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Splitting the Differences: A Structural Alignment View of Similarity

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The similarity of a pair increases with its commonalities and decreases with its differences (Tversky, 1977, *Psychological Review*, 79(4), 281–299). This research addresses how the commonalities and differences of a pair are determined. We propose that comparisons are carried out by an alignment of conceptual structures. This view suggests that beyond the commonality–difference distinction, there is a further distinction between differences related to the common structure (alignable differences), and differences unrelated to the common structure (nonalignable differences). In two experiments, subjects were asked to list commonalities and differences of word pairs and/or to rate the similarity of these pairs. Three predictions for this task follow from the structural alignment view: (1) pairs with many commonalities should also have many alignable differences, (2) commonalities and alignable differences should tend to be conceptually related, and (3) alignable differences should outnumber nonalignable differences. The data support the structural alignment proposal. The implications of these findings for theories of similarity and of cognitive processes that involve similarity are discussed.

Similarity is a vital part of cognitive processing. Models of categorization (Medin & Schaffer, 1978; Rosch & Mervis, 1975; Smith & Medin, 1981), skill acquisition (Singley & Anderson, 1989; Thorndike & Woodworth, 1901), transfer (Logan, 1988), and affect (Kahneman & Miller, 1986) assume that new items are processed based on their similarity to previous experiences. Because of this centrality, similarity itself has been the focus of extensive research.

Much current research in similarity has its roots in Tversky's seminal *contrast model* (Tversky, 1977). The contrast model formalized the fundamental insight that the psychological similarity of a pair of objects increases with its commonalities and decreases with its differences. However, there is no general procedure for deciding what counts as a commonality and what counts as a difference. The scenes in Fig. 1 illustrate this problem. When determining the similarity of these pictures, we could focus on the similarity between the two robot arms. Given this match, the fact that one robot arm is repairing something while the other is being repaired would be a difference. Alternatively, we could focus on the similarity that both scenes depict "repairing." In this case, the fact that the robot performs the repair in one scene while a man performs the repair in the other scene would be a difference. To model similarity, we need an account of the comparison process that arrives at the commonalities and differences between two items.

In this paper, we will outline a *structural alignment* account of similarity in which the commonalities and differences of a pair are determined via the comparison of structured representations (Gentner & Markman, in press; Goldstone, Medin, & Gentner, 1991). This approach is based on previous research in analogical reasoning that

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has focused on methods for finding correspondences between representations (Gentner, 1983, 1989; Holyoak & Thagard, 1989).

STRUCTURE IN SIMILARITY

The approach here is an extension of Gentner's (1983, 1989) structure-mapping theory of analogy. The structural alignment process takes a pair of structured representations and computes the correspondences between them by seeking the maximal *structurally consistent* match (Gentner, 1983, 1989; Falkenhainer, Forbus, & Gentner, 1986, 1989). A structurally consistent match is one that has *one-to-one correspondences* and *parallel connectivity*. One-to-one matches are those for which each element (e.g., attribute, relation or object)[1] in one representation is placed in correspondence with at most one element in the other representation. Parallel connectivity applies when the arguments of corresponding predicates can themselves be placed in correspondence. According to this view, object mappings are determined not only on the basis of their intrinsic similarities, but also on the basis of their playing similar roles in like relational structures. Finally, mappings involving coherent higher-order matches (i.e., *systematic* mappings) are preferred to correspondences involving only isolated relational matches.

For example, the match between the pictures in Fig. 1 could be organized around the relational similarity that both scenes depict something repairing something else. On this interpretation, parallel connectivity requires that the robot arm in the first scene be placed in correspondence with the man in the second scene, because both are repairing something. Likewise, the car in the first scene is placed in correspondence with the robot arm in the second scene, because they are both being repaired. Despite the perceptual similarity between the robot arms, the robot arm in the first scene cannot be placed in correspondence with *both* the man *and* the robot arm in the second scene because of the one-to-one mapping constraint.

The calculation of structurally consistent matches is a computationally viable process. For example, the Structure-Mapping Engine instantiates structural alignment with a local-to-global alignment algorithm that first matches all identical predicates (and functions) in two representations (Falkenhainer et al., 1986, 1989). This initial mapping may be inconsistent, but in the next phase these local matches are coalesced into a global structure. Structural consistency is enforced by requiring that the arguments of matching predicates also match and that each object in one representation is placed in correspondence with at most one object in the other representation. As in human comparison, this algorithm may yield more than one consistent interpretation for a pair such as the robot pictures. Forbus and Gentner (1989) discuss how competing matches may be evaluated. A local-to-global process has been incorporated into other models of comparison as well (Goldstone & Medin, in press; Hofstadter, 1984; Hofstadter & Mitchell, in press; Holyoak & Thagard, 1989).

The structurally consistent match yielded

[1] Predicates that connect two or more arguments (e.g., **repair**(x,y)) are called *relations*. For example, the central action in the top scene of Fig. 1 could be represented as **repair**(robot, car). This notation explicitly encodes the connection between the action being performed and the objects involved in the action. The arguments of a relation can be objects, as here, or other predicates. Relations taking other relations as arguments (higher-order relations) are important because they represent causal or logical connections between first-order assertions. In addition to relations, there are predicates that have only one argument. We call these predicates *attributes*, because they often describe properties of particular objects (e.g., **red**(car1)). These distinctions are psychological, not logical. For example, the same information (e.g., that car1 is red) can be represented as a relation (e.g., **color-of**(car1,red)), as an attribute (e.g., **red**(car1)), or as a *function* (e.g., **color**(car1) = red). Each of these representations captures a different psychological interpretation of a situation. The representations that we offer here are intended as typical construals.

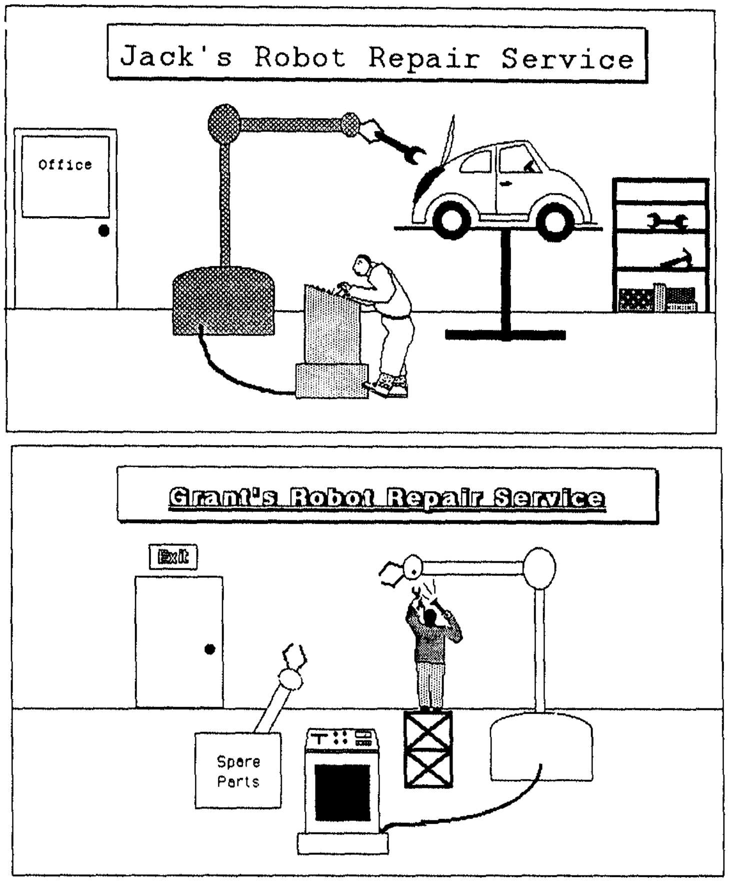

FIG. 1. Sample pair of scenes containing cross-mappings, like those used by Markman and Gentner (1990).

by the alignment process is used to determine the commonalities and differences of the pair. These comparisons give rise to three types of elements: matches, mismatches that are connected to the matching structures, and mismatches that are not related to the matching structures. For example, in the scenes in Fig. 1, the objects could be placed in correspondence based on the relational similarity of the scenes. Then, the fact that both scenes depict something *repairing* something else would be a commonality of the scenes. Furthermore, this interpretation places some dissimilar objects in correspondence. For example, in Fig. 1 the *robot* repairing the car in the top scene is mapped to the *man* repairing the car in the bottom scene. Because this difference occurs within elements connected to the common structure, we refer to it as an *alignable difference* (AD). In contrast, other differences are independent of the matching structure. For example, the box of spare parts in the bottom scene does not match any object in the top scene. We call this type of difference a *nonalignable difference* (NAD).

