Transitive Inference by Visual Reasoning

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Abstract

Two experiments are reported that investigated the influence of linear spatial organization on transitive inference performance. Reward/no-reward relations between overlapping pairs of elements were presented in a context of linear spatial order or random spatial order. Participants in the linear arrangement condition showed evidence for visual reasoning: They systematically mapped spatial relations to conceptual relation and used the spatial relations to make inferences on a reasoning task in a new spatial context. We suggest that linear ordering may be a "good figure", by constituting a parsimonious representation for the integration of premises, as well as for the inferencing process. The late emergence of transitive inference in children may be the result of limited cognitive capacity, which -- unless an external spatial array is available -- constrains the construction of an internal spatial array.

Introduction

Transitive inference describes one of the most fundamental processes in reasoning. A subject first learns a relationship between two stimuli *a* and *b*, *a*R*b*, then a relationship between stimuli *b* and *c*, *b*R*c*. The combination of these two premises in order to infer the relationship between *a* and *c*, *a*R*c*, is called "Transitive Inference" (TI). Experimental investigations of TI often use verbal three-term series problems such as *"Bob is taller than Mary"*, *"Mary is taller than Susan"*, with the conclusion *"Bob is taller than Susan"*, or nonverbal problems such as comparing the relative value of physical objects, for instance, *"Red object is bigger than blue object"*, *"Blue objects is bigger than yellow object"*, and the conclusion *"Red object is bigger than yellow object"*. Because the relation between *a* and *c* has not been stated or observed, arriving at the correct answer requires a deductive process of some sort.

Two popular explanations of transitive inference postulate that TI is based on the application of inferencing information -- either linguistic rules or mental models. In general, linguistic theories of TI (e.g., Clark, 1969) emphasize the formal logical properties. For instance, proponents of mental logic (e.g., Braine, 1978) claim that deductive schemata which are based on the logical form of the premises account for deductive processes. In this view, the representations underlying deductions are rules which are specific for each logical connective. Accurate TI performance is taken as evidence for possession of the principle of transitivity, i.e. that if A>B and B>C, then A>C. One problem for such rule theories is that people do not always follow logical rules or always make errors: the same individual may show TI in one circumstance and not another.

Mental model theories (e.g., Johnson-Laird & Byrne, 1993) address such variability in reasoning performance by arguing that people reason by constructing a set of semantic mental models based on given problem information. Conclusions are drawn by asking whether, given this problem information, a certain model is possible or not. Because these models capture essential properties of the situation, they can explain the variable performance that rule theories do not. Critics of mental model theories contend that semantic information alone is inadequate for specifying the model construction process, and syntactic or structural information must also be considered (Braine, 1993).

A third possibility is that transitive inference is based on spatial models -- the internal or external construction of ordered spatial representations which are structural analogs for the given conceptual relations (i.e., DeSoto, London & Handel, 1965). The advantage of spatial models is that they incorporate semantic and structural information, and specify how models are constructed for reasoning. DeSoto et al. (1965) suggested that people map non-spatial relations between objects onto linear spatial representations by means of what they call a "spatial paralogic." Based on principles of Gestalt psychology, linear ordering can be viewed as constituting a "good figure." "The prototypic example of *good arrangement* is order in its narrow sense of *linear arrangement* (DeSoto et al., 1965, p. 520, italics added)." Similarly, Huttenlocher (1968) proposes that when solving relational problems, adults manipulate spatial images in the same way as they would manipulate real objects. Indeed, when participants were faced with problem situations where arranging physical objects would have been difficult, arranging imagined objects was difficult, too.

