Spatial Alignment Facilitates Visual Comparison in Children

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Abstract

Visual comparison is a key process in everyday learning. Matlen et al. (2020) recently proposed the Spatial Alignment Principle, based on the broader work of structure-mapping theory in comparison. According to the principle, visual comparison is more efficient when pairs are arranged in *direct placement*: i.e., so that the visuals are juxtaposed orthogonally to their structural axes. In this placement (a) the intended relational correspondences are readily apparent, and (b) the influence of potential competing correspondences is minimized. Thus, this placement should make the relational alignment maximally easy to notice. The results of a same-different task in adults supported this claim. The current study asks whether the Spatial Alignment Principle applies in children's visual comparison. 6-year-old children performed a same-different task for visual relational patterns. The results indicated that direct placement led to faster and more accurate comparison, both for concrete same-different matches (matches of both objects and relations) and for purely relational matches.

Keywords: spatial alignment; visual comparison

Introduction

Analogical comparison, the ability to perceive and transfer relational structure across situations, is important in conceptual learning (Gentner, 2010; Gentner & Hoyos, 2017) and education, particularly in mathematics and science (Alfieri et al., 2013; Goldwater & Schalk, 2016; Richland & Simms, 2015; Rittle-Johnson & Star, 2009). We focus here on visual comparisons, which are ubiquitous in children's everyday learning as well as in classroom contexts. Visual comparison can be used to highlight spatial relational commonalities, aiding children in learning spatial concepts such as *symmetry* and facilitating transfer between different spatial arrays (Christie & Gentner, 2010, Loewenstein & Gentner, 2001; Hribar et al., 2012; Yuan et al., 2017). Visual comparison has been shown to aid students in learning mathematical principles and procedures (Begolli & Richland, 2016; Richland & McDonough, 2010; Rittle-Johnson & Star, 2009) and to support children's learning of a basic engineering principle (Gentner et al., 2016). In this paper, we briefly review the literature on visual comparison before turning to a newly discovered principle, the Spatial Alignment Principle, and describe a study testing whether this principle is operative in children's visual comparison.

Visual Comparison Processing

Visual comparison has been analyzed using the structure-mapping framework (Gattis, 2002; Sagi et al., 2011; Markman & Gentner, 1993; Yuan et al. 2017). In this framework, comparison entails structural alignment based on matching common relational structure (Gentner, 1983, 2010); objects are placed into correspondence based on having like roles within the relational structure. Comparison and structural alignment supports noticing relational commonalities that can be important in abstraction and transfer (Gentner, 2010; Richland & Simms, 2015). It also fosters noticing alignable differences connected to the common structure (Gentner & Gunn, 2001; Gentner & Markman, 1994; Sagi et al., 2012). There is much evidence that structural alignment is critical for relational comparison (Gentner et al., 2016; Krawzyck et al., 2004; Markman & Gentner, 1993).

In visual figures, much of the critical information is conveyed by the spatial configuration. Thus, comparing two visual figures requires aligning their spatial relational structures and mapping corresponding elements – that is, elements that play the same role in the common structure (Gentner & Markman, 1997). As in conceptual analogies, structural alignment can reveal commonalities and differences.

As an example of how visual comparison highlights commonalities, Christie and Gentner (2010) showed 3- and 4-year-old children a novel spatial pattern. They were told that it was a 'dax' (for example), and asked to choose another dax. Children strongly preferred an alternative that shared an object over one that shared the relational pattern. But when children were given the two standards simultaneously and invited to compare them, the results were striking: the comparison group was several times more likely to choose the relational match than was the sequential group.

Visual comparison can also highlight alignable differences – that is, differences that play corresponding roles in the two (mostly) aligned structures. For example, Gentner et al., (2016) used visual comparison to teach 6- to 8-year-old children the engineering principle that a diagonal brace confers stability. Children were shown two model buildings, one with a diagonal brace (which was therefore stable) and one with a horizontal crosspiece, lacking a diagonal brace (which was unstable). The buildings were either highly similar and easy to align or dissimilar and harder to align. When children were asked ‘Which is stronger’ and allowed to wiggle them, they discovered that the stable building barely moved, while the unstable one could be bent nearly to the ground. Although all children recognized *which* building was stronger, the high-alignment group was far more likely to discover *why*: they were significantly more likely to spontaneously utilize brace structure in a subsequent task.

