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Differentiation by Domain in Young Children's Analogical Reasoning

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Abstract

How much does children's performance on analogy tasks reflect general analogical reasoning versus specific knowledge? We asked this by comparing young children's performance on conceptual (e.g., whole, broken) versus spatial (e.g., above, overlapping) analogies. We asked two primary research questions. First, does children's performance correlate across tasks that depict conceptual versus spatial analogies? Second, if children complete the easier analogical task first, does that experience boost performance on the second, harder task? Successfully solving analogy problems in one domain could provide insights to children that may carry over to a new domain. However, if poor performance reflects an underlying lack of knowledge, rather than weak analogical reasoning, then additional analogy experience will not be beneficial. Results showed that children performed significantly better on conceptual than spatial analogies, and that the order of tasks did not influence performance. Furthermore, performance was not correlated across domains. These results suggest that performance on these two tasks primarily reflects children's understanding of the concepts and relations needed to complete the analogies, rather than analogical reasoning.

Keywords: analogy; spatial cognition; development; early childhood

Analogical and Spatial Reasoning

Analogical and spatial reasoning are both foundational cognitive abilities that form the basis of higher order cognition. Analogical reasoning is defined as the ability to perceive and use relational similarities between two arrays, situations, or events (Gentner & Smith, 2012). Spatial reasoning is the ability to perceive, remember, and communicate about relations among objects or parts (Newcombe & Huttenlocher, 2000). There are many commonalities between spatial and analogical reasoning. Both skills have a protracted developmental trajectory, showing continued improvement up to middle childhood (Sternberg & Rifkin, 1979; Vasilyeva & Lourenco, 2010). There have also been similar explanations proposed for developmental improvements in these skills (e.g., language; Loewenstein & Gentner, 2005; Pruden, Levine, & Huttenlocher, 2011). Additionally, individual differences in these skills are present into adulthood and predict success in science, technology, engineering, and math fields (e.g., Dunbar, 2000; Wai, Lubinski, & Benbow, 2009).

Although analogical and spatial reasoning bear these similarities, it is unknown whether the two skills are related. It is possible that the processes are unrelated but share comparable developmental timing and similar mechanisms. Alternatively, it is possible that the skills are related: due to common underlying processes; due to domain-general abilities like abstraction or selective attention (Miller & Simmering, 2018; Miller, Vlach, & Simmering, 2017); or by interactions between systems (cf. van der Maas et al., 2006). The current literature does not directly address this contrast. On one hand, analogical and spatial reasoning have generally been studied separately, with each field establishing its own theories of developmental change. On the other hand, both the methods developed and the theoretical explanations of change share common features across domains. Analogy tasks often involve reasoning about spatial relations (Loewenstein & Gentner, 2005) and some spatial assessments rely on analogical reasoning (e.g., Huttenlocher & Levine, 1990). The current study asks whether similarities in analogical and spatial reasoning are domain specific or develop from the same domain general processes.

Within domains of analogical and spatial reasoning, some theorists propose that these skills arise from specific knowledge within the domains. For example, there is evidence that infants possess basic analogical reasoning abilities (Chen, Sanchez, & Campbell, 1997), but the application to specific analogical tasks depends on familiarity with the concepts involved. Goswami and Brown (1990) showed that children as young as 3 years could perform above chance in an analogy task if it used concepts familiar to that age group (e.g., cut or broken), in contrast to prior research that suggested analogical reasoning did not emerge until middle childhood (e.g., Sternberg & Rifkin, 1979). These results suggest that analogical reasoning is a basic skill, evident from early development that can be applied to increasingly diverse tasks as children gain specific knowledge. By extension, when children perform poorly on analogical tasks, it could be reasoned that they lack specific knowledge within a domain and not a domain general ability.

Within spatial cognition, some theorists propose a typology of spatial abilities that underlies performance on spatial tasks (see Uttal et al., 2013, for discussion). For example, Linn and Petersen (1985) proposed three categories of abilities: spatial perception, mental rotation, and spatial visualization. Uttal et al. (2013) suggested a two-dimensional separation of skills, one differentiating intrinsic versus extrinsic information, and the other separating static from dynamic tasks. While theorist differ in their divisions, these typologies suggest that spatial abilities could arise from domain-specific abilities that are not shared with those of analogical reasoning.