In the experiments that follow, we will examine four predictions of structural alignment. First, there should be a *numerical link between commonalities and alignable differences*. Because alignable differences are defined in terms of correspondences, pairs with many commonalities should also have many alignable differences and pairs with few commonalities should have few alignable differences. Second, *alignable differences should be more numerous than should be nonalignable differences*. This prediction results from the assumption that similarity comparisons focus on matching information. Third, there should be a *conceptual relationship between the commonalities and alignable differences*. This prediction is derived from the fact that links between predicates and their arguments represent conceptual connections between elements. The fourth prediction, which also follows from Tversky (1977), is that *the similarity of a pair increases with its commonalities and decreases with both its alignable and nonalignable differences*.

We can contrast these predictions with those of a feature matching view that assumes that mental representations consist of sets of independent features. On this view, commonalities are the intersection of the feature sets, and differences are those features not in the set intersection: there is no distinction between alignable and nonalignable differences. Pairs with many commonalities are predicted to have few differences, and pairs with few commonalities are predicted to have many differences. Finally, commonalities and differences are not predicted to be conceptually related.

Experiment 1

To test these predictions, we asked subjects to list commonalities and differences of 20 highly similar word pairs and 20 highly dissimilar word pairs. Subjects were given 1 min to list either as many commonalities, or as many differences (but not both) as they could for each word pair. According to the predictions of structural alignment outlined above, more commonalities and alignable differences should be listed for similar pairs than for dissimilar pairs. In addition, more alignable differences should be listed overall than should nonalignable differences. Finally, similarity (as assessed by ratings obtained from a separate group of subjects) should increase with commonalities and decrease with differences, although alignable and nonalignable differences may have different strengths of effect.

With the commonality and difference methodology we hope to tap the output of the comparison process involved in similarity ratings. Furthermore, this task allows us to see the kinds of features subjects believe to be relevant to particular comparisons, as opposed to attribute-listing tasks that only make use of properties subjects list for the items in isolation (Tversky, 1977). Thus, this methodology allows for the possibility that the features of an object that are relevant to a particular comparison may not be relevant for other comparisons in which the same object is paired with something else. These advantages have led other researchers to use a commonality and difference-listing methodology as well (Medin & Goldstone, in press; Tourangeau & Rips, 1991).

Method

Subjects. Subjects in the similarity rating task were 22 undergraduates at the University of Illinois. Subjects in the commonality and difference listing task were 32 students from the same population. All subjects were native speakers of English. They received course credit in an introductory psychology course for their participation.

Materials. The stimuli were 40 word pairs: 20 highly similar pairs and 20 highly dissimilar pairs. The experimenters generated the similar and dissimilar pairs, but their intuitions were confirmed by subjects' ratings. For the similarity rating task, two random orders of the words were generated. Beneath each word pair was a similarity scale ranging from 1 (Highly Dissimilar) to 9 (Highly Similar). There were 8 word pairs on each page.

For the commonality and difference listing task, each word pair was printed on two white index cards. At the top of one card were the words "Commonalities of" and at the top of the second card were the words

"Differences between." The word pairs are presented in Appendix 1.

Procedure. Subjects in the similarity rating task were given booklets with the similarity rating sheets. Subjects were told that they would see pairs of words and were asked to rate their similarity using the nine-point scale provided. Subjects in this task were run in small groups.

Subjects in the commonality and difference listing task were run individually at a table with a tape recorder and a stack of cards placed face down in front of them. Each subject was presented with 20 Commonalities cards and 20 Differences cards. Subjects listed commonalities for 10 High Similarity and 10 Low Similarity pairs. They also listed differences for 10 High Similarity and 10 Low Similarity pairs. Thus, it took two subjects to get a complete set of listings for the entire stimulus set. Subject to these restrictions, 8 random stimulus orders were generated.

Subjects were instructed to turn over the first card on the stack, and to list out loud either the commonalities or differences of the pair, depending on the card's instructions. There were no practice trials, as subjects were comfortable doing this task from the beginning. The experimenter timed each trial with a watch. Each trial was terminated after 1 min, or 30 s of silence, whichever came sooner. Subjects were allowed to finish an utterance if they spoke for the full minute, but then the trial was ended. A short break was given after half of the trials were completed. The entire experiment was recorded on an audio cassette tape, which was then transcribed. A session took approximately 45 min to complete.

Design. There were two levels of Similarity (Low and High). For the commonality listings, the dependent measure was the number of commonalities listed. For the difference listings, the number of alignable differences and nonalignable differences were counted. The total number of differences listed was also recorded.

Scoring. The full set of transcripts was scored by one rater who knew the hypothesis under study (the first author). A random 20% subsample of the data was then scored by a naive rater. The raters agreed on 92% of their scorings, and analysis of the differences yielded no consistent tendency for one rater to overestimate or underestimate the number of commonalities or differences relative to the other.

In scoring the commonality listings, one commonality was counted for each item that subjects listed as true of both objects. Generally, each utterance beginning with "Both (items) are x" was counted as a single commonality. For example, in the sample commonality protocol in Table 1, lines like "They both have sirens" were counted as one commonality. Commonalities of the form "Both [items] are *not* x" (e.g., Both [a police car and an ambulance] are not grape-

TABLE 1
SAMPLE PROTOCOLS FROM EXPERIMENT 1

Commonalities of Police Car and Ambulance (6 Commonalities)
They both have sirens. They both have lights on the top and they're both driven by people with authority. [pause] They both have preference over other cars on the road, so if you see one, you should pull over. They're both automobiles. They both have four tires.
Differences between Police Car and Ambulance (3 ADs, 1 NAD, 1 Word Surface Difference)
An ambulance is involved with carrying someone who is hurt to a hospital, a police car is involved with carrying a criminal, or someone who is alleged to commit a crime to a police station or a jail. A police car is involved with law enforcement, an ambulance is involved with rescuing injured people. Police car is a car, an ambulance is usually a van. Police car usually has weapons in it, ambulance doesn't. [pause] Police car is two words, ambulance is one.

fruits) were also scored as commonalities. In contrast, commonalities (and differences) in the surface form of the words, or of their grammatical category (e.g., "Both have the letter 'a' in them" or "Both are nouns") were not counted as commonalities. Finally, associations between the objects were not counted as commonalities (e.g., "A police car could pass an ambulance on the street").