The benefit of spatial model theories is that inferencing about implicit conceptual relations is based on corresponding explicit spatial relations, a process known as visual reasoning (Gattis & Holyoak, 1996, Gattis, 1997). For instance, a spatial model containing a linear order in which A is to the left of B and B is to the left of C also explicitly represents that A is to the left of C. This benefit of visual reasoning is, however, dependent on systematic rules for mapping concepts to space; without systematic rules for mapping, visual reasoning would involve a time and resource consuming process of searching for the appropriate structural analog. Research indicates that despite their lack of experience with graphs or similar representations, young children asked to reason about rate relations with graph-like diagrams exhibit very similar judgment patterns to adults, and furthermore that these judgment patterns are based on structural similarities between conceptual and spatial schemas, indicating that systematic rules for mapping conceptual and spatial schemas do indeed constrain visual reasoning (Gattis & Holyoak, 1996; Gattis, 1997).

The experiments presented here investigated whether similar constraints on mapping conceptual relations to spatial relations also govern reasoning about relations between elements -- the basis of transitive inference. We hypothesized that because a linear spatial order is a structural analog for a set of ordered relations, that learning ordered conceptual relations from a spatial linear organization would lead to better learning and higher levels of TI. While most investigations of spatial mapping in transitive inference with humans have used verbal problems such as the three term series problem (Clark, 1969; DeSoto et al., 1965; Sternberg, 1980) or have involved learning verbal labels for values on physical dimensions (Bryant & Trabasso, 1971), we employed an alternate strategy, a mostly non-verbal task inspired by studies of serial ordering and transitive inference in non-human animals. Our reason for choosing a mostly non-verbal task was to avoid introducing linguistic representations of relations contained in the task, and thus to test the usefulness of spatial models in a TI task with little or no linguistic structure. We did this to address Clark's (1969) claim that linguistic structures alone may explain TI performance. Both experiments introduced a reward/no-reward relation between overlapping pairs of elements to young children. The pairs were presented either in a context that included spatial structure (linear order) or did not (a random order), to test whether providing children with a linear spatial representation of ordered conceptual relations facilitated performance on a subsequent test of transitive inference.

This paradigm was based on previous comparative studies which indicate that non-human animals are able to use known relations between elements to choose between two elements for which the relation is not known (Davis, 1992; Gillan, 1981; McGonigle & Chalmers, 1977; Roberts & Phelps, 1994). In one set of studies, Roberts and Phelps (1994) trained rats to learn the sequence of A>B>C>D>E>F by associating relative values to olfactory cues. Stimuli were presented in either a linear or random spatial organization. Each rat was presented with two distinctly scented containers at a time, only one of which was rewarded. For example, box A was rewarded (A+), B was nonrewarded (B-), in the next trial B was rewarded (B+), and nonrewarded (C-), and so on. This was done for all adjacent pairs of stimuli A through F. In one condition, boxes were presented in a linear arrangement, that is, two boxes in adjacent locations were presented at a time with each box being associated with a certain position on the training board. In the other condition, the spatial arrangement was random, no stimulus could be associated with a specific location. Roberts and Phelps (1994) found that rats that learned relations from a linear arrangement chose B more often in a subsequent BD test, while rats that learned from a random spatial arrangement chose B and D equally often on a BD test.

These and other results indicating that non-human animals can perform TI provide a sharp contrast to debates in developmental psychology about whether young children are capable of TI. Considerable research effort has addressed the question to what extent, and at what age children are able to succeed on TI tasks. Although Piaget and others (e. g., Inhelder & Piaget, 1958) assumed that only children around 7-8 years and older perform correctly on TI tasks, younger children (Bryant & Trabasso, 1971; Riley and Trabasso, 1974) have been reported to show TI if given extensive training on premise pairs over multiple days. Bryant and Trabasso (1971) demonstrated that with extensive training of the premises, and testing for memory of the premises to eliminate the possibility of memory-mediated failures, children as young as 4.5 years performed above chance on a subsequent TI test. Bryant and Trabasso concluded that failure in TI tasks can be due to limitations in working memory rather than to cognitive deficits.

Given these comparative and developmental results, we reasoned that the late emergence of transitive inference in children may well be due to limited processing capacity, constraining not only the retention of learned elements and relations, but also constraining construction of a spatial representation based on mapping learned conceptual relations to advantageously explicit spatial relations.