Alternatively, other theorists in these domains believe that analogical and spatial skills develop from general capabilities that could relate to performance across domains. For example, Gentner and colleagues proposed that analogical reasoning skills develop from the "relational shift": over development, children move from attending to featural similarities among entities to attending to relations among entities (Gentner, 1988). One mechanism purported to drive this relational shift is the acquisition of relational language (e.g., Loewenstein & Gentner, 2005; Rattermann & Gentner, 1998b). Another general mechanism is changes in executive functioning (e.g., Richland, Morrison, & Holyoak, 2006; Thibaut & French, 2016). For example, performance in analogical reasoning tasks is thought to depend on the ability to inhibit distractions (e.g., perceptual similarity and focus on relational similarity) and to be flexible in identifying relations. These potential mechanisms of change are general cognitive abilities that could also be implicated in the development of spatial cognition.

Similar domain-general mechanisms have been proposed as explanations of spatial development as well. For example, some theorists propose that changes in spatial cognition arise from abilities to use relational words (e.g., Hermer-Vazquez, Moffet, & Munkholm, 2001; Pruden et al., 2011). Others suggest that basic attentional skills that are used to identify task-relevant information could underlie changes in spatial cognition (Miller & Simmering, 2018; Miller et al., 2017).

Although perspectives differ regarding which mechanisms support development of analogical reasoning and spatial cognition, to our knowledge no study has tested how these processes relate. As a step in this direction, we investigated relations between analogical and spatial reasoning in the context of the same type of task. We used modified versions of two prior tasks, one that has been applied to spatial domains and one that has been applied to conceptual domains, to assess whether common processes could account for young children's performance across both tasks.

For the spatial task, we used the Spatial Analogies Task (Huttenlocher & Levine, 1990). In this task, children view a target image showing a spatial relation (e.g., a small object above a larger object, two identical object side-by-side) and are told to pick which of four choices "goes best" with the target. The correct answer shows the same spatial relation as the target. Although this task clearly requires making analogies, it is generally used as an assessment of children's spatial reasoning. Young children's performance in this task correlates with their performance on other spatial tasks including the Mental Transformation and Block Design Tasks, as well as spatial language (Miller & Simmering, 2018; Miller et al., 2017; Pruden et al., 2011). This suggests that this task relies on or shares mechanisms with other spatial abilities. However, this task is notably more difficult for young children than other spatial tasks, even those with which it correlates, suggesting possible contributions from other cognitive abilities (i.e., analogical reasoning).

For the conceptual task, we are using an analogies task developed by Goswami and Brown (1990) that tests abilities to make analogies based on familiar concepts to young children. The task uses an A:B::C:D structure, children are shown an A:B relation, such as a solid chocolate bar and a melted chocolate bar, and then are shown a target C (solid snowman) and need to pick which picture D (melted snowman) finishes the pattern. This task was chosen because children as young as 3 years of age showed above-chance performance, suggesting that it is sensitive to younger children's abilities in this domain. To our knowledge, children's performance has not previously been compared between conceptual and spatial analogies.

The current study examined correspondence in young children's performance across analogy tasks relying on spatial and conceptual knowledge. We tested 4-year-old children because this is an age group that has been tested previously with both types of tasks, ensuring that the tasks are appropriate for this age. This is also an age point at which individual differences in spatial skills have been shown to relate to other cognitive abilities (e.g., Verdine, Golinkoff, Hirsh-Pasek, & Newcombe, 2017).

The study had two primary goals. The first goal was to examine whether individual differences in performance were correlated between the conceptual and spatial tasks. If performance across tasks is driven primarily by similar domain-general analogical reasoning abilities, then performance should be positively correlated. However, if domain-specific abilities related to spatial and conceptual knowledge are the primary contributions to performance across respective tasks, then we should expect no relation between spatial and conceptual analogies tasks.

Our second goal was to investigate whether children's performance on an easier analogy task could support their performance on a harder one. Based on prior literature, we expected the conceptual task would be easier than the spatial task.[1] If the two tasks rely on similar processes, despite assessing different content knowledge, we would expect carry-over effects. Specifically, we predicted that performing the conceptual analogies task first would facilitate children's performance on the spatial analogies task.