In scoring the difference listings, we used a conservative measure of alignable differences. Subjects had to make explicit or implicit mention of a different value along some dimension for both objects. Thus, "A police car is a car, an ambulance is a van" and "Police cars and ambulances are different kinds of vehicles" would be alignable differences. All other differences (e.g., "A police car has weapons in it, an ambulance does not") were considered nonalignable differences. The total number of differences for a pair was simply the sum of the alignable and nonalignable differences. The primary advantage of this criterion is that it can be applied simply. One disadvantage of the criterion is that it probably underestimates the number of alignable differences actually listed, because subjects could say "Cars have four wheels, and motorcycles don't" when they actually mean "Cars have four wheels, motorcycles have two." However, since we predicted large numbers of alignable differences, we preferred to err on the conservative side. Finally, we dropped items for which the subject did not know the meaning of one of the words in the pair, or used a different sense of the word than the one that we intended.

Results

As expected, the mean rated similarity was significantly higher for pairs in the High Similarity group (m = 7.4) than for pairs in the Low Similarity group (m = 1.8), $t(38) = 30.28$, $p < .001$. Table 2 presents the mean number of commonalities, total differences, alignable differences, and nonalignable differences listed for Low and High Similarity pairs. As predicted, more commonalities were listed for High Similarity pairs (m = 6.63) than were listed for Low Similarity pairs (m = 2.78), $t(38) = 9.60$, $p < .001$. More alignable differences were listed for High Similarity pairs (m = 4.14) than were listed for Low Similarity pairs (m = 3.32), $t(38) = 3.11$, $p < .005$. This evaluation was specific to alignable differences: fewer nonalignable differences were listed for High Similarity pairs (m = 0.62) than were listed for Low Similarity pairs (m = 2.07), $t(38) = 5.57$, $p < .001$. Interestingly, the total number of differences listed for High Similarity pairs (m = 4.91) and Low Similarity pairs (m = 5.23) did not differ significantly, $t(38) = 1.40$, $p > .10$.

As predicted, the commonalities and alignable differences were numerically related, as is evident in a correlational analysis. There was a significant positive correlation between the number of commonalities and number of alignable differences listed for each pair, $r(38) = 0.45$, $p < .05$. In contrast, there was a negative correlation between the number of commonalities and the number of nonalignable differences $r(38) = -0.58$, $p < .05$. The correlation between the number of commonalities and

TABLE 2
MEAN NUMBER OF LISTED PROPERTIES FOR LOW AND HIGH SIMILARITY PAIRS IN EXPERIMENT 1

		Listed properties			
Similarity of pair	Rated similarity	Commonalities	Alignable differences	Nonalignable differences	Total differences
Low	1.8	2.78	3.32	2.07	5.23
High	7.4*	6.63*	4.14*	0.62*	4.91

* $p < .05$ t test

the total number of differences was not significant, $r(38) = -0.13$, $p > .10$.

The data also support the prediction that alignable differences should be more numerous than nonalignable differences. As shown in Table 2, more alignable differences were listed than were nonalignable differences for both High and Low Similarity items. Paired t tests treating items as individuals support this interpretation, $t(19) = 15.69$, $p < .001$ for the High Similarity pairs; $t(19) = 4.13$, $p < .005$ for the Low Similarity pairs.

A regression analysis was carried out to test the assumption that similarity increases with commonalities and decreases with differences. Considering similarity as a function of commonalities, alignable differences and nonalignable differences we find that (using standardized regression weights)

$$\begin{aligned} \text{Similarity} = {} & 0.75\ (\text{Commonalities}) \\ & - 0.06\ (\text{AD}) \\ & - 0.22\ (\text{NAD}). \end{aligned} \qquad [1]$$

Thus similarity does indeed increase with the number of commonalities and decrease with the number of alignable and nonalignable differences. The multiple correlation for this equation is .87. The finding that commonalities receive more weight in the regression than do either alignable or nonalignable differences is consistent with that of previous studies of similarity that have found that commonalities are more important to rated similarity than are differences (Krumhansl, 1978; Sjöberg, 1972; Tversky, 1977).

Discussion

The results supported the view that similarity comparison is fundamentally a process of finding aligned systems of commonalities, and that differences related to those common systems (alignable differences) are psychologically distinct from unrelated differences (nonalignable differences). First, commonalities and alignable differences were numerically linked. As demonstrated by the correlation between commonalities and alignable differences, when a pair had many commonalities, it also had many alignable differences. Second, alignable differences were more numerous than were nonalignable differences. Finally, the regression analyses suggest that rated similarity increased with the number of commonalities of a pair and decreased with the number of differences.

There are some aspects of Experiment 1 that require clarification. First, this study only used pairs of High and Low similarity. Thus, the correlations we obtained may be inflated by our use of the ends of the similarity scale, and not the middle. In addition, words were used in either a High Similarity or a Low Similarity pair, but not both. Thus, the similarity of the pairs was completely confounded with the words used. Finally, we have not yet provided any support for the prediction that commonalities and alignable differences are conceptually related. In order to address these issues, we repeated the methodology of the first study using a wider range of stimuli. In addition, we performed a detailed analysis of the conceptual relationships between the listed commonalities and differences which we present in Experiment 2b.

Experiment 2

This study extends the first experiment by using word pairs that span a range of similarities. Similarity was manipulated by constructing a simple ontology like those used by Sommers (1959), Keil (1979), and Lenat and Guha (1990). We assume that the representations of items that are close in this ontology are more easily alignable than are the representations of items that are distant in the ontology. Thus, we expected similarity to vary inversely with ontological distance.[2]

The ontology tree used in this experiment

[2] We are not attempting to test the psychological reality of this ontology. Work by Gerard and Mandler (1983) has demonstrated that, at best, there are multiple ontological hierarchies. However, the basic assumption that ontologically similar pairs will be more similar than ontologically dissimilar pairs is still tenable for these stimuli.

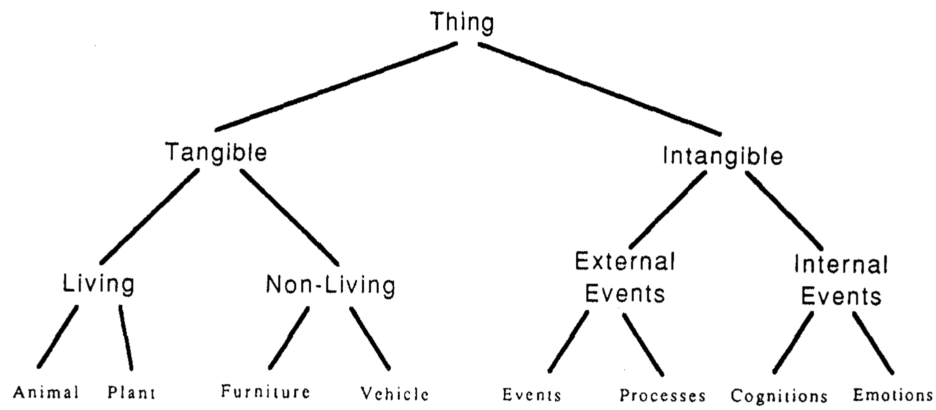

FIG. 2. Ontology used to generate stimuli in Experiment 2.

is shown in Fig. 2. Eight objects were placed at each leaf of the tree: four from each of two categories that satisfied the constraints of that path in the tree. For example, land and air vehicles are under the "vehicles" node of the tree. The ontological distance of a pair was measured as the number of nodes in the tree that had to be traversed to get from one word to the other. For example, a pair consisting of two vehicles (e.g., a car and a motorcycle) was of distance 0. A pair with a vehicle and a piece of furniture was of distance 1, a pair with a vehicle and an animal was of distance 3, and a pair with a vehicle and an abstract object was of distance 5. From this tree, we made two stimulus sets of 32 word pairs. Each set had 16 pairs of distance 0 and 16 pairs of distance greater than 0. This preponderance of high similarity pairs was desirable, because the results of Experiment 1 suggested that listing commonalities and differences for dissimilar pairs can be difficult and frustrating for subjects.