Experiment 1

Experiment 1 was similar to Roberts and Phelps (1994) but differed in several respects. Instead of olfactory stimuli, containers in different colors were used, based on the assumption that for humans, color provides a better identity cue than scent, and stickers rather than food pellets were used as rewards. Because pilot training using six stimuli showed that it was extremely difficult for the children to learn all five premises to an acceptable criterion, only five stimuli (A, B, C, D, E) were used, and thus children were exposed to four reward/no-reward premise pairs during learning (each adjacent pair). Like Roberts and Phelps, we used a comparison of B and D as the TI test pair following learning.

Reinforcement during testing trials also differed from Roberts and Phelps (1994). When participants made a mistake, they were allowed to check if the reward was in the other container, but they were not given the reward. We used this procedure to maintain children's motivation to learn which element of a pair contained the reward.

Method

Participants. The participants were 62 first graders (mean age: 6.9; range: 6-8 years) recruited from grade schools in Munich, Germany. Half of the children were randomly assigned to the linear condition and half to the random condition. In the linear condition, two children did not reach criterion, in the random condition, 13 children did not reach criterion. After excluding the data of children who did not reach criterion, the data of 47 children were analyzed.

Apparatus, Procedure and Design. The experimenter brought each child individually to the experimental room (Figure 1). For the training procedure, a 1.5 m long white board with five black cardboard "cups" on it was put on the floor. Two red x's on the floor on two opposite sides of the board marked the points from which the child was asked to start searching.

Five corrugated cardboard containers each 18 cm in diameter in red, yellow, blue, green, purple with lids (diameter 21 cm) in the same colors were used. Each lid had a black plastic handle on it and could comfortably be placed on and removed from the container. For each trial, two containers were placed onto adjacent locations on the training board, and one of these two contained a reward, a small sticker. Thus, two containers at a time formed the following premises: A+ B-, B+ C-, C+ D-, D+ E- ("+" means that that the choice was rewarded with a sticker, "-" means that the container was empty). The child was instructed that a sticker was inside of one of the two containers, and that the purpose of the game was to look for the sticker. If the sticker was in the first container opened, the child could keep it. If it was not, the child should look in the other container to find the sticker, but could not keep it. Lifting up the lids of both containers ensured that the child saw the actual location of the sticker on every trial.

At the beginning of each trial, the child was asked to stand at one end of the board, marked with a red x. Once the child stood on the x, the experimenter signaled the child to begin searching. The side of the board from which search began was alternated from trial to trial, to encourage an exocentric spatial representation of the experimental set-up and to prevent children in the linear condition from using a simple rule such as "Choose the object on the left side."

The entire procedure consisted of three phases: initial training for each of the four adjacent pairs (36 trials), a criterion phase (between 8 and 24 trials), and finally a BD test. Children in both conditions first learned pair A+B-, then B+C-, and so on, in that order. The training procedure was adapted from the method used by Gillan (1981). In the first training block the child was exposed to the stimulus pair A+ B- four times in a row. In the second block, B+ C- was presented four times. The third block consisted of presenting both A+ B- and B+ C- in irregular order, four times each, for a total of 8 trials. The remaining stimuli pairs were introduced in the same manner by first presenting an individual pair four times each and then combining that pair with previously presented pairs in a random order. After 36 trials all premises had been introduced and the criterion phase followed. The criterion was set to be three correct choices out of four (random combination of all the four premises) twice in a row, from a minimum of 8 trials and a maximum of 24 trials. Altogether the learning phase (initial pair training plus criterion phase) thus consisted of a minimum of 44 trials and a maximum of 80 trials.