Method

Participants

Thirty-eight young children (age range: 3.93-5.10 years, M = 4.33, SD = .29; 17 girls) participated in this study. One additional child participated but was excluded from analyses for not answering any test trials correctly. The majority of participants (n = 33) were recruited through a database comprising families interested in research participation from

[1] See Appendix for a secondary n analysis supporting a secondary goal, testing whether the A:B::C:D version of the spatial analogies tasks was easier for children than the standard version.

the surrounding area complied by the Waisman Center. The remaining participants (n = 5) were recruited and tested within their respective childcare centers in Dane County. Participants came from primarily White middle-class backgrounds (individual demographic data were not collected). Children who participated in the lab were compensated for their participation with a small prize (e.g., stuffed toy, book). Childcare centers were given donations of educational materials (e.g., books, art supplies) as a thank-you. Parents of participants gave informed consent before participation. This study was approved by the University of Wisconsin-Madison Education and Social/Behavioral Science Institutional Review Board.

Materials

Children completed two analogy tasks that we created for this study by modifying existing tasks. The spatial analogies task was adapted from Huttenlocher and Levine (1990) and the conceptual analogies task was adapted from Goswami and Brown (1990). Both tasks were presented on 8.5" x 11" sheets of paper within an easel ring binder. The binder stood upright in a landscape orientation on a desk in front of the participant. The task stimuli were presented in an A:B::C:D format with three foil options (see Figure 1, first panel). In this format, two pictures (A and B) depicted the target relation for the analogy, with a third picture (C) and a blank (D) for the child to complete. Three options were presented down the right side of the page.

We created our own stimuli for practice trials, which were taxonomic relations we expected to be highly familiar to children in this age range (see Appendix). On these practice trials, we also chose foils that would not be likely to produce errors. Our goal was to make the trials easy enough for all children to learn how to perform the task correctly. Note that these tasks were more similar to the conceptual trials than the spatial trials, although they differed in that the conceptual trials (as described below) all included transformations of an object (e.g., on/off, dry/wet), whereas the practice trials included more abstract relations (e.g., offspring, clothing).

In the spatial analogies task, we used the same spatial relations as in the original design but with some substitutions of objects (e.g., a corded telephone was replaced with an ice skate; see Figure 1, center panel) and one fewer foil option. Similarly, in the conceptual analogies task, we used the same conceptual relations as in the original design with some modification of objects (e.g., playdough was replaced with a log; see Figure 1, right panel) and two fewer foil options. Unlike Goswami and Brown (1990), we did not use perceptual matches and our foil options were always the same object as the object depicted in C but with different physical transformations. The reduction of foil options from four to three for spatial analogies, and from five to three for conceptual analogies, was intended to make the tasks less difficult for young children who may not easily make the necessary comparisons across all foil options. The relations used across practice, spatial, and conceptual trials are listed in Table A1 and shown in Figure A1 in the Appendix.

Procedure

The two tasks were presented in a counterbalanced order, with half of the participants performing the conceptual analogies first, and half performing the spatial analogies first. During the study, the child was seated at a desk facing the binder either in the lab testing room or a quiet space in a preschool classroom. The task was introduced to children as a game where they would find pictures to make patterns. On every trial the experimenter said, "Look at this pattern" while pointing to A and B. Then the experimenter pointed to the response options and said, "Which picture goes best here [pointing to the empty box] to complete the pattern?"

Each session began with five practice trials, presented in the same order to all participants. During the practice trials, if the child made an error, the experimenter pointed out the correct response and explained the reasoning to ensure the child understood the goal of the task. For example, if a child missed the practice trial shown in Figure 1, the experimenter would point to the pictures and say, "Look, if the dog goes with the puppy, then the cat should go best with what?" The child was allowed to choose again, and if the choice was still incorrect, the experimenter would say "If the dog goes with the puppy, then the cat goes best with the kitten" while pointing to the corresponding pictures.