Alignment Principles for Visual Comparison

Given the importance of visual comparison both in classroom learning (Alfieri et al., 2013; Richland & McDonough, 2010; Begolli & Richland, 2016) and in everyday learning (Gentner et al., 2016; Haryu et al., 2011; Shao & Gentner, 2016), it is of particular interest to both psychologists and educators to understand what factors prompt comparison and facilitate structural alignment of visual pairs. Three factors that have been identified in prior work are spatiotemporal proximity, high overall similarity, and common labels (Gentner & Hoyos, 2017). We briefly describe these, focusing chiefly on the first two factors, which are most relevant to the present research. Then we turn to the proposed new factor, spatial alignment.

Common Labels When the same label is applied to different objects, young children (Gentner, 2010; Gentner & Namy, 1999) and infants (Ferry et al., 2010; Fulkerson & Waxman, 2007) are more likely to compare them and form a category than if the objects do not receive a common label.

High Overall Similarity Children (and adults) are more likely to spontaneously engage in comparison between similar items than between dissimilar ones. Further, high overall similarity facilitates structural alignment (Gentner & Hoyos, 2017; Gentner & Rattermann, 1991). Overall similarity matches (where object similarity supports the relational alignment) are easier to process than analogies for both children (Gentner & Toupin, 1986) and adults (Gentner & Kurtz, 2006). Overall similarity is particularly important for young children, whose representations are often rich in objects but sparse in relations. Thus, comparison between similar items can lead to better learning outcomes for young children than more distant comparisons. Of course, more distant comparisons can support greater generalization, but only if the learner can align them.

Spatiotemporal Proximity. There is considerable evidence that children are more likely to compare and align two things if they are spatially and temporally juxtaposed. For example, in Christie and Gentner’s (2010) study (described above), young children who compared two juxtaposed exemplars of a spatial pattern were able to abstract and transfer the pattern; but they failed to learn the pattern if the same two exemplars were shown sequentially. Simultaneous presentation has also been shown to improve classroom learning in mathematics (Begolli & Richland, 2016; Rittle-Johnson & Star, 2009) and geoscience (Matlen et al., 2011). For example, Begolli and Richland (2016) taught fifth graders the ratio concept by comparing correct division strategies to misconceptions. All examples were either left visibly on the board throughout the presentation or only available sequentially when being discussed. The results indicated that simultaneous presentation led to better posttest performance and understanding of the ratio principle than sequential presentation.

Spatial Alignment Principle

Recently, a previously unexplored factor has emerged as important in visual comparison: the *spatial alignment principle* (Matlen, Gentner & Franconeri, 2020). The idea is that the comparison process should be more fluent to the degree that (a) the intended relational correspondences are readily apparent, and (b) the influence of potential competing correspondences is minimized. Visual comparison is impeded when there are intervening potential correspondences between the correct corresponding components. More specifically, this principle states that visual comparison is more fluent when the visual are placed orthogonally to their structural axes (i.e., the axes along which the main relations apply)[1]. Figure 1 depicts two examples of molecular notations. In the left panel, the molecule forms an ABA pattern and has a horizontal structural axis – in other words, the main relational pattern is presented horizontally. A comparison to its notation is facilitated if they are vertically placed, and impeded if they are horizontally placed. The reverse is true in the right panel, where the same molecular structure is now vertically presented (i.e., it has a vertical structural axis).

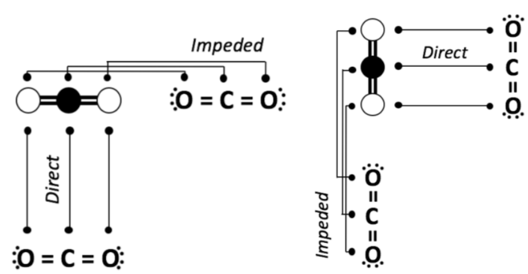

Figure 1: Color triplets with horizontal structural axes in direct and impeded placement. Adapted from Matlen et al. (2020)

What are the advantages of orthogonal placement? When visuals are juxtaposed and orthogonally placed, direct placement is achieved because spatially corresponding

[1] It is possible that in some cases there may be more than one structural axis for a given figure or pair of figures. For simplicity, we restrict our current account to cases where there is a clear axis.

elements and relations are juxtaposed and relatively far from competing non-corresponding elements. This makes the relational alignment maximally easy to notice. In contrast, impeded placement occurs when other potential correspondences intervene between the two corresponding elements. As a result, the correct structural alignment may take longer to discover or be missed altogether. Figure 2 illustrates this principle with example pairs used by Matlen et al. (in press), as well as in the current experiment. Here, all triplets have horizontal structural axes. Direct placement is shown in 2A, where the triplets are placed vertically, and impeded placement is shown in 2B, where the triplets are placed side by side. According to the spatial alignment principle, processing visual comparison in direct placement should be more efficient than that in the impeded case, even though the triplets are presented simultaneously and are overall similar to each other.