In the linear arrangement group, during the training phase the containers were placed in a linear spatial sequence, for example, A was always placed on position 1 of the board (see Figure 1), B was always on position 2, etc. For the random arrangement group, the positions of the containers changed randomly between trials, for example, in one trial A was on position 4, and B on position 5. In a different trial, A was on position 3, and B was on 2, etc. Thus, for the random arrangement group, no position nor relative position could be associated with a certain color, nor with reward or no reward. For the BD-test, the long board was removed and a short board (0.60 m) with two black cups was used. Red tape was placed on one side of the training board to indicate the point from where the child would start searching on the BD-test (see Figure 2).

The B+ D- pair was then placed on the test board. The position of B and D was manipulated, so that for half of the children B was on the door side, whereas for the other half of the children B was on the window side of the board (see Figure 2). This meant that for children in the linear condition, the alignment of BD was either consistent with training or reversed from training. This manipulation allowed us to test whether children used spatial alignment as an inference cue. Then the child was asked to start searching by uncovering the containers. The BD-test was administered once per child.

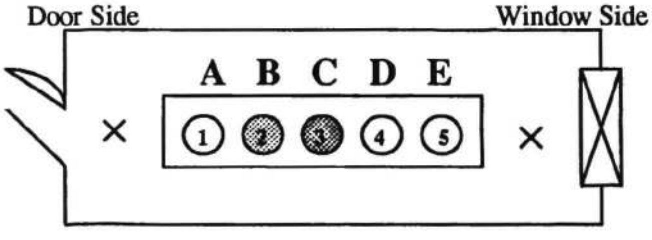

Figure 1: Experimental set-up for training period.

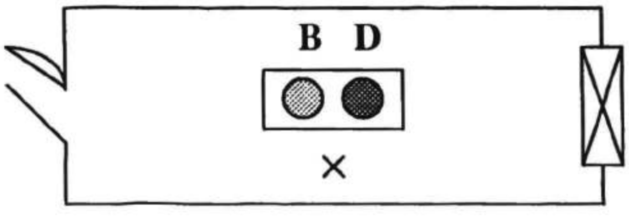

Figure 2: Experimental set-up for BD-test

Results and Discussion

Table 1 displays the participants' correct choices of B on the BD-test. Although both groups performed equally well in terms of the total percent of B choices (50% for the linear arrangement group, 52% for the random arrangement group), it's important to note that performance on the BD test strongly interacted with BD alignment. BD alignment was a crucial factor in test performance, but only for the linear condition: when the order of presentation on the test was consistent with the order of presentation during the training period, participants chose B 92% of the time, compared to 8% when the order of presentation was reversed, χ^2 (1, N = 24) = 13.50, p <.001. Within the linear group, binomial probabilities showed that performance in the consistent group was significantly above chance (p = .003), whereas for the reversed order, it was significantly below chance (p = .999).

A separate χ^2 was calculated comparing the two test positions of B for the random arrangement group, and, as expected, no difference was found, χ^2 (1, N = 23) = 1.07, p > .2. Obviously, for this group, varying the alignment of the test pair was not a meaningful factor.

Table 1: Number of correct choices on the BD-test.

BD alignment on test compared to alignment on training	Arrangement condition	
	Linear	Random
Consistent	11[a]	8[a]
Reversed	1[a]	4[b]
total	12	12

Note: [a] number of correct choices out of 12 trials.
[b] number of correct choices out of 11 trials.

Experiment 1 showed that providing children with a linear organization of reward/no-reward relations indeed facilitated performance on a subsequent test of a non-trained pair -- as long as the spatial relations present during training were maintained during test. Children who had been presented reward/no-reward pairs in a linear organization clearly used that organization as the basis of their choice on the BD test. When BD alignment was consistent with training, children in the linear condition chose B, and when BD alignment was reversed from training, children in the linear condition chose D, thus demonstrating their capability to abstract and utilize a spatial cue as the basis of transitive choice, even from an extremely short training period. In contrast, the BD choices of children who had been presented reward/no-reward pairs in a random organization were not affected by spatial position at test.

