Research Article

STRUCTURAL ALIGNMENT IN COMPARISON: No Difference Without Similarity

Dedre Gentner and Arthur B. Markman
Northwestern University

Abstract-*Theories of similarity generally agree that the similarity of a pair increases with its commonalities and decreases with its differences. Recent research suggests that this comparison process involves an alignment of structured representations yielding commonalities, differences related to the commonalities, and differences unrelated to the commonalities. One counterintuitive prediction of this view is that it should be easier to find the differences between pairs of similar items than to find the differences between pairs of dissimilar items. This prediction is particularly strong for differences that are related to the commonalities. We tested this prediction in two experiments in which subjects listed a single difference for each of a number of word pairs. The results are consistent with the predictions of structural alignment. In light of these findings, we discuss the potential role of structural alignment in other cognitive processes that involve comparisons.*

The process of determining the similarity of a pair of items is central to diverse mental processes, including categorization (Smith & Medin, 1981), problem solving (Novick, 1990; Ross, 1987), and affect (Kahneman & Miller, 1986). The general consensus of research on similarity is that a pair's similarity increases with its commonalities and decreases with its differences (Tversky, 1977). Much recent research extends this general point by suggesting that similarity comparisons involve a process of *structural alignment* akin to the comparison process involved in analogy (Gentner & Markman, in press; Goldstone, Medin, & Gentner, 1991; Markman & Gentner, 1993a, 1993b; Medin, Goldstone, & Gentner, 1993). This view assumes that mental representations consist of hierarchical systems that encode objects, attributes of objects, relations between objects, and relations between relations. These structured representations may encode information about perceptual as well as conceptual relations. For example, the configurations in Figure la could be represented by the structural representations depicted in Figure lb.

As in the structure-mapping theory of analogy (Gentner, 1983), we assume that the process of comparison is one of structural alignment between two mental representations to find the maximal *structurally consistent* match between them. A structurally consistent match is one that satisfies the constraints of *parallel connectivity* and *one-to-one mapping* (Falkenhainer, Forbus, & Gentner, 1989; Gentner, 1983, 1989; Holyoak & Thagard, 1989; Keane, 1988; Markman & Gentner, 1993b; Medin, Goldstone, & Gentner, 1990, 1993). Parallel connectivity says that if two predicates are matched, then their arguments must also match. For example, if the "above" relations in the configurations in Figure 1 are matched, then the two items on top must be placed in correspondence (the striped circle with the striped square), and likewise the two items on the bottom must be placed in correspondence (the checked square with the checked circle). One-to-one mapping requires that each element in one representation correspond to at most one element in the other representation. Thus, in Figure 1, the circle in the left-hand configuration could not be placed in correspondence simultaneously with both the circle and the square in the right-hand configuration. As this example illustrates, in many cases more than one structurally consistent interpretation is possible for a given comparison. Here, on one interpretation, the commonality is that both configurations contain circles. On another interpretation, the commonality is that both have something above something else.

According to the *systematicity principle* (Gentner, 1983, 1989), when there are multiple interpretations of a pair, all else being equal, the one that preserves the maximal (i.e., largest and deepest) connected relational structure is preferred (Forbus & Gentner, 1989; Gentner & Landers, 1985; Gentner, Rattermann, & Forbus, 1993). This interpretation can then be used to calculate a similarity rating for the items or to subserve some other cognitive process that requires a comparison.

On this account, the commonalities and differences of a pair are determined relative to an interpretation (Falkenhainer et al., 1989; Markman & Gentner, 1993a; Medin et al., 1993). The commonalities are simply the elements of the matching representational structure. For example, the best interpretation of the comparison in Figure 1 might involve placing the "above" relations in correspondence, making that relation a commonality. The differences are separated into two types: those related to the common structure (called *alignable differences)* and those not related to the common structure (called *nonalignable differences).* For example, on this interpretation, the fact that the circle is on top in one configuration while the square is on top in the other is an alignable difference, because the circle and square are nonidentical elements placed in correspondence by virtue of their like roles in matching structures. In contrast, the triangle in the left-hand configuration is a nonalignable difference, because it does not correspond to anything in the right-hand configuration. To put it another way, alignable differences arise from and are connected to the common structure, whereas nonalignable differences are independent of the common structure.