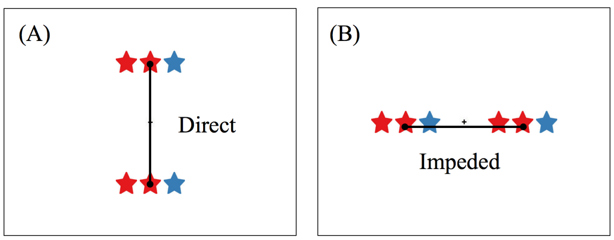

Figure 2: Color triplets with horizontal structural axes in direct and impeded placement.

To test this prediction, Matlen et al. conducted a same-different judgment task in adults. Participants saw pairs of triplets and were asked to identify whether the pair was the same or different as fast and accurately as possible. For example, red-red-blue has a different pattern than red-blue-red, so the response should be 'different'. The placement and structural axes of triplets were systematically manipulated to create direct and impeded comparisons for both horizontal and vertical triplets. As predicted by the spatial alignment principle, people were faster and more accurate on direct trials than on impeded trials. These result patterns were found for shape (e.g., square-square-triangle) triplets as well (see Figure 3).

In a second study, Matlen et al. paired together shape and color triplets to form relational-only trials. Here participants needed to do a relational same-different judgment and were told that *square-triangle-square* has the same relational pattern as *red-blue-red*. The results again supported the spatial alignment principle, with faster performance on direct trials. Furthermore, participants were slower on relational-only trials (i.e., cross-dimension trials) than on object+relation trials (i.e., within-dimension trials) (although there was no significant difference in accuracy). This is consistent with prior findings that comparison is in general easier when there exist object correspondences as well as relational correspondences (Gentner & Rattermann, 1991; Gentner & Toupin, 1986). Overall, the findings provide strong support for the spatial alignment principle.

Testing the Spatial Alignment Principle in Children

Given the importance of visual comparison in children's learning, it is crucial know to what extent the spatial alignment principle also operates in children. Answers to this question would shed light on the development of visual comparison ability and provide educators with a better understanding of how to design instructional materials. In this study, we focus on 6-year-oldsbecause a pilot study suggested that this is the minimal age for children to comply with the computer task instructions.

There were two predictions. First, we predicted that children's performance would follow the spatial alignment principle. Specifically, children should be faster and/ or more accurate in visual comparison for direct placement than for impeded placement.

Second, we predicted children's performance to be better on object+relation trials than on relation-only trials. This is based on findings that young children find purely relational matches harder to process than concrete object+relation matches (Gentner & Rattermann, 1991; Kotovsky & Gentner, 1996). As noted earlier, in Matlen et al.'s study, adults were slower on relation-only trials than on object+relation trials, consistent with the idea that among adults as well as children, object+relation matches are easier to process than relation-only matches. (Accuracy didn't differ between the two kinds of trials).

Experiment

In this study, we adapted the procedures in Matlen et al. (2020) to be child-friendly (For example, we provided more explanation and practice trails prior to the actual study.) Participants were asked to provide same-different judgment for pairs of triplets. The test pairs consisted of either color or shape triplets in the first two blocks (the object+relation, within-dimension blocks) and color/shape triplets in the last block (the relation-only, cross-dimension block). The order was intentionally determined to let children practice with the more straightforward same-different task before engaging in the purely relational judgment. This is consistent with the idea of progressive alignment, wherein carrying out close similarity matches highlights common relational structure and enables children to do far relational transfers that they might otherwise fail (Kotovsky & Gentner, 1996). Pairs also systematically varied in triplet orientation and placement.

Method

Participants Twenty-nine 6-year-old children participated in the study (M = 6.51 years, Range = 6.00 to 7.06 years, 11 females). One additional child was recruited but excluded due to failure to complete the experiment. Children were recruited from a large Midwestern city.

Materials and Design Stimuli were adapted from Matlen et al. (2020). Children were shown a pair of triplets and either gave a same-different judgment (for within-dimension pairs) or responded as to whether the relational patterns were the same or different (for cross-dimension pairs). Three types of triplet pairs were used (color-color, shape-shape, and color-shape; referred to as Dimension). Pairs varied systematically in the structural axes of triplets (both vertical or both horizontal; referred to as Orientation) and relative placement between them (direct or impeded; referred to as Placement). The design was within-subject and consisted of 2 Dimension (within vs. cross) x 2 Orientation (horizontal vs. vertical) x 2 Placement (direct vs. impeded) x 2 Concordance (same vs. different).