While verifying the utility of spatial organization for transitive choice, these results also demonstrate that the spatial cue influenced children's choices more strongly than any other cue, including the identity cue of color. In this experiment, children's overriding use of the spatial cue was resourceful: for children in the linear condition, spatial organization was a 100% predictor of reward during training - the rewarded item was always the item closer to the door (see Figure 1) - whereas color was a 50% predictor. Most of the time, successful TI performance requires the utilization of both an identity cue (in this case color) and relational cues (in this case linear organization as well reward/no-reward). We wondered whether children in the linear condition were also learning identity information, but revealed only knowledge of the spatial relational cue because that cue was still present at test.

For this reason, a second experiment was conducted to dissociate the spatial organization of learning from the spatial organization of testing. In Experiment 2 it became crucial for participants to recall and integrate the premises from the learning set, since mapping on an external spatial array was not possible.

Experiment 2

Although Experiment 1 demonstrated that children who learned relations in a linear organization did use the spatial cue of relative position to make a choice about a non-exposed pair, it did not demonstrate that those children had successfully learned the identities of the individual elements (color) or could use that knowledge on the BD-test. In Experiment 2, we tried to maximize the use of the color cue in the test phase by eliminating the spatial cue provided in the training trials. A new TI test was created by using 8 very small envelopes in the colors of the BD pair, four of each color. During the BD test, the envelopes were shaken in a clear plastic bowl, so it was obvious to the child that the location of the stimuli was completely arbitrary.

As in the first experiment, we hypothesized that children who had learned reward/no-reward pairs in a linear arrangement condition should be more successful at learning pairs and more successful on the BD test than children who learned reward/no-reward pairs in a random arrangement.

Method

Participants. 81 first graders (mean age: 7.10, range: 6-9 years) recruited from grade schools in Munich, Germany, served as participants. Half of the children were randomly assigned to the linear condition and half to the random condition. In the linear condition, 9 children did not reach criterion, in the random condition, 28 children did not reach criterion.

Apparatus, Procedure and Design. The apparatus for the training procedure in this experiment was identical to the one used for Experiment 1. The procedure of Experiment 2 was nearly identical to that of Experiment 1 with three exceptions. An equal number of criterion trials, only 8, were given to all children following the initial 36 trials in which relations between adjacent pairs of A-E were introduced. Learning thus consisted of 44 trials (11 trials for each relation) for all children in both conditions. In addition, all children were given the BD test regardless of performance on the 8 criterion trials. Finally, the BD test was changed to a test in which no spatial cues were available during testing.

The BD test did not involve the board nor the containers used in the training phase. Instead, the experimenter put 8 small sealed envelopes in the colors of the BD pair into a clear plastic bowl and moved them around. The child was told that some of the envelopes contained stickers, and was asked to choose four of the envelopes.

Results and Discussion

Learning. Children in the linear condition were significantly more likely to master criterion (three correct choices out of four trials, twice in a row), χ^2 (1, N = 81) =26.87, $p < .001$. In the linear arrangement group, 80.43% reached criterion, compared to 20.00% in the random arrangement group.

BD Test. Table 2 shows the frequencies of responses on the BD-test for all children, regardless of criterion. Both groups show about the same proportion of chance responses (.61 for the linear arrangement group, .60 for the random arrangement group), and therefore, the rest of our analyses concentrate on differences in unequal B and D responses. Based on binomial probabilities, the linear arrangement group shows a significantly higher proportion of three or more B responses (p = .004), compared to a non-significant proportion for the random arrangement group (p = .090). Furthermore, the two groups differed significantly in the proportions of people who had three or more B choices, depending on whether training performance was above or below criterion, z (N = 25) = 2.96, p = .003 (see Table 3).