This proposal is related to previous suggestions that similarity focuses primarily on the commonalities of a pair (Krumhansl, 1978; Sjoberg, 1972). Our proposal goes beyond this idea in suggesting that not only are commonalities central, but even

Address correspondence to Dedre Gentner, Northwestern University, Department of Psychology, 2029 Sheridan Rd., Evanston, IL 60208.

the differences that are considered are those related to the commonalities (i.e., the alignable differences). In other studies, we provided evidence for this view by asking subjects to list the commonalities and differences of word pairs (Markman & Gentner, 1993a). We found that subjects could list more commonalities for similar pairs of words than for dissimilar pairs. However, the reverse did not hold: Subjects did not list more differences for dissimilar pairs than for similar pairs. Instead, as we would expect if commonalities and alignable differences are deeply related, subjects listed more alignable differences for similar pairs than for dissimilar pairs and more nonalignable differences for dissimilar pairs than for similar pairs. The total number of differences was roughly consistent across similarity. Further sorting tasks revealed conceptual relationships between the commonalities and the alignable differences, but not between the commonalities and the nonalignable differences, bearing out the claim that alignable differences are related to commonalities but nonalignable differences are not. Indeed, the number of commonalities was positively correlated with the number of alignable differences, but not with the number of nonalignable differences. Finally, there was evidence that alignable differences are considered more important than nonalignable differences in that subjects listed more alignable differences than nonalignable differences overall.

The idea that alignable differences are more salient in the comparison process than are nonalignable differences has one startling implication. Because there are more commonalities for similar pairs than for dissimilar pairs, there should also be more alignable differences for similar pairs than for dissimilar pairs. Thus, if, as suggested by the previous findings, subjects find it easier to report commonalities for high-similarity pairs than for low-similarity pairs, then they should generally be able to find differences (at least alignable differences) more easily for similar pairs than for dissimilar pairs.

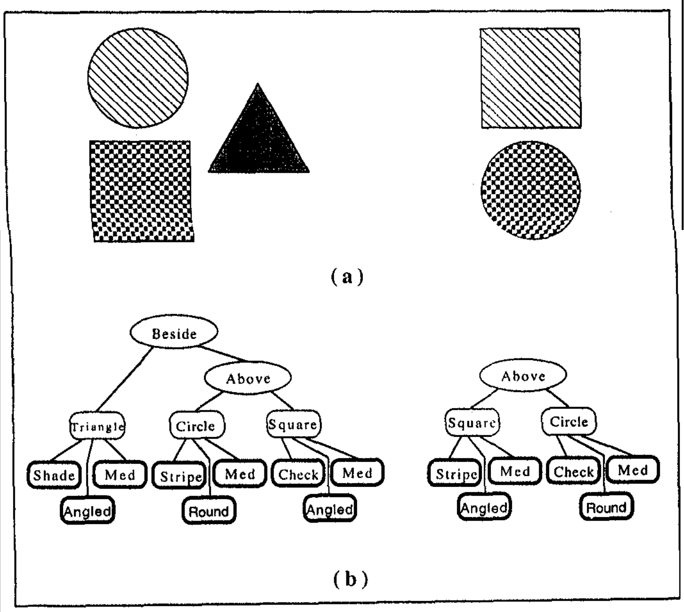

Fig. 1. Illustration of the role of alignment in comparison. The geometric configurations (a) can be encoded by the structured representations in (b). In these structured representations, ovals denote relations, rounded boxes denote objects, and bold rounded boxes denote attributes. "Med" denotes "medium sized."

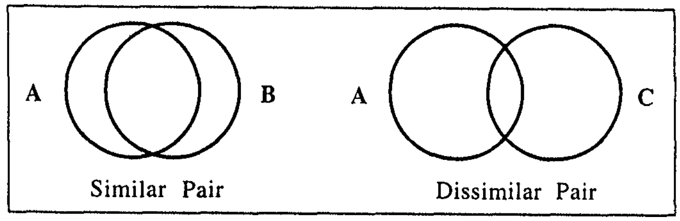

Fig. 2. Venn diagrams illustrating the comparison of a similar pair and a dissimilar pair.