The predictions for this task are the same as those for Experiment 1. We expect to obtain evidence that commonalities and alignable differences are numerically linked. We also expect to find that alignable differences are generally more numerous than are nonalignable differences. In addition, we should obtain evidence that similarity increases with commonalities and decreases with differences. Finally, we will examine the properties listed by subjects to see whether the commonalities and alignable differences are conceptually linked.

Method

Subjects. Subjects in the similarity ratings task were 40 undergraduates from the University of Illinois. Subjects in the commonality and difference listing task were 44 undergraduates from the University of Illinois. All subjects received course credit in an introductory psychology course for their participation.

Materials. Two stimulus sets were generated from the words we placed into the ontology tree shown in Fig. 2. Words that were placed in high similarity pairs (distance 0) in one set, were placed in low similarity pairs (distance greater than 0) in the other set. Each stimulus set contained 16 pairs of distance 0, 8 pairs of distance 1, and 4 pairs each of distances 3 and 5.[3] Each word pair was printed on two index cards. Subjects received an equal number of commonality and difference listings for pairs at each distance. The complete set of materials is presented in Appendix 2.

Procedure and scoring. The procedure and scoring were identical to those used in

[3] Two errors were made in the creation of the stimuli. First, one pair of distance 5 (hang glider-fear) became a pair of distance 3 (hang glid*ing*-fear). Second, the words "moral" and "promise" were each used in two pairs of distance 0 in Set 1 and one pair of distance greater than 0 in Set 2. For this reason, the words "secret" and "thought" did not appear in Set 1.

TABLE 3
MEAN NUMBER OF LISTED PROPERTIES FOR PAIRS AT EACH ONTOLOGICAL DISTANCE IN EXPERIMENT 2

		Listed properties			
Distance of pair	Rated similarity	Commonalities	Alignable differences	Nonalignable differences	Total differences
0	5.1	3.56	2.67	0.73	3.40
1	3.0	2.50	2.34	1.01	3.35
3	2.0	1.17	2.18	1.25	3.43
5	1.6	0.48	1.65	1.71	3.36

the previous experiment. One rater who knew the hypothesis under study (the first author) scored the complete data set. A random 20% subsample of the data was then scored by a naive rater. The raters agreed on 89% of their judgments. The differences in scoring did not appear to be systematic.

Design. This study had four within-subject distance conditions (0, 1, 3, and 5). The two stimulus sets were run between subjects. The dependent measures were Commonalities, Alignable Differences, and Nonalignable Differences.

Results and Discussion

Similarity and ontological distance. The assumption that the distance of a pair in the ontology was inversely related to the similarity of the pair was supported by subjects' similarity ratings as shown in Table 3. A one-way ANOVA indicated that the mean-rated similarity decreased significantly as distance in the ontology increased, $F(3,60) = 25.18$, $p < .001$. Further analysis indicated that higher similarity ratings were given to pairs of distance 0 than to pairs of distance greater than 0, $F(1,60) = 75.12$, $p < .001$.[4] No other differences were significant.

Numerical link between commonalities and alignable differences. The mean number of commonalities and differences listed for pairs at each ontological distance is shown in Table 3. A one-way ANOVA on the number of commonalities listed for pairs at each distance indicates that the number of listed commonalities varied with distance, $F(3,60) = 11.65$, $p < .001$. Post hoc tests indicate that significantly more commonalities were listed for pairs of distance 0 than were listed for pairs of greater distance, $F(1,60) = 31.36$, $p < .001$. Similarly, significantly more commonalities were listed for pairs of distance 1 than were listed for pairs of distance 3 and distance 5, $F(1,60) = 9.79$, $p < .05$. The number of commonalities listed for pairs of distance 3 and distance 5 did not differ significantly, $F(1,60) = 0.83$, $p > .05$.

The graph in Fig. 3 shows that subjects tended to list more alignable differences for ontologically close pairs than did for ontologically distant pairs, although these differences were only marginally significant, $F(3,60) = 2.33$, $p = .08$. However, the prediction that commonalities and alignable differences should be numerically linked is supported by the significant positive correlation between the number of listed commonalities and the number of listed alignable differences for items in this study, $r(62) = 0.71$, $p < .001$.

As predicted, nonalignable differences show a different pattern than do alignable differences: subjects listed increasingly more nonalignable differences as ontological distance increased, $F(3,60) = 6.93$, $p < .001$. Fewer nonalignable differences were listed for pairs of distance 0 than were for pairs of greater distance, $F(1,60) = 17.21$, $p < .001$. Similarly, fewer differences were listed for pairs of distance 1 than were for pairs of distance 5, $F(1,60) = 7.77$, $p < .05$.

[4] The significance levels for all post hoc tests reported in this paper are corrected using the Bonferroni inequality.

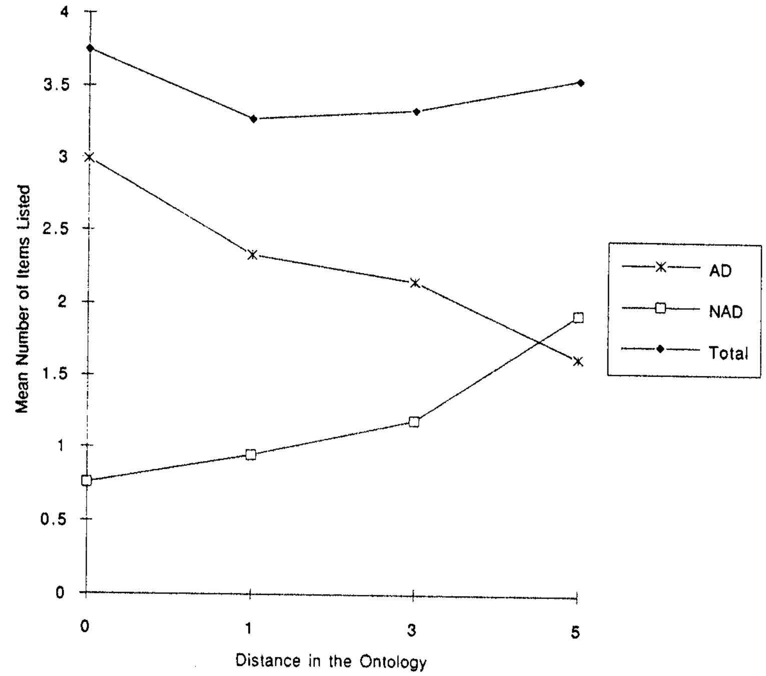

FIG. 3. Total number of listed differences, as well as number of alignable and nonalignable differences at each ontological distance in Experiment 2.

No other differences were significant. Finally, no correlation was found between the number of listed commonalities and the number of listed nonalignable differences for each pair, $r(62) = -0.12$, $p > .10$. When combined, the total number of differences listed did not differ significantly at different ontological distances, $F(3,60) = 0.01$, $p > .10$. However, the correlation between commonalities and total differences was significantly greater than 0, $r(62) = 0.53$, $p < .05$.

Alignable differences more numerous than nonalignable differences. As predicted, significantly more alignable differences were listed overall ($m = 2.41$) than were nonalignable differences ($m = 0.98$), $t(63) = 9.76$, $p < .001$ (paired t test treating items as individuals). As shown in Table 3 significantly more alignable differences than nonalignable differences were listed for pairs of distance 0, $t(31) = 9.65$, $p < .001$; distance 1, $t(15) = 5.80$, $p < .001$; and distance 3, $t(8) = 3.36$, $p < .05$. For the highly dissimilar pairs of distance 5, the number of listed alignable and nonalignable differences did not differ significantly, $t(6) = 0.34$, $p > .10$.