After the practice trials, the experimenter next presented the spatial analogies trials, followed by the conceptual analogies trials (or vice versa for the other counterbalanced order). Within each type of analogy, trials were presented in either a forward order (shown in Appendix) or a backward order (reversed), randomly assigned across participants. As in the practice trials, on each of the test trials the experimenter said, "Look at this pattern" while pointing to A and B. Then the experimenter pointed to the response options and said, "Which picture goes best here [pointing to the empty box] to complete the pattern?" Unlike the practice trials, the test trials included no feedback on correctness, but children were

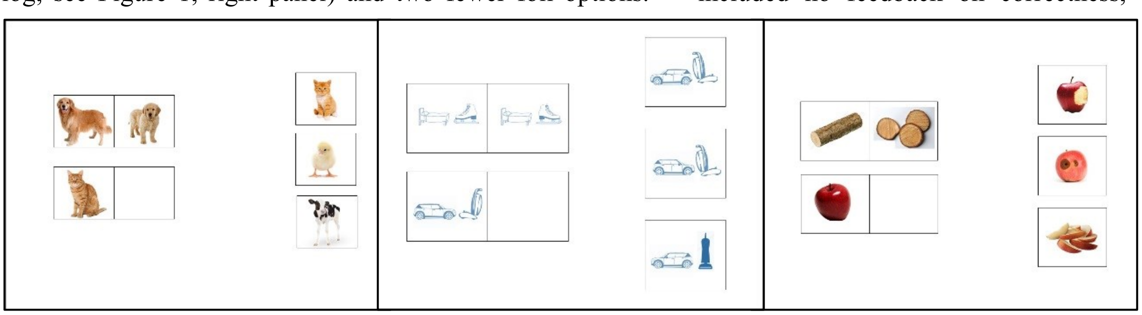

Figure 1. Sample trials showing practice/ taxonomic (left), spatial (center), and conceptual (right) analogies

praised for responding. As children made their choices on each trial, the experimenter marked the choice on a session sheet for later analysis. Sessions lasted 10-15 minutes.

Results

Table 1 shows descriptive statistics of children's performance. As expected, children performed generally higher on conceptual than spatial analogies. There was a difference in performance between the orders that was not predicted, with children who did spatial analogies first performing overall higher than children who did conceptual analogies first. For both tasks in both orders, 95% confidence intervals indicate that children performed above chance (.33).

Table 1: Proportion correct across tasks and orders

Order	Task	*M*	*SD*	95% CI
Conceptual First (n=19)	Conceptual	.49	.16	.42 - .56
	Spatial	.39	.13	.34 - .45
	Overall	.43	.10	.39 - .47
Spatial First (n=19)	Conceptual	.53	.18	.45 - .61
	Spatial	.45	.17	.37 - .52
	Overall	.48	.13	.42 - .54

We addressed a series of research questions with our analyses. First, we considered whether performance was correlated across the two different types of analogy tasks, which would suggest a strong contribution to both from general analogical reasoning. As shown in Figure 2, proportion correct was essentially unrelated across conceptual and spatial analogies (Pearson's r_{36} = .06), providing no support for that hypothesis. It is possible that a relation does exist, but we were unable to detect it due to our small sample and relatively few trials per task.

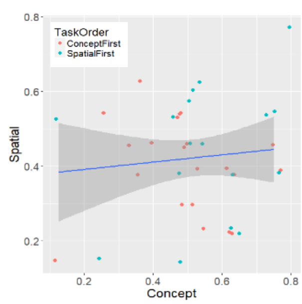

Figure 2: Proportion correct across Task Type.

Next, we considered whether children did reliably better on conceptual analogies, and if so, whether completing it first carried over. We analyzed children's choices (coding correct choices as 1 and incorrect choices as 0) across test trials with a mixed logistic regression model accounting for Task Type (contrast coded: conceptual, spatial), Order (contrast coded: conceptual first, spatial first), and Age (mean-centered as a continuous factor), treating subject as a random effect. Both Age (b = 1.35, SE = 0.68, $\chi^2(1)$ = 3.94, *p* = .047) and Task Type (b = -0.40, SE = 0.20, $\chi^2(1)$ = 3.97, *p* = .046) significantly predicted performance, as shown in Figure 3. The Age effect reflects a general developmental improvement, and the Task Type effect indicates better performance on conceptual versus spatial analogies. Order was not a significant predictor alone or in interactions (*p*s > .41), suggesting no benefit from completing the easier task first.