The idea that differences are easier to find for similar pairs than for dissimilar pairs runs against the plausible intuition that differences should be easier to find the more different the pair. We schematize this intuition in Figure 2, borrowed from Tversky (1977). The objects' representations are the sets of properties represented by the circles, and the match between representations corresponds to the overlap of the sets. This diagram suggests that all objects are represented in equal detail and that there should be more differences for dissimilar pairs than for similar pairs provided that the commonalities and differences are independent of one another. Thus, differences should be easier to find for dissimilar pairs than for similar pairs.[1]

The two studies we present here examine the claim that subjects should find differences more easily for pairs of similar items than for pairs of dissimilar items. In the first experiment, subjects saw 40 word pairs on a sheet of paper and were told to write one difference for as many different pairs as they could. They were told that they would not have enough time to respond to all of the pairs, so they should try to do the easy pairs first. Half the pairs were of high similarity and half were of low similarity (based on intuitions that were confirmed by subjects' similarity ratings).

The predictions are straightforward, though counterintuitive. If similarity comparisons involve structural alignment, then subjects should list more differences (and particularly more alignable differences) for similar pairs than for dissimilar pairs.

EXPERIMENT 1

Method

Subjects

The subjects in the difference listing task were 32 undergraduate students from Northwestern University who received course credit in introductory psychology for their participation. The subjects in the similarity rating task were 40 undergraduate students from the same population.

1. Such an independent-features account is consistent with,, but not mandated by, Tversky's (1977) contrast model.

Materials

The same 80 words were used to create two stimulus sets. In each set, there were 20 similar pairs and 20 dissimilar pairs. The second stimulus set was created from the first by re-pairing high-similarity pairs to form low-similarity pairs and low-similarity pairs to form high-similarity pairs. High- and low-similarity pairs were generated initially by the experimenters' intuitions. Similarity ratings obtained from independent subjects yielded a mean similarity of 7.00 for the high-similarity pairs and 1.67 for the low-similarity pairs (on a 9-point scale). The complete set of stimuli is presented in the appendix. The 40 word pairs in a set were ordered randomly in two columns on a single page. Four different orders were made for each stimulus set.

Procedure

Subjects were told that they would see 40 word pairs on a page, and that they should list one difference for as many different pairs as they could. They were informed that they would have only 5 min to perform this task. They were warned that 5 min was not enough time to list one difference for every pair, so they should do the "easiest" pairs first. Subjects were run in small groups, and the experimenter timed the experiment with a watch.

Scoring

The criterion used to separate alignable differences from nonalignable differences was a modified version of the technique we have described elsewhere (Markman & Gentner, 1993a). A listed difference was counted as an alignable difference if (a) the subject mentioned contrasting properties of the two items (e.g., "A hotel is expensive; a motel is cheap") or (b) the subject used an explicit comparative construction (e.g., "A hotel is more expensive than a motel"). All other differences were considered nonalignable differences, including simple negation of one item's property as applied to the other (e.g., "You read a magazine, but you do not read a kitten"). The only exception to this rule was that a difference counted as an alignable difference if the two raters agreed that people generally represent the absence of a property explicitly for a given object (e.g., a convertible is specifically a car that does not have a roof). Properties of the words themselves (e.g., "One begins with an h, the other with an *m*") were not counted. Each difference was scored as either alignable or nonalignable. Two different raters each scored the entire data set individually. The initial scorings showed 97% agreement, and all discrepancies were resolved by discussion.

Design

There were two levels of similarity (low, high) run within subjects. The two stimulus sets were presented to different groups of subjects (16 subjects per set) in four different orders (4 subjects per order). For each subject and each item, the total number of differences listed was determined, as were the numbers of alignable and nonalignable differences listed.

Results and Discussion

Number of differences listed

The results are presented in Table 1. Repeated measures analyses of variance (ANOVAs) with the number of differences listed by each subject as a within-subjects factor and the stimulus set as a between-subjects factor were performed for the total number of differences, the number of alignable differences, and the number of nonalignable differences listed by each subject. Because none of the analyses showed main effects or interactions of stimulus set (all $Fs < 1$), we do not consider this factor further.