Commonalities, differences and rated similarity. The relationship between rated similarity and listed commonalities and differences was examined in a regression analysis. We found that

$$\begin{aligned}\text{Similarity} = {} & 0.67\ (\text{Commonalities}) \\ & - 0.16\ (\text{AD}) \\ & - 0.52\ (\text{NAD}).\end{aligned} \tag{2}$$

Thus, as for Experiment 1, rated similarity increased with commonalities and decreased with both alignable and nonalignable differences. Once again, the regression coefficient for nonalignable differences was larger than was the coefficient for alignable differences. The multiple correlation for this regression analysis was 0.82.

Concrete and abstract pairs. One striking aspect of the data was that subjects had much greater success listing properties for concrete pairs than for abstract pairs. Subjects listed significantly more commonalities for concrete pairs ($m = 4.04$) than for abstract pairs ($m = 1.68$), $t(55) = 6.61, p < .001$.[5] Subjects also listed more alignable differences for concrete pairs ($m = 3.23$) than for abstract pairs ($m = 1.75$), $t(55) = 7.64, p < .001$. In addition, they listed more nonalignable differences for concrete pairs ($m = 1.23$) than for abstract pairs ($m = 0.54$), $t(55) = 5.23, p < .001$. Although we did not predict this result, many studies have found that subjects are more fluent with concrete concepts than they are with abstract concepts (Schwanenflugel, 1991). We analyzed the data for abstract and concrete pairs separately to determine whether the overall pattern was the same for both sets of items.

Overall, the same general pattern of data was obtained for both abstract and concrete pairs. To illustrate, Table 4 presents the correlation between listed commonalities and listed alignable and nonalignable differences. These correlations are presented for all the data combined, and also separately for abstract and concrete pairs. These correlations for abstract and concrete pairs are always of the same sign as for the data as a whole. The only difference we found was that the correlation between commonalities and nonalignable differences was significantly less than 0 for concrete pairs, but nonsignificant for abstract pairs. The regression analyses relating similarity to rated commonalities and differences also show a similar pattern as the combined data. For concrete pairs, the regression equation was

$$\begin{aligned}\text{Similarity} = {} & 0.54\,(\text{Commonalities}) \\ & - 0.04\,(\text{AD}) \\ & - 0.40\,(\text{NAD}), \qquad [3]\end{aligned}$$

and for abstract pairs the regression equation was

TABLE 4
CORRELATIONS BETWEEN NUMBER OF LISTED COMMONALITIES AND NUMBER OF LISTED ALIGNABLE AND NONALIGNABLE DIFFERENCES FOR ALL DATA, AND SPLIT BY ABSTRACT AND CONCRETE PAIRS

	Pair type		
Correlation	All data	Concrete only	Abstract only
r(Comm,AD)	0.71*	0.38*	0.51*
r(Comm,NAD)	−0.12	−0.62*	−0.18

* $p < .05$

$$\begin{aligned}\text{Similarity} = {} & 0.63\,(\text{Commonalities}) \\ & - 0.21\,(\text{AD}) \\ & - 0.42\,(\text{NAD}). \qquad [4]\end{aligned}$$

Thus, for both concrete and abstract pairs, rated similarity increases with commonalities and decreases with differences.

Conceptual link between commonalities and alignable differences. Inspection of subjects' protocols supports the claim that commonalities and alignable differences are conceptually linked. For example, 92% of the subjects listing commonalities for the pair bus–bicycle said that both have wheels, but 82% of the subjects listing differences said that buses have more wheels than do motorcycles. Similarly, 80% of the subjects listing commonalities for the pair toad–cardinal said that both are animals, while 45% of the subjects listing differences noted that toads are amphibians, while cardinals are birds. In Experiment 2b, we examined this pattern more systematically. We assembled all of the commonalities and differences of the concrete pairs that were listed by at least three subjects and asked other subjects to match the commonalities and differences that they felt were conceptually related. According to structural alignment, subjects should often link alignable differences with commonalities, but should rarely link nonalignable differences with commonalities. Note that a simple featural view does not predict any relationships between commonalities and differences.

[5] Pairs of distance 5 were not used in these analyses, because they contain one abstract and one concrete word. In general, subjects listed very few commonalities or differences for these items.

Experiment 2b

Method

Subjects. Subjects were 12 undergraduates at Northwestern University who received course credit in an introductory psychology course for their participation.

Materials. This study included commonalities and differences from 26 of the 28 concrete pairs from Experiment 2.[6] For each item, every commonality and difference listed by at least three subjects in Experiment 2 was written on an individual index card.

Procedure. Half the subjects were given a stack of cards corresponding to the commonalities of one of the items (the other half of the subjects performed the reverse task). The difference cards were spread haphazardly on the table in front of the subject. For each commonality card, subjects were asked to point to all of the differences that they felt were conceptually related to that commonality. Subjects were told explicitly *not* to select items as related simply because they had the same number of words, or used the same letters. They were told to feel free to say that none of the pairs were related. When subjects completed this procedure for all of the commonalities for a given pair, they were given the stack of cards for the next pair, and the procedure was repeated.

Design. All subjects described the relationship between commonalities and differences for all pairs. Stimuli were presented in a different random order for each subject.

Results and Discussion

To assess the claim that commonalities and alignable differences should be conceptually related, we counted only those commonality–difference pairs that 9/12 (75%) of the subjects selected. This conservative criterion biases our results against the possibility that subjects simply selected some pairs at random because of the demands of the task. In all, there were 688 possible combinations of commonalities and differences, and, on average, subjects found relationships between 104 (15%) pairs of commonalities and differences. Using a binomial distribution with the probability of selecting a commonality and difference as 0.20, the probability of a particular commonality and difference being selected by 9 or more subjects is approximately .0001.

Despite the low chance probability, there were many conceptually related commonalities and differences: 36 pairs of commonalities and differences were deemed related by at least 9 subjects. These items are presented in Appendix 3. Indeed, 21/26 (81%) of the pairs had linked commonalities and differences. The central hypothesis that commonalities and alignable differences would be conceptually related was also supported. Of the 36 pairs of related commonalities and differences, 34 (94%) related a commonality and an alignable difference, even though alignable differences made up only 79% of the differences included in the study.[7]

An examination of the 36 pairs indicates some interesting regularities. Of these pairs, 10/36 (28%) turn on taxonomic connections (e.g., Both [roses and pines] are plants/Roses are flowers, pines are trees). Nine of the 36 pairs (25%) involve functional relations (e.g., Both [chairs and dressers] are useful to man/Chairs are for sitting, dressers hold clothes). Seven of the 36 related (19%) pairs turn on part–whole relations (e.g., Both [cars and motorcycles] have wheels; Cars have four wheels, motorcycles have two wheels). These three

[6] Two of the concrete items did not have any commonalities listed by at least three subjects. The abstract items were excluded from this study, because subjects listed few properties for abstract items, so there were few commonalities or differences listed by more than three subjects for these items.

[7] The same pattern emerges if we consider all pairs deemed related by only 6/12 subjects. Under this criterion, there are 67 pairs of related commonalities and differences, of which 61 (91%) included a commonality and an alignable difference.

categories—taxonomic relations, functions and part–whole relations—may be pervasive relational types that provide alignment, even between dissimilar items.