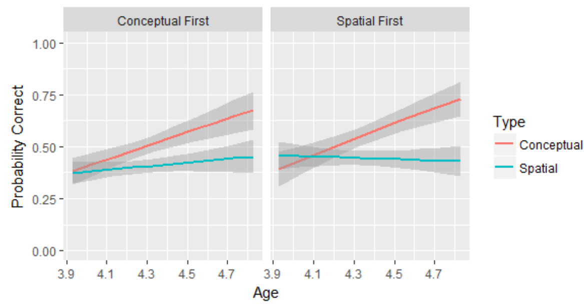

Figure 3: Probability of correct responses by Age and Task Type, separately for each Task Order.

Discussion

This study compared young children's performance across conceptual and spatial analogies tasks. Our motivation came from shared characteristics between spatial and analogical reasoning over development. However, little prior research has investigated how these skills relate over development. Our results showed that performance was not correlated between the two task, suggesting that individual differences in these tasks primarily reflect children's knowledge of the concepts or relations tested, rather than a general ability to solve analogies. Further, children performed better on the conceptual analogies than spatial analogies, but that there was no apparent benefit from completing the easier analogy type first. Lastly, children's performance across analogy tasks generally improved with age.

Overall, our results are consistent with the notion that young children's ability to solve analogies relates strongly to the specific domains being tested (cf. Goswami & Brown, 1990). In order to perform these tasks, children must have at least basic analogical reasoning abilities. However, if they lack the knowledge of the concept or relation that forms the basis of the analogy (e.g., not noticing symmetry, not recognizing part/whole relations), they will be unable to solve the task. This idea is consistent with Gentner's (1988) relational shift hypothesis, in that children must transition from focusing on features of objects to thinking about relations. Rattermann and Gentner (1998a) suggested that this shift occurs at different times across domains, as children build domain-specific knowledge. This account, and our results, contrast with notions that global changes in cognition, such as increases in executive functioning drive changes in analogy (e.g., Richland et al., 2006; Thibaut & French, 2016).

Although our results do not suggest a global change in cognitive abilities that supports analogical reasoning across domains, the notion of a relational shift in children's thinking could connect spatial skills to analogies. Attention to relations is critical for mature spatial skills, and it is possible that learning about relations in non-spatial domains could help children know to look for relations in space. This type of "learning to learn" phenomenon has been noted in language acquisition: as toddlers expand their vocabulary, they learn about regularities in language that help them make inferences about what new words might mean. This biases their attention to certain types of features (e.g., a shape bias for count nouns) which in turn facilitates learning more words (Perry & Samuelson, 2011). The timescale of such learning would be longer than we could observe in a laboratory session, but perhaps providing children with repeated exposure to analogies across domains could help facilitate children's attention to spatial relations.

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Appendix

As an exploratory question, we asked whether children's performance in our modified version of the spatial analogies task, with the addition of practice trials and the A:B::C:D format, would facilitate better performance compared to the standard version. We reasoned that the practice trials could help children understand the task goals more clearly. Additionally, the A:B::C:D format might support children's performance by highlighting the relevant relation through the contrast between A and B and also provided two analogical relations (A to B and A to C) to support identifying the correct choice for D.

To evaluate this question, we compared mean performance between our current sample and two previous studies from our lab. Because the standard version of the task included four choices, and our modified version included only three, they differ in levels of chance performance (.25 in the standard version, .33 in the modified version). We therefore did not analyze choices using logistic regression, but rather calculated means, normalizing for different levels of chance. We normalized scores by taking each child’s proportion correct minus chance, then dividing by one minus chance, resulting in scores of 0 for chance performance and 1 for perfect performance.

Using the normalized scores, children in the current sample had a mean of .15 (SD=.23) on the modified spatial analogies task. For comparison, we calculated analogous scores for the 40 children in Miller et al. (2017) and the 55 children in Miller & Simmering (2018) who all completed the standard task, resulting in means of .25 (SD=.25) and .18 (SD=.25), respectively. Inspection of these means indicates that children in the current study performed numerically worse than children in the prior studies, leaving no need to statistically test whether our modifications resulted in higher performance. This comparison indicates that our speculation that the current version of spatial analogies would be easier for children – either through the A:B::C:D structure, or from the practice trials – was not supported.

Table A1: Concepts and spatial relations used across trials.

