 1, all stimuli were held by the experimenter (for 3D) or presented on a computer screen (for 2D) such that the intersecting plane was at an approximate 90 degree angle to the child.

Results

Table 3 presents the mean proportion correct across age groups within the 2D and 3D conditions. A 2x2x6 ANOVA (condition by gender by age group) revealed a significant interaction between condition and age group, $F(5,46)=5.16$,

3D	*M*	*SE*	*n*	2D	*M*	*SE*	*n*	*p*
3 years	0.47	0.05	6	3 years	0.50	0.05	5	.70
4 years	0.45	0.08	8	4 years	0.54	0.05	6	.35
5 years	0.65	0.06	6	5 years	0.52	0.02	7	**.043**
6 years	0.72	0.03	6	6 years	0.48	0.08	7	**.016**
7 years	0.80	0.03	5	7 years	0.63	0.05	4	**.023**
8-9 years	0.75	0.10	4	8-9 years	0.92	0.04	5	.12
Total	0.62	0.03	35	Total	0.58	0.03	34	.20

Table 3. Mean proportion correct (standard error) on the cross-sectioning task for each condition (2D vs. 3D) by age group.

p=.001. Specifically, there was a benefit for those in the 3D condition in the 5, 6 and 7 year age groups (see Table 3), but not in 3-4 year olds or 8-9 year olds. There was also a main effect of age, $F(5,46)=8.42$, $p<.001$, such that performance significantly increased with age overall, from early (4 years) to late (8 years), $p<.01$ Bonferroni (3 yrs=48% correct, 4 yrs=49%, 5 yrs=58%, 6 yrs=59%, 7 yrs=72%, and 8-9yrs=84%). This replicates the developmental trend found in Experiment 1 that children improve basic understanding of cross-sections over time, and extends the earliest age tested successfully to 3 years old.

Additionally, we compared performance on individual test items between the 3D and 2D versions of the task (Table 4). Again, the most difficult test items were incongruent cross-sections (e.g, the pyramid cut horizontally to reveal a square cross-section), while shapes with congruent cuts were much easier for children to grasp (e.g., the pyramid cut vertically to reveal a triangle). A 2x2 ANOVA (condition by item type), revealed significantly higher performance for congruent compared to incongruent items, $F(1, 67)=107.21$, $p<.001$, but no effect of condition ($p=.34$) or interaction between condition and item type, ($p=.17$).

Table 4. Mean percent correct (standard error) of cross-section task items for 3D (*n*=34) and 2D (*n*=35) stimuli.

Item type	Item Shape	Cross-section	3D	2D
Congruent	Triangular Prism	Triangle	66	65
	Cylinder	Circle	77	76
	Rectangular Prism (2)	Rectangle	86 67	87
	Cone (2)	Triangle	74 77	71
	Pyramid	Triangle	89	88
		Total	76.7 (4.3)	77.7 (3.5)
Incongruent	Rectangular Prism	Square	77	53
	Cylinder	Rectangle	60	53
	Triangular Prism	Rectangle	43	18
	Cone	Circle	34	26
	Pyramid	Square	11	9
		Total	41.1 (4.3)	31.2 (3.3)

Discussion

In the present experiments we found that young children do reason about cross-sections and this ability can be assessed successfully using a task that involves either three-dimensional simple geometric shapes or two-dimensional photographs of simple geometric shapes. This ability develops over time, such that basic understanding of cross-sections improves from 3 to 8 years of age. Further, cross-sectioning ability is independent from other spatial skills, but is related to mental rotation more so than the water-level task.

According to Linn & Petersen (1985), spatial visualization tasks require maintaining mental representations and performing multistep manipulations on them. Thus, cross-sectioning skills, which involve such complex mental operations and rotations, would likely be categorized as a spatial visualization skill. As such, we found that cross-sectioning is distinct from mental rotation, as assessed by the Thurstone mental rotation test, and spatial perception, as assessed by the water-level task. Although some studies have not successfully measured cross-sectioning ability in children younger than adolescence, we found that a basic understanding of cross-sections emerges as young as preschool.

Further, it is possible to assess cross-sectioning ability in children using either real objects or photographs of real objects. Although using 3D objects provided a significant advantage for children between 5 and 7 years of age, performance across the 2D group was still above chance levels. The absence of a 3D advantage in the youngest children (3 and 4 year olds) may be due to the use of a simple shape matching strategy for both 3D objects and 2D photographs. For example, the triangular shaped cone matches the isosceles triangle. However, we included at least one foil item that had a similar shape as the correct answer to prevent this strategy always leading to the answer. In contrast, the absence of a 3D advantage in 8-9 year olds may reflect the development of the ability to think about 2D images as 3D objects. When asking about cross-sections of any stimuli presented in 2D, one must successfully infer the object as 3D prior to performing mental operations. However, if children are unable to accurately process 2D information into 3D structures, they are already starting at a disadvantage. Further study is needed to examine possible strategy differences in children with lower cross-sectioning ability compared to those with more advanced skills. Also, we aim to assess various methods for improving cross-sectioning ability across the preschool to early elementary ages.

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