General Discussion

Commonalities, Differences and Alignment

The results found here provide evidence for the view that similarity comparisons involve the alignment of structured representations. Our first prediction was that commonalities and alignable differences would be numerically linked. In both experiments, we found that pairs with many commonalities also had many alignable differences, while pairs with few commonalities had few alignable differences. This pattern was most evident in the strong positive correlations between the number of listed commonalities and alignable differences in both studies. Second, we predicted that commonalities and alignable differences would be conceptually related. In Experiment 2b, we found conceptual relationships between many commonalities and alignable differences, and few relationships between commonalities and nonalignable differences. Third, we predicted that alignable differences would be more numerous than would nonalignable differences. In both experiments, more alignable differences were listed than were nonalignable differences. Finally, our results were consistent with previous research (Tversky, 1977), in that rated similarity increased with the commonalities of a pair and decreased with the differences. Regression analyses in both experiments supported this claim.

As described above, a simple featural model of similarity would make different predictions for this task. If items are represented as collections of independent features, similar pairs should have many commonalities and few differences, while dissimilar pairs should have few commonalities and many differences. Further, since this view makes no distinction between alignable and nonalignable differences, there is no basis for predicting the patterns of correlation found here. Finally, on this account, we would not expect to find relationships between commonalities and differences. Thus, an independent features model does not provide a satisfying account of our results. Our findings suggest that similarity comparisons operate across representations consisting of interconnected elements rather than across representations consisting of independent elements.

One potential weakness of this methodology is that we cannot identify the properties listed by subjects as the ones they actually use when rating similarity (or when performing some other task that involves similarity). Further research will have to address whether our belief that the properties listed by subjects in the commonality and difference-listing task are those that are used as the basis for their similarity judgments.

Similarity and Structural Alignment

These data are consistent with an emerging view that similarity involves the alignment of conceptual structures (Medin, Goldstone, & Gentner, in press; Gentner & Markman, in press). For example, it has been demonstrated that similarity comparisons are sensitive to relations in stimuli. Rattermann and Gentner (1987) found that stories with similar plots and different characters (and hence common relational structures) were often rated as more similar than were stories with different plots and similar characters. Similarly, proverbs with similar morals and different surface objects were generally given higher similarity ratings than were proverbs with different morals and similar surface objects (Schumacher & Gentner, 1987). In addition, it has been demonstrated that attributes and relations are psychologically distinct (Goldstone et al., 1991). They found that adding a new relational commonality to a pair (e.g., making the shading of all items in a configuration the same) was more effective when the pair already had many relational commonalities (e.g., both configurations were symmetric) than when it was added to a pair that shared mostly attribute commonalities (e.g., same patterns on objects).

Additional research has demonstrated that similarity comparisons heighten sensitivity to matching relational structure (Markman & Gentner, 1990, in press). Subjects were presented with pairs of scenes like those in Fig. 1. These scenes contained a *cross-mapping* (Gentner & Toupin, 1986): perceptually similar objects (e.g., the robot arms) played different relational roles in each scene. In one condition, the experimenter pointed to the cross-mapped object in one scene (e.g., the robot arm) and asked the subject to select the object in the other scene that went with that object. Subjects generally selected the perceptually similar object (e.g., they mapped the robot arm to the other robot arm). A second group of subjects rated the similarity of the scenes before doing the same one-shot mapping task. These subjects selected the object playing the same relational role significantly more often than did the first group (e.g., they mapped the robot arm to the man repairing the robot). This finding suggests that similarity comparisons involve structural alignment.

Not only do comparisons promote a focus on relations, but these comparisons generally yield structurally consistent mappings. Spellman and Holyoak (1992) gave subjects the premise that the conflict between Iraq and the United States was similar to that of World War II. They asked subjects who corresponded to George Bush if Saddam Hussein corresponded to Hitler. Subjects who said that Bush was like Roosevelt also tended to say that the United States in the recent conflict matched to the United States in World War II. In contrast, subjects who said that Bush was like Churchill also tended to say that the United States in the recent conflict matched Great Britain.

It has also been shown that the importance of a particular match to similarity is related to the connection between that feature and other correspondences. Goldstone and Medin (in press) presented subjects with pairs of scenes each containing two schematic butterflies. For these stimuli, they defined a *match-in-place* as a feature match between butterflies that would be placed in correspondence based on the probable overall alignment. A *match-out-of-place* was a cross-mapped feature match: one occurring between butterflies that would not have been placed in correspondence based on overall similarity. They found that matches-in-place had a greater impact on rated similarity than matches-out-of-place. A parallel finding was obtained by Clement and Gentner (1991), who demonstrated that the contribution of a pair of matching facts to the strength of an analogy was greater when the causal antecedents of the facts also matched than when they did not match.

The work by Clement and Gentner (1991) also demonstrated that systems of connected relations are a crucial determinant of further analogical inferences. They presented subjects with pairs of stories that were analogically similar (e.g., an organism that eats rock, and a robot probe that takes in data). The base story had two key facts that had no corresponding facts in the other story, but which could readily be mapped to the target story. One of these facts was connected to a causal antecedent that matched a fact in the other story, but the other had no matching causal antecedent. In a free prediction task, in which subjects were asked to predict some new fact about the second story, subjects were significantly more likely to project the causally connected fact than the unconnected fact.

The Role of Structural Alignment in Cognitive Processes

Although the present experiments provide evidence that similarity judgments involve an alignment process, subjects rarely need to put a rating on their feelings of similarity, and determining the degree of similarity is generally not the end goal of their cognitive processing. Rather, subjects often make comparisons to subserve other cognitive processes including categorization and decision making. In the following sections, we discuss the role of alignment and the distinction between alignable and nonalignable differences in other cognitive processes.

Alignment and Categorization

Categorization is an area for which comparisons are crucial. When a new item is encountered, the features of the new exemplar must be compared to the features of stored category representations (be they exemplars or prototypes). Alignment is modeled in different ways. In vector models of categorization, the alignment of features is based on the position of features within the vector (Estes, 1986; Gluck & Bower, 1988; Hintzman, 1986). In models based on mental distance, alignment takes place via positions in a mental space (Nosofsky, 1986). For models based on feature lists, identical features are placed in correspondence (Barsalou & Hale, 1993). All of these alignment processes assume less complex representations than does structural alignment. Simplification of the alignment process is a valuable assumption for these models, because it allows them to focus on other factors that are important to categorization. For example, it is easier to focus on the role of cue validity in category learning when the alignment of features is assumed to be automatic. Consistent with this assumption, the stimuli in many studies of categorization are explicitly designed to have a limited number of easily alignable dimensions. (See Wisniewski & Medin (in press) for a review of this work.)

However, in the general case, the relevant features of new items may not be immediately obvious. In these cases, a more complex alignment process that allows elements to be placed in correspondence based on their position in a matching relational structure may assist categorization. Structural alignment may be particularly important when categorizing novel exemplars. For example, Wisniewski and Medin (in press) have examined the way college students categorize children's drawings. This work suggests that features must be constructed during categorization, and that often elements in two drawings are placed in correspondence because they play the same role in subjects' theoretical beliefs about the categories. For example, when subjects believed that one category of drawings contained items with missing limbs, a missing hand in one drawing was placed in correspondence with a missing foot in another drawing. This kind of relational match is a central part of structural alignment.

Alignable and Nonalignable Differences in Decision Making

Structural alignment, and particularly the distinction between alignable and nonalignable differences, may provide an important theoretical framework for studies of decision making. Extensive work has been devoted to understanding how people choose between alternatives and how they justify their decisions. Much of this work can be recast as suggesting that subjects focus on alignable differences between alternatives when choosing between them (Tversky, 1972; Tversky, Sattath, & Slovic, 1988). For example, according to Tversky's (1972) elimination-by-aspects model, individuals choosing between a set of items focus on one common aspect or dimension of the alternatives at a time. The probability that they will focus on a particular dimension is roughly equivalent to its importance. After finding a relevant aspect, subjects eliminate any alternatives with unsatisfactory values along that dimension. This process is repeated until only one alternative remains.