Trials of the same stimulus type were blocked together. Within-dimension trials were either color trials (i.e., pairs of color triplets) or shape trials (pairs of shape triplets). In color trials, each triplet consisted of two reds and one blue. In shape trials, each triplet consisted of three black geometric shapes (two squares and one triangle; see Figure 3). The pattern of colors and shapes within each triplet was fully counterbalanced, resulting in 3 possible orderings for a triplet and 9 [3 x 3] possible pairings for a pair. A similar plan was used for cross-dimension trials, where a color triplet was paired with a shape triplet. A "same" response was called for when triplets within a pair contained the same patterns (e.g., blue-red-red shares the same pattern with triangle-square-square but not with square-triangle-square).

We systematically varied the orientation and placement of each pair and created 4 possible combinations (2 Orientation: horizontal vs. vertical x 2 Placement: direct vs. impeded). Together, our manipulation resulted in 36 test trials for each within-dimension block and 72 for the cross-dimension block, with a total of 144 test trials. Additional training and catch trials were given at the beginning and the end of each block, respectively.

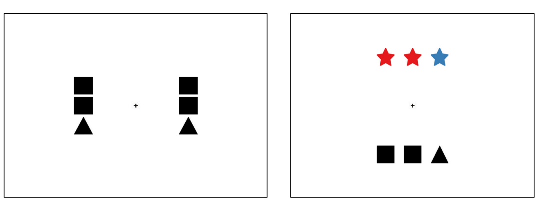

Figure 3: Examples of shape triplets and color-shape triplets.

Procedure The experiment consisted of two phases: training and testing, run on the software platform of PsychoPy3 (v3.0.6; Peirce et al., 2019) on a 13-inch MacBook Pro. Training familiarized children with the task instructions. The testing phase was made up of three blocks as described above.

Results

Two main variables of interest were accuracy and response time for test trials. Data in a block were excluded if participants failed the catch trials per the criteria determined a priori. Across participants, performance on 3 within-dimension and 3 cross-dimension blocks were excluded. We also excluded any trial with response time three standard deviations longer than the mean time (with respect to each subject and block dimensionality). This constituted 1.8% of all trials. Response time was only analyzed for correct trials. We conducted 2 Placement x 2 Dimension x 2 Orientation x 2 Concordance repeated-measures ANOVAs for error rates and response time, with subject as the error term. To recapitulate, we predicted that children's performance (in terms of response and accuracy) would be better for direct placement than for impeded placement, and for within-dimension pairs than for cross-dimension pairs. Therefore, planned t-tests focused on the main effects of placement and dimension. Follow-up t-tests explored other significant effects.

Error Rates The repeated-measures ANOVA on error rates revealed a significant main effect of placement, $F(1, 380) = 24.10$, $p < .001$, $\eta_p^2 = .06$, and a marginal effect of dimensionality, $F(1, 380) = 3.33$, $p = .07$, $\eta_p^2 = .01$. There was no other significant effect (see Figure 4). Planned t-tests showed that children made more errors on the impeded ($M = 0.12$, $SD = 0.15$) than the direct trials ($M = 0.07$, $SD = 0.11$), $t = 3.96$, $p < .001$, $d = .39$, 95% CI = .19-.58, and in the cross-dimension ($M = 0.11$, $SD = 0.16$) than the within-dimension blocks ($M = 0.08$, $SD = 0.11$), $t = 2.15$, $p = .03$, $d = .21$, 95% CI = .02-.41. The results were in line with our first and second predictions, respectively.

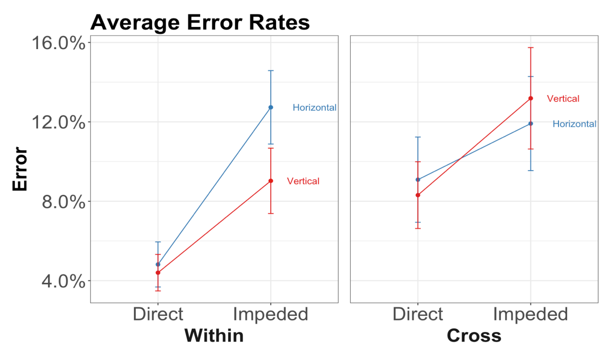

Figure 4: Graph for error rates (error bars represent standard errors).