As predicted by the structural alignment view, subjects listed differences for more high-similarity pairs (M = 11.44) than low-similarity pairs (M = 5.88), $F(1, 30) = 31.88$, $p < .001$. Subjects, then, apparently found it considerably easier to list differences for high-similarity pairs than for low-similarity pairs. Also consistent with the structural alignment position, this difference was specifically concentrated in the number of alignable differences listed: Subjects listed significantly more alignable differences for the high-similarity pairs (M = 8.97) than for the low-similarity pairs (M = 3.88), $F(1, 30) = 31.37$, $p < .001$. In contrast, no significant difference was found for the number of nonalignable differences listed for the high-similarity (M = 2.47) versus low-similarity (M = 2.00) pairs, $F(1, 30) = 1.39$, $p > .10$. Taken together, these findings are consistent with the view that comparison-even for the purpose of finding differences-is accomplished via an alignment process.

Table 1. *Mean number of differences listed for high- and low-similarity items in Experiments 1 and 2*

	Alignable differences		Nonalignable differences		Total	
Experiment	Low similarity	High similarity	Low similarity	High similarity	Low similarity	High similarity
1	3.88	8.97**	2.00	2.47	5.88	11.44**
2	11.54	15.63*	2.25	2.79	13.79	18.42*

* $p < .05$ by t test. ** $p < .001$ by t test.

Kinds of differences

A possible concern here is that, rather than carrying out structural alignment, subjects may simply have developed some simple algorithm for listing differences that happened to be easier to do for high-similarity pairs than for low-similarity pairs. For example, subjects might have consistently listed differences along a particular dimension. Such a method might be easier to apply to the high-similarity pairs because the probability of their sharing any given dimension is high. This explanation predicts a narrower range of differences for the high-similarity pairs than for the low-similarity pairs. To evaluate this possibility, we examined the types of differences that were listed. Table 2 presents the kinds of differences that make up at least 4% of the differences listed for high- and low-similarity pairs. The results show that a considerably wider range of differences was available for the similar pairs than for the dissimilar pairs. The four most frequent types of differences listed for low-similarity pairs account for 76% of the differences listed, while the seven most frequently listed differences for high-similarity pairs account for only 62% of the differences listed. Thus, it does not appear that subjects adopted a narrow strategy that favored the high-similarity pairs.

The fact that a wider range of differences was available for similar pairs than for dissimilar pairs is consistent with the structural alignment tenet that perceived commonalities and differences are intimately related. On this view, similar items, which have much common structure, have more points of partial overlap that can give rise to associated differences. Furthermore, the differences for similar pairs are likely to be specific and variable because there are many points of partial overlap to choose from (e.g., power source and temperature). In contrast, for the dissimilar pairs, there are fewer points of overlap, and thus a few general dimensions, such as function and category type, gave rise to most of the listed differences.

An alternative account of the data

These results suggest that differences are found more easily for similar pairs than for dissimilar pairs. However, it is possible that subjects responded more often to the high-similarity pairs than to the low-similarity pairs simply because the high-similarity pairs were more salient. In this case, the greater number and variety of differences listed for high-similarity pairs would simply reflect greater attention to these pairs, not greater ease of computing differences for them. To check this possibility, we repeated the methodology of Experiment I with pair similarity as a between-subjects factor. Thus, in Experiment 2, half of the subjects received only high-similarity pairs, while the other half received only low-similarity pairs. On the structural alignment view, subjects presented with high-similarity pairs should list more differences (specifically, alignable differences) than subjects presented with low-similarity pairs. If the advantage for high-similarity pairs in Experiment 1 reflected neglect of the low-similarity pairs, the effect should disappear or be reversed in this between-subjects version.

EXPERIMENT 2

Method

Subjects

Subjects were 49 undergraduate students at Northwestern University. One subject was dropped from this study for listing commonalities instead of differences, leaving 48 subjects (24 per condition).

Materials

The same word pairs were used as in Experiment 1. In this study, the 40 high-similarity word pairs were placed in two columns on one sheet. The 40 low-similarity word pairs were also placed on one sheet. Four different orders were created for each set.