Research by Johnson (1988, 1989) on consumer choice behavior also demonstrates the importance of alignment. He finds that when people select between two similar products (e.g., two toasters) they engage in a choice strategy based on aligning and comparing the particular attributes of the products involved (e.g., number of bread slots or time to toast bread). When the products are dissimilar (e.g., a toaster and a smoke alarm), and therefore difficult to align, subjects revert to other strategies.

There is also evidence that, when both alignable and nonalignable differences are available, subjects give greater weight to alignable differences. Slovic and MacPhillamy (1974) asked subjects to guess which one of a pair of students had a higher freshman GPA given two test scores for each individual. One score was from the same test (e.g., an English proficiency test), while the other score was unique for each individual (e.g., SAT for one person and the ACT for the other). They found that subjects in the prediction task attended more heavily to the score on the common test than to the score on the unique test. These examples suggest that processes of alignment and the identification of alignable differences may be crucial to the processes of decision and choice.

Conclusions

The results described here suggest that similarity comparisons are carried out by an alignment process akin to analogical mapping that places parts of structured representations in correspondence. According to this view, comparisons yield commonalities, alignable differences and nonalignable differences. These elements can be used to determine the overall similarity of the objects or can serve as the input to another cognitive process. By focusing on the process of comparison, rather than simply the degree of likeness, the study of similarity can be extended to encompass the general role of alignment and comparison in cognitive processing.

Appendix 1: Word Pairs in Experiment 1

Similar pairs		Dissimilar pairs	
Yacht	Sailboat	Curtain	Ball Bearing
Hotel	Motel	Eggplant	Giraffe
VCR	Tape Deck	Restaurant	Strobe Light
Kite	Hang Glider	Bank Check	Light Bulb
Broom	Mop	Magazine	Kitten
Watch	Clock	Mug	Speaker
Ice Cream Sundae	Banana Split	Phone Book	Lamp Shade
Sculpture	Painting	Postage Stamp	Microphone
Police Car	Ambulance	Lock	Asphalt
Rocket	Missile	Blanket	Bowl
Chair	Stool	Cab Driver	Antenna
Calculator	Abacus	Air Conditioner	Cloud
Army	Navy	Door	Sidewalk
Bed	Couch	Stove	Dumpster
Casino	Horse Track	Notebook	Piano
Store	Boutique	Traffic Light	Shopping Mall
Hammock	Lounge Chair	Freezer	Personal Computer
Stairs	Escalator	Trapeze	Fork
McDonald's	Burger King	Parade	Tennis
Football	Hockey	Handcuffs	T-Shirt

APPENDIX 2: WORD PAIRS USED IN EXPERIMENT 2

	Stimulus set 1		
Table	Overseeing	Promise	Theory
Promise	Moral	Salamander	Bench
Desk	Sofa	Writing	Talking
Sparrow	Discussion	Palm	Bus
Blimp	Plane	Robin	Bluebird
Hang Gliding	Fear	Carnation	Compromise
Regret	Apathy	Love	Generosity
Toad	Maple	Marching	Trust
Stool	Bicycle	Secret	Honesty
Car	Motorcycle	Lizard	Frog
Cabinet	Helicopter	Party	Thought
Vacation	Striding	Class	Game
Rose	Pine	Cardinal	Orchid
Speech	Reading	Oak	Daffodil
Idea	Moral	Jogging	Running
Debt	Selfishness	Chair	Dresser
	Stimulus set 2		
Toad	Cardinal	Running	Theory
Stool	Cabinet	Chair	Car
Table	Bench	Helicopter	Hang Glider
Robin	Rose	Lizard	Oak
Sparrow	Salamander	Bluebird	Meeting
Selfishness	Fear	Game	Generosity
Maple	Palm	Pine	Motorcycle
Thought	Compromise	Bicycle	Bus
Plane	Apathy	Discussion	Party
Frog	Sofa	Orchid	Carnation
Class	Writing	Idea	Love
Honesty	Trust	Reading	Overseeing
Dresser	Moral	Secret	Debt
Striding	Marching	Daffodil	Talking
Promise	Regret	Vacation	Speech
TV Show	Jogging	Desk	Blimp

APPENDIX 3

Related word pairs in Exp. 2b	Number of subjects
Sofa–Desk	
Both are made of wood Desks have drawers, Sofas do not.	9
You can sit at both You sit at a desk, you sit on a sofa.	10
Salamander–Sparrow	
Both are animals Salamanders are reptiles, Sparrows are birds	12
Both move Salamanders walk, Sparrows fly	12
Chair–Dresser	
Both are useful to man Chairs are for sitting, Desks hold clothes	10
Rose–Pine	
Both have sharp points Roses have thorns, Pines have needles	11
Both are plants Roses are flowers, Pines are trees	11

APPENDIX 3—*Continued*

Related word pairs in Exp. 2b	Number of subjects
Lizard–Frog	
none	
Robin–Bluebird	
Both are found in North America Both are found in different locations	9
Helicopter–Cabinet	
Both are manufactured Chairs are made of wood, Helicopters are made of metal	10
Toad–Maple	
Both are part of nature Toads are animals, Maples are plants	10
Both are living things Toads are animals, Maples are plants	12
Plane–Blimp	
Both fly Planes have wings, Blimps do not	9
Both carry people Planes hold more people than blimps	9
Maple–Palm	
Both have leaves Maples and Palms have different leaves	11
Desk–Blimp	
Both are man made Desks and Blimps are made from different materials	10
Table–Bench	
none	
Rose–Robin	
Both are living Roses are plants, Robins are animals	9
Chair–Car	
You can sit in both Chairs hold one person, Cars hold many	11
Helicopter–Hang Glider	
none	
Oak–Lizard	
Both are green Oaks and Lizards can be different colors	10
Cardinal–Orchid	
Both are part of nature Cardinals are birds, Orchids are flowers	10
Stool–Bicycle	
Both have seats to sit on You sit on a Stool, you pedal a Bicycle	9
Both are made of many materials Bicycles are made primarily of metal, Stools are made primarily of wood	9

APPENDIX 3—*Continued*

Related word pairs in Exp. 2b	Number of subjects
Both are useful Bicycles are transportation, Stools are furniture	11
Orchid–Carnation	
Both are given as gifts Orchids are more expensive than Carnations	10
Both are flowers Orchids and Carnations are different kinds of flowers	11
Cardinal–Toad	
Both are animals Toads are amphibians, Cardinals are birds	12
Both have homes Toads live in the ground, Cardinals live in trees	11
Frog–Sofa none	
Daffodil–Oak	
Both are living Oaks live longer than Daffodils	10
Both are plants Oaks are trees, Daffodils are flowers	12
Bicycle–Bus	
Both have wheels Buses have many wheels, Bicycles have two wheels	11
Both are means of transportation You drive a Bicycle, you are a passenger on a Bus	
Both are ridden You ride on a Bicycle, you ride in a Bus	11
Bench–Salamander	
Both can be the same color Benches are one color, Salamanders change color	12
Car–Motorcycle	
Both have engines Cars have bigger engines than do Motorcycles	10
Both carry people Cars carry more people than do motorcycles	11
Both can be dangerous Motorcycles require helmets, Cars require seatbelts	11
Both have wheels Cars have four wheels, Motorcycles have two wheels	10
Cabinet–Stool	
none	

REFERENCES

BARSALOU, L. W., & HALE, C. R. Components of conceptual representation: From feature lists to recursive frames. In V. Mechelen, J. Hampton, R. Michalski, & P. Thewns (Eds.), *Categories and concepts: Theoretical views and inductive data.* San Diego, CA: Academic Press, 1993.

CLEMENT, C. A., & GENTNER, D. (1991). Systematicity as a selection constraint in analogical mapping. *Cognitive Science*, **15**, 89–132.