Response Time The repeated-measures ANOVA on response time revealed main effects of placement, $F(1, 380) = 11.65$, $p < .001$, $\eta_p^2 = .35$, and dimensionality, $F(1, 388) = 200.30$, $p < .001$, $\eta_p^2 = .03$ (see Figure 5). Planned T-tests showed that children were faster on the direct ($M = 2904$, $SD = 1573$) than on the impeded trials ($M = 3221$, $SD = 1695$), $t = 1.99$, $p = .05$, $d = .19$, 95% CI = .00-.38, and in the within-dimension ($M = 2486$, $SD = 758$) than in the cross-dimension blocks ($M = 3709$, $SD = 2070$), $t = 7.90$, $p < .001$, $d = .80$, 95% CI = .60-1.00. These results corroborated those of error rates, and supported our predictions: Children's performance (1) was better for direct placement than for impeded placement, and (2) was better when there was object match as well as a relational match (the within-dimension blocks) than when only a relational match was available (the cross-dimensional blocks).

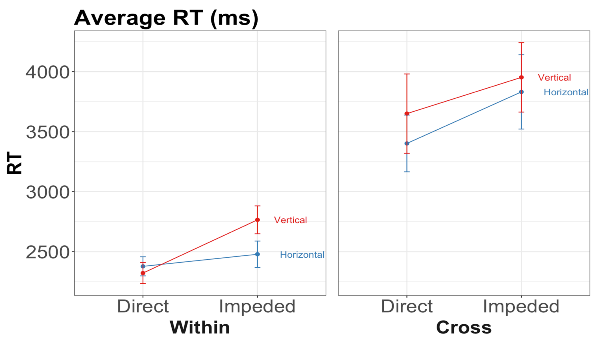

Figure 5: Graph for response time (error bars represent standard errors).

Discussion

In summary, the results showed that 6-year-old children were both faster and more accurate for direct placement than for impeded placement. This was the case for both concrete object+relation matches and purely relational matches. This is consistent with the spatial alignment principle, which suggests that visual comparison is more efficient when spatial arrangements minimize the influences of potential competing correspondences. The results also showed that children performed worse for the purely relational matches than for the concrete object+relation matches. This is consistent with structure-mapping theory (Forbus et al., 2017; Gentner, 1983, 2010; Gentner & Hoyos, 2017), which holds that although people rely on the same mechanism for purely relational and concrete matches, overall similarity is easier to process. Together, our findings support the idea that visual comparison involves a process of structural alignment, and that this process is facilitated by spatial alignment.

These findings suggest a deeper look at past findings that have found that spatiotemporal proximity facilitates visual comparison. Researchers have proposed that spatiotemporal juxtaposition is effective because having the analogs co-present encourages learners to compare them (Christie & Gentner, 2010) and reduces the cognitive processing load in carrying out such alignment (Richland & McDonough, 2010). However, the current findings suggest another advantage: that in many cases, part of the advantage of spatiotemporal juxtaposition may have stemmed from spatial alignment. In many of the prior studies, the visual figures were optimally place, in terms of the spatial alignment principle. This raises the intriguing question of how much of the observed gain from spatiotemporal proximity is due to high spatial alignment.

One limitation of the current study is that the cross-dimension block always followed the within-dimension blocks. This could have contributed to children's worse performance on the cross-dimension trials. For example, children might have been more distracted or tired towards the end of the experiment, contributing to their lower accuracy and speed. On the other hand, the current order might also have overestimated children's cross-dimension performance. This is because children had the opportunity to engage in within-dimension pattern matching before the more difficult cross-dimension matching task. Based on the idea of progressive alignment (Kotovsky & Gentner, 1996), the relatively easy within-dimension matches (in which the object similarities support the relational alignment) could have acted to highlight the relational structure; this could have facilitated children's performance on the later purely relational matches. Future studies should counterbalance the order of block dimensionality to address these concerns.

Although our results showed remarkable continuity in visual comparison between children and adults, adults were overall faster and more accurate. Future studies could explore further influences on developmental change. One example is related to the role of experience in visual processing. Matlen et al. (2020) found a response time advantage for horizontal pairs over vertical pairs on impeded trials across all cases in adults. This suggests that horizontal spatial patterns may be encoded more robustly and/ or faster, making the alignment process less vulnerable to the adverse effect of impeded placement. They speculated that this horizontal advantage might be attributable to adults' fluent reading skills. Further studies with children learning to read could help decide this question.

In sum, the current study examined the developmental aspect of the spatial alignment principle, a recently discovered factor that facilitates structural alignment for visual comparison. This principle could help guide the construction of educational materials in order to better support students' science and mathematics learning.

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