Table 2: Number of responses on BD-test

	Arrangement condition	
	Linear	Random
More B	15	10
Equal B/D	28	21
More D	3	4
total	46	35

Table 3: Number of participants with three or more correct choices

Training level	Arrangement condition	
	Linear	Random
Above criterion	12	2
Below criterion	3	8
total	15	10

The results suggest that the two different ways of presenting the premises, linear vs. random arrangement, lead to different performance in learning the premises as well as in succeeding on the TI test. Without separating out participants in terms of reached criterion, participants in the linear arrangement condition chose consistently more often the correct stimulus. Although participants in the random arrangement condition also chose somewhat more often B over D, when factoring in learning of the premises to criterion, the results are even more clearly in favor of our hypothesis. Out of all subjects in the random arrangement group who performed above chance on the BD-test, only a few (20.00 %) had mastered the criterion in the training trials. The opposite was the case for the linear arrangement group: Most of the children (80.00 %) who had performed up to criterion also performed above chance on the TI test. In other words, arrangement of premises during training mediated learning, as well as retrieval of the premises.

As with Experiment 1, the results of Experiment 2 demonstrate that learning pairwise relations from a linear organization indeed facilitated performance on a subsequent test of a non-trained pair. Furthermore, whereas test performance in Experiment 1 depended on maintaining during test the spatial relations present during training, in Experiment 2, the benefit of learning pairs with a spatial organization was demonstrated in a new spatial context. The more frequent B choices made by children in the linear condition indicate that when given the BD test, children recalled the linear array acquired during training and used the relationship of BD in that memorial array as the basis of their choice on the BD test.

Altogether, by eliminating spatial cues during the TI test trials, Experiment 2 supports the hypothesis that when using explicit spatial coding strategies in order to integrate premise information, the resulting spatial representation also facilitates inferences in a non-spatial context.

General Discussion

The results of the two experiments presented in this paper strongly support the hypothesis that providing children with linear spatial structure facilitates the process of mapping conceptual relations onto spatial relations, and thus, facilitates visual reasoning.

Children utilized space to represent relational information, as well as identity information of given elements. In our example, the spatial arrangement helped encoding the linear organization, as well as the color cue of the premises. However, the two components of the spatial representation were not equally powerful: As shown in the first experiment, when present in both learning and recalling of the premises, the spatial cue of the linear organization dominated over other aspects, such as color, of the premises.

DeSoto et al. (1965) had suggested that a linear order is a "good figure", and our results corroborate this view. The linear arrangement is the most parsimonious representation for overlapping ordered relations in two respects: First, when integrating premises, the shortest possible line connecting two or more elements is always a straight line. Second, when making inferences about the premises, no additional models have to be created: The conclusion can simply be "read off" one spatial model which contains all necessary information, similar to the model theory proposed by Glenberg and Langston (1992). Thus it seems very likely that one of the systematic rules of mapping concepts onto space is that a linear array is being preferred over other arrangement of elements. In addition, linear arrangement may provide the most essential information when making inferences, as found in the first experiment.

If reading off the conclusion for a TI problem by means of a spatial structure is such an effortless process as we suggest here, why do young children often not succeed in doing so, whereas even animals seem to be able to make transitive inferences? The problem seems not to lie within the inference process, but in constructing a linear representation in the first place. Young children's limited cognitive capacity may constrain recall of the relations among premises, as well as the construction of spatial models, and the two may well be causally related: perhaps children cannot remember multiple premises *because* they are not yet able to construct a linear spatial representation. Providing children with an external spatial organization should therefore circumvent the difficulties in constructing an internal model, and that is precisely what we found in two experiments. Remarkably, once an internal spatial representation has been constructed, it needs not be present during the TI test phase, since the children in our second experiment were successful on a TI task in a new spatial context. Our explanation for the late emergence of transitive inference is also consistent with computational models of reasoning which suggest that an important constraint on reasoning is computational capacity, not simply for remembering relations, but more importantly for combining relations (Hummel & Holyoak, 1997). The same explanation for successful TI performance may hold for Roberts and Phelps (1994) and other comparative studies: Presenting an external spatial representation facilitates the construction and utilization of an internal spatial model. Given our results, a common coding strategy for both humans and animals is indeed very conceivable, and most likely, this strategy is based on spatial models.

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