Trial type, number	Concept (B/D choices) or spatial relation
Practice 1	offspring (puppy/kitten)
Practice 2	official vehicle (police car/firetruck)
Practice 3	clothing for body part (sock/glove)
Practice 4	utensil (paintbrush/toothbrush)
Practice 5	clothing for season (swim/winter wear)
Concept 1	burning (candle/paper)
Concept 2	dirty (dog/jeans)
Concept 3	closed (door/box)
Concept 4	wet (car/dog)
Concept 5	cut (log/apple)
Concept 6	off (TV/lamp)
Concept 7	melted (chocolate/snowman)
Concept 8	broken (bulb/egg)
Spatial 1	two partially overlapping
Spatial 2	two relative size
Spatial 3	small object above larger objects
Spatial 4	multiple objects stacked in triangle
Spatial 5	two vertically aligned objects
Spatial 6	two objects, one up-side down
Spatial 7	two next to and touching
Spatial 8	two objects in horizontal mirror image
Spatial 9	two objects in vertical mirror image
Spatial 10	two different objects facing right
Spatial 11	small object in corner of larger object
Spatial 12	nested shapes open at bottom
Spatial 13	three relative size

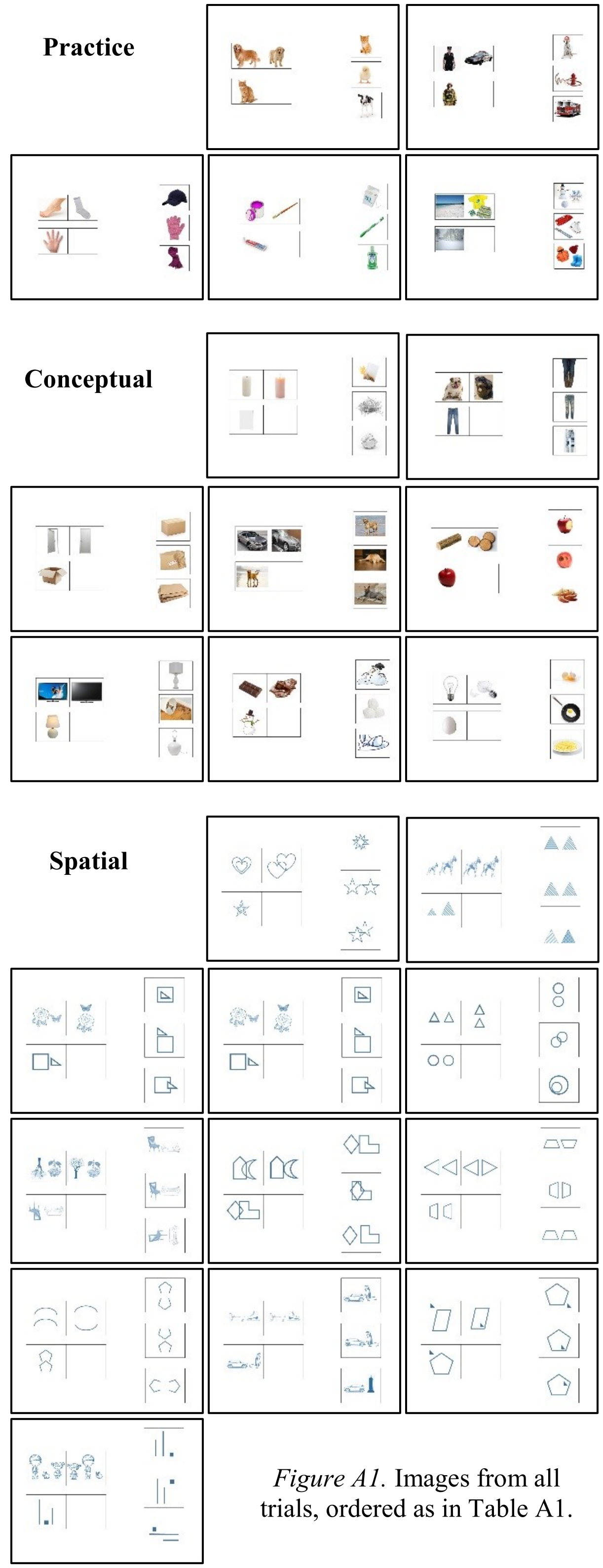

Figure A1. Images from all trials, ordered as in Table A1.