Procedure and scoring

The procedure and scoring for this study were the same as for Experiment 1. The initial scorings showed 98% agreement, and all discrepancies in scoring were resolved by discussion.

Design

Two levels of similarity (low and high) were varied between subjects. There were four stimulus orders for each level of sim-

Table 2. *Types of differences accounting for at least 4% of the total in Experiment I*

Low-similarity pairs		High-similarity pairs	
Type	Percentage	Type	Percentage
Function	42	Parts	18
Category	23	Function	17
Parts	6	Size	8
Material	5	Location	6
		Power source	5
		Age	4
		Temperature	4
Total	76	Total	62

Table 3. Types of differences accounting for at least 4% of the total in Experiment 2

Low-similarity pairs		High-similarity pairs	
Type	Percentage	Type	Percentage
Function	54	Parts	17
Category	20	Function	12
		Size	11
		Power source	7
		Temperature	5
		Age	4
		Complexity	4
		Location	4
Total	74	Total	64

ilarity. The numbers of alignable differences and nonalignable differences were counted as in Experiment 1.

Results and Discussion

Number of differences listed

As shown in Table 1, the results of this study resembled those of Experiment 1. More differences were listed for the high-similarity pairs ($M = 18.42$) than for the low-similarity pairs ($M = 13.79$), $t(46) = 2.69$, $p < .01$. Also as in Experiment 1, this difference stems chiefly from the greater number of alignable differences listed for high-similarity pairs ($M = 15.63$) than for low-similarity pairs ($M = 11.54$), $t(46) = 2.06$, $p < .05$. Once again, the number of nonalignable differences listed did not differ significantly between groups ($M = 2.79$ for the high-similarity pairs, $M = 2.25$ for the low-similarity pairs), t(46) -- 0.47, $p > .10$. These data rule out the possibility that the results of Experiment 1 can be attributed to subjects' selection of salient pairs. These results provide additional support for the prediction that differences are found more easily when the pairs are easy to align than when they are hard to align.

Kinds of differences

As before, we analyzed the content of the difference listings. Table 3 presents the types of differences accounting for 4% or more of the total for high- and low-similarity pairs. This analysis parallels the content analysis for Experiment 1. Once again, many fewer categories are required to account for the differences listed for the low-similarity pairs than to account for the differences listed for the high-similarity pairs. As in Experiment 1, it appears that subjects had a greater variety of differences to choose from for high-similarity pairs than for low-similarity pairs.

GENERAL DISCUSSION

Taken together, these studies provide strong support for the claim that similarity comparisons highlight differences related to the common structure. Subjects were able to find differences for similar pairs more easily than for dissimilar pairs, even though virtually any property of the items in the dissimilar pairs was probably a difference. These rather striking results bear out the claim that the natural way of making comparisons favors alignable differences and add support to the view that the process of similarity comparison is one of structural alignment.' This finding lends further support to our proposed taxonomy of commonalities, alignable differences, and nonalignable differences (Markman & Gentner, 1993a).

The content analyses help to emphasize the flexibility of comparison. For dissimilar pairs, the comparison makes only a few general types of differences easily available (i.e., those of function, parts, category, and material). In contrast, a wide range of differences was listed for high-similarity pairs. Thus, a number of commonalities and differences are made available for similar pairs, which are likely to be important to other cognitive processes. Further, these differences often reflect specific properties of items. These results are consistent with Goldstone and Medin's (in press) finding that in picture comparison, people are more sensitive to mismatches between features of highly alignable pairs than to mismatches between features of pairs that are difficult to align.

The results obtained here suggest that commonalities and differences are fundamentally related. There is some evidence suggesting that commonalities and differences are seen as linked early in development. Webb, Oliveri, and O'Keeffe (1974) found that young children who were asked to select objects that were different from each other often selected similar, or even identical, objects. Even older children selected similar objects, although they selected identical objects less often than younger children. In other work, Karmiloff-Smith (1990) asked children to draw pictures of people that "do not exist." Like medieval monks drawing demons, these children tended to draw figures with many commonalities with and a few alignable differences from real people (e.g., a person with two heads, three legs, and .ix arms). Thus, the range of allowable "non-

2. We leave open the possibility that there are instructions that would lead subjects to find differences more easily for dissimilar pairs than for similar pairs.

people" seems to be constrained by the addition of alignable differences rather than by the addition of nonalignable differences. Taken together, these findings suggest that children act as if similarity and difference are intimately relate,!.