ESTES, W. K. (1986). Array models for category learning. *Cognitive Psychology*, **18**, 500–549.

FALKENHAINER, B., FORBUS, K. D., & GENTNER, D. (1986). The structure-mapping engine. In *Proceedings of AAAI-86*, Philadelphia, PA.

FALKENHAINER, B., FORBUS, K. D., & GENTNER, D. (1989). The structure-mapping engine: Algorithm and examples. *Artificial Intelligence*, **41**(1), 1–63.

FORBUS, K. D., & GENTNER, D. (1989). Structural evaluation of analogies: What counts? In *The Proceedings of the Eleventh Annual Conference of the Cognitive Science Society*. Ann Arbor, MI: Erlbaum.

GENTNER, D. (1983). Structure-mapping: A theoretical framework for analogy. *Cognitive Science*, **7**, 155–170.

GENTNER, D. (1989). The mechanisms of analogical learning. In S. Vosniadou & A. Ortony (Eds.), *Similarity and Analogical Reasoning*. London: Cambridge Univ. Press.

GENTNER, D., & MARKMAN, A. B. Similarity is like analogy. In C. Cacciari (Ed.), *The Proceedings of the Workshop on Similarity at the University of San Marino*. Milan: Bompiani, in press.

GENTNER, D., & TOUPIN, C. (1986). Systematicity and surface similarity in the development of analogy. *Cognitive Science*, **10**, 277–300.

GERARD, A. B., & MANDLER, J. M. (1983). Ontological knowledge and sentence anomaly. *Journal of Verbal Learning and Verbal Behavior*, **22**, 105–120.

GLUCK, M. A., & BOWER, G. H. (1988). From conditioning to category learning: An adaptive network model. *Journal of Experimental Psychology: General*, 117(3), 227–247.

GOLDSTONE, R. L., & MEDIN, D. L. Similarity, interactive-activation and mapping. In K. J. Holyoak & J. A. Barnden (Eds.), *Advances in connectionist and neural computation theory. Vol. 2: Analogical connections*. Norwood, NJ: Ablex, in press.

GOLDSTONE, R. L., MEDIN, D. L., & GENTNER, D. (1991). Relational similarity and the nonindependence of features. *Cognitive Psychology*, **23**, 222–262.

HINTZMAN, D. L. (1986). "Schema abstraction" in a multiple trace memory model. *Psychological Review*, **93**(4), 411–428.

HOFSTADTER, D. R. (1984). *The Copycat project: An experiment in nondeterminism and creative analogies*, No. AI memo 755. The MIT AI Lab.

HOFSTADTER, D. R., & MITCHELL, M. An overview of the Copycat project. In K. J. Holyoak & J. A. Barnden (Eds.), *Advances in connectionist and neural computation theory. Vol. 2: Analogical connections*. Norwood, NJ: Ablex, in press.

HOLYOAK, K. J., & THAGARD, P. (1989). Analogical mapping by constraint satisfaction. *Cognitive Science*, **13**(3), 295–355.

JOHNSON, M. D. (1988). Comparability and hierarchical processing in multialternative choice. *Journal of Consumer Research*, **15**, 303–314.

JOHNSON, M. D. (1989). The differential processing of product category and noncomparable choice alternatives. *Journal of Consumer Research*, **16**, 300–309.

KAHNEMAN, D., & MILLER, D. T. (1986). Norm theory: Comparing reality to its alternatives. *Psychological Review*, **93**(2), 136–153.

KEIL, F. C. (1979). *Semantic and Conceptual Development: An Ontological Perspective*. Cambridge, MA: Harvard Univ. Press.

KRUMHANSL, C. L. (1978). Concerning the applicability of geometric models to similarity data: The interrelationship between similarity and spatial density. *Psychological Review*, **85**(5), 445–463.

LENAT, D., & GUHA, R. V. (1990). *Building large knowledge-based systems*. San Francisco: Addison–Wesley.

LOGAN, G. D. (1988). Toward an instance theory of automaticity. *Psychological Review*, **95**, 492–527.

MARKMAN, A. B., & GENTNER, D. (1990). Analogical mapping during similarity judgments. In *Proceedings of the Twelfth Annual Meeting of the Cognitive Science Society*. Boston, MA: Erlbaum.

MARKMAN, A. B., & GENTNER, D. Structural alignment during similarity comparisons. *Cognitive Psychology*, in press.

MEDIN, D. L., & SCHAFFER, M. M. (1978). Context theory of classification. *Psychological Review*, **85**(3), 207–238.

MEDIN, D. L., & GOLDSTONE, R. L. Predicates of similarity. In C. Cacciari (Ed.), *The Proceedings of the Workshop on Similarity at the University of San Marino*. Milan: Bompiani, in press.

NOSOFSKY, R. M. (1986). Attention, similarity and the identification-categorization relationship. *Journal of Experimental Psychology: General*, **115**(1), 39–57.

RATTERMANN, M. J., & GENTNER, D. (1987). Analogy and similarity: Determinants of accessibility and inferential soundness. In *The Proceedings of the Ninth Annual Conference of the Cognitive Science Society*. Seattle, WA: Erlbaum.

ROSCH, E., & MERVIS, C. B. (1975). Family resemblances: Study in the internal structure of categories. *Cognitive Psychology*, **7**, 573–605.

SCHUMACHER, R., & GENTNER, D. (1987). Similarity-based remindings: The effects of similarity and interitem difference. In *The Proceedings of the Annual Meeting of the Midwestern Psychological Association*, Chicago, IL.

SCHWANENFLUGEL, P. J. (1991). Why are abstract concepts hard to understand? In P. J. Schwanenflugel (Eds.), *The psychology of word meanings*. Hillsdale, NJ: Erlbaum.

SINGLEY, M. K., & ANDERSON, J. R. (1989). *The transfer of cognitive skill*. Cambridge, MA: Harvard Univ. Press.

SJÖBERG, L. (1972). A cognitive theory of similarity. *Göteborg Psychological Reports*, **2**,(10).

SLOVIC, P., & MACPHILLAMY, D. (1974). Dimensional commensurability and cue utilization in comparative judgment. *Organizational Behavior and Human Performance*, **11**, 172–194.

SMITH, E. E., & MEDIN, D. L. (1981). *Categories and concepts*. Cambridge, MA: Harvard Univ. Press.

SOMMERS, F. (1959). The ordinary language tree. *Mind*, **68**, 160–185.

SPELLMAN, B. A., & HOLYOAK, K. J. (1992). If Saddam is Hitler then who is George Bush? Analogical mapping between systems of social roles. *Journal of Personality and Social Psychology*, **62**(6), 913–933.

THORNDIKE, E. L., & WOODWORTH, R. S. (1901). The influence of improvement in one mental function upon the efficiency of other functions. *Psychological Review*, **8**, 247–261.

TOURANGEAU, R., & RIPS, L. J. (1991). Interpreting and evaluating metaphors. *Journal of Memory and Language*, **30**, 452–472.

TVERSKY, A. (1972). Elimination by aspects: A theory of choice. *Psychological Review*, **79**(4), 281–299.

TVERSKY, A. (1977). Features of similarity. *Psychological Review*, **84**(4), 327–352.

TVERSKY, A., SATTATH, S., & SLOVIC, P. (1988). Contingent weighting in judgment and choice. *Psychological Review*, **95**(3), 371–384.

WISNIEWSKI, E. J., & MEDIN, D. L. The fiction and nonfiction of features. In R. S. Michalski & G. D. Tecuci (Eds.), *Machine Learning: A Multistrategy Approach*. San Mateo, CA: Morgan Kauffmann, in press.

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