We believe that the notion of structural alignment and the connection between commonalities and differences can illuminate the study of other psychological processes as well. For example, in decision making, Tversky's (1972) elimination-by-aspects model postulates that when deciding between multiple alternatives, people first find' a relevant aspect (e.g., dimension or property) of the choices and then eliminate all alternatives that do not have a satisfactory value for that aspect. If more than one item remains, another aspect is selected, and the process repeats. In this model, the decision process utilizes alignable differences among alternatives.

In other work, Slovic and MacPhillamy (1974) presented subjects with test scores of pairs of students. One score came from a test taken by both students, and the second came from two different tests, each taken by only one of the students. Subjects consistently gave more weight to the scores on the test that both students had taken. This finding may be interpreted as evidence that subjects found alignable differences (different scores on the same test) more relevant to the choice task than nonalignable differences (different scores on different tests). Similarly, Tversky and Kahneman (1986) varied the ease with which the dimensions of choices could be aligned and found that subjects' decisions were more likely to stray from optimality when the dimensions of the choices were hard to align than when they were easy to align. Such findings suggest that the ability to make decisions that appear rational may depend in part on people's ability to align the aspects of the choices appropriately.

CONCLUSIONS

Recent evidence suggests 'that the process that determines similarity may be profitably characterized as alignment and mapping between structured representations. The present studies extend previous findings by suggesting that the determination of correspondences between representations is a vital part of comparison, even in tasks that call for finding the mismatches between representations. Thus, commonalities and alignable differences are crucial components of similarity. Further work must examine the role of alignable differences in other cognitive processes that involve comparisons.

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APPENDIX

Table AI. High- and low-similarity word pairs used in Experiments I and 2

Similar pairs		Dissimilar pairs	
Light bulb	Candle	VCR	Lounge chair
Kitten	Cat	Hammock	Horse track
Magazine	Newspaper	Bed	Hockey
Bowl	Mug	Football	Boutique
Phone book	Dictionary	Kite	Painting
Microphone	Stereo speaker	Sculpture	Navy
Piano	Organ	Army	Abacus
Air conditioner	Furnace	Calculator	Escalator
Freezer	Refrigerator	Stairs	Stool
Hammer	Mallet	Broom	Sailboat
Bicycle	Tricycle	Yacht	Missile
Dumpster	Garbage can	Chair	Banana split
Lake	Ocean	Ice cream sundae	Clock
Telephone	CB radio	McDonald's	Couch
Diamond	Ruby	Police car	Burger King
Sponge	Towel	Rocket	Motel
Computer	Typewriter	Hotel	Tape deck
Staple	Paper clip	Watch	Ambulance
Shoe	Sandal	Casino	Mop
Chemistry	Biology	Stove	Hang glider
VCR	Tape deck	Light bulb	Cat
Hammock	Lounge chair	Kitten	Newspaper
Bed	Couch	Magazine	Mug
Casino	Horse track	Bowl	Dictionary
Police car	Ambulance	Phone book	Stereo speaker
Football	Hockey	Microphone	Organ
Store	Boutique	Piano	Furnace
Kite	Hang glider	Air conditioner	Mallet
Sculpture	Painting	Hammer	Tricycle
Army	Navy	Bicycle	Refrigerator
Calculator	Abacus	Freezer	Ocean
Stairs	Escalator	Lake	Garbage can
Broom	Mop	Dumpster	CB radio
Yacht	Sailboat	Telephone	Ruby
Chair	Stool	Diamond	Towel
Rocket	Missile	Sponge	Typewriter
Hotel	Motel	Computer	Sandal
Ice cream sundae	Banana split	Shoe	Paper clip
McDonald's	Burger King	Staple	Biology
Watch	Clock	Chemistry	Candle