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Nonintentional Similarity Processing

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Similarity in cognitive processing

Similarity is a compelling part of everyday experience. In the visual world, objects that are similar in shape or color may seem to leap to our attention. In conceptual processing, we have an immediate sense of whether a pair of concepts is similar. The prominence of similarity in conscious experience has made it an important explanatory construct in psychological theories. New problems are assumed to be solved on the basis of their similarity to known problems (e.g., Reed, Ernst, & Banerji, 1974; Ross, 1987). Objects are assumed to be classified on the basis of their similarity to some stored category representation (e.g., Medin & Schaffer, 1978; Reed, 1972). Predictions of new features of an item may be based on what other similar items have those features (e.g., Blok & Gentner, 2000; Heit & Rubinstein, 1994; Osherson, Smith, Wilkie, Lopez, & Shafir, 1990; Sloman, 1993).

Yet despite extensive work on mechanisms of similarity, there has been very little discussion of *why* and *how* similarity is important in cognitive processing beyond the general recognition that similarity often provides a good basis for generalization (Shepard, 1987). In this chapter, we consider the role of similarity in the cognitive architecture and the relationship of similarity to automatic processing. We suggest that some types of similarity are determined automatically. When the cognitive system recognizes similarities, they influence cognitive processing, even when the person does not intend for their processing to be affected by similarities. In order to support this claim, we first outline three different approaches to similarity. Then, we examine how similarity can influence both low-level processes like attention and memory retrieval and higher cognitive processes like analogical reasoning and decision making. Next, we explore a number of examples in which cognitive processing is influenced by the presence of similarities in a stimulus set. Finally, we broaden the discussion to include similarities in more deliberate cognitive processes.

Three Approaches to Similarity

Representation and Similarity

When a person makes a similarity comparison, the result is typically both a judgment of similarity and also some awareness of the commonalities and differences of the pair compared. A model of similarity must account for both of these outputs. How they do so is bound up with proposals about mental representation. Similarity processing involves the comparison of two representations. Thus the selection of a formalism for representation in a model of similarity influences not only the complexity and computational resources required but also the nature of the output.

In this section, we start by discussing similarity models that assume spatial representations. These models are fairly simple both in their output and their processing requirements. Then, we turn to more complex featural and structural models of representation and the comparison processes that operate over them. In the next section, we will examine the implications of these models for the cognitive architecture.

The spatial view of similarity is embodied in multidimensional scaling models of similarity, as well as in distributed connectionist models and high-dimensional semantic space models (e.g., Gärdenfors, 2000; see Gentner & Markman, 1995; Markman, 1999; Medin, Goldstone & Gentner, 1993 for discussion). According to spatial models, concepts are represented as points or vectors in a semantic space (e.g., Shepard, 1962). Calculating similarity involves finding the distance between points or vectors using some metric. These models have the important advantage that finding distance in a space is a computationally simple calculation. Thus similarity comparisons do not require significant processing resources. However, spatial models have two major disadvantages as psychological models. First, the comparison process gives rise only to a distance between concepts. This scalar value can be used to model similarity judgments, but there is no way to access the specific commonalities and differences that form the basis of the similarity judgment. Second, similarity in a space is influenced only by the differences between concepts, not by their similarities. Adding dimensions to the space along which two concepts are the same will not increase similarity, but adding dimensions on which two concepts differ will decrease similarity (Tversky, 1977). Thus, spatial representations cannot capture Tversky's (1977) finding that the same pair (e.g. U.S.A./Canada) can be both more similar and more different to each other than another pair (e.g., Venezuela/Bolivia).

While spatial models of similarity have been used to model many similarity phenomena (see Shoben, 1983 for a review), the above limitations, along with others catalogued by Tversky (1977), make spatial models problematic as a general theory of similarity (though see Krumhansl, 1978 and Nosofsky, 1986; for attempts to address some of the shortcomings of spatial models). Spatial models yield only a scalar measure of similarity, and only differences influence the calculation of similarity. Thus they fail to capture the fact that people are able to access the commonalities and differences of pairs in addition to rating their similarity; and similarity judgments are if anything more influenced by the pair's commonalities as by its differences (Markman & Gentner, 1993b; Tversky, 1977).

In response to these shortcomings, Tversky (1977) proposed a featural approach to similarity called the *contrast model*. According to the contrast model, concepts are represented by sets of features. Pairs of feature sets can be compared using elementary set operations. Features in the intersection of the sets are commonalities of a pair and features not in the intersection are differences. Rated similarity increases with the commonalities of a pair and decreases with the differences. Thus, this model is able to calculate a scalar rating of similarity that is influenced by both commonalities and differences, but it also permits access to the particular commonalities and differences of a pair. Like spatial models, the calculation of similarity in featural models is computationally inexpensive, as each feature in the representation of one item simply needs to be matched against the set of features representing the other item.

A third approach to similarity was developed to account for phenomena that demonstrate the importance of relations in similarity (Gentner, 1983; Gentner & Markman, 1997; Markman & Gentner, 1993b; Goldstone, Medin & Gentner, 1991). For example, Figure 1a depicts two simple geometric configurations. These configurations could be viewed as being similar because there is a circle and a square in each or because there is one figure above another in each. On a featural representation like the one in Figure 1b, it is not clear how to match up the features in the two lists. Indeed, the first seven features in each feature list are the same, they are just listed in a different order. When the intersection of these feature sets is taken as in Tversky's (1977) contrast model, the features are matched without regard to the way they are ordered. While it might be possible to add configural features such as square-above-circle to this list in order to account for way objects are attached to relation, the number of configural features required as new relations are added quickly becomes unwieldy (Foss & Harwood, 1975; Markman & Gentner, 2000).

Structured representations, like the ones in the graphs in Figure 1c are useful for dealing with relations. These representations consist of *entities*, *attributes*, and *relations*. Entities such as Square_1, stand for the objects in a domain. Attributes [e.g., shaded(x)]represent descriptive properties (e.g., the property of being shaded). Attributes take one argument (in this case, x), which binds the attribute to a particular object. For example, shaded(Square_1) means that Square_1 is shaded. Relations like above(x,y), are representational elements that relate two or more arguments. The arguments to a relation may be objects, attributes or other relations – that is, relations that take other relations as arguments – *Higher-order relations* are particularly important, because they often capture system-level connections within a domain such as causal and functional relations and implications.

Comparing pairs of relational representations like the ones depicted in Figure 1c involves a process of *structural alignment* – part of the structure-mapping process that is proposed as the basis of analogical comparisons (Falkenhainer et al., 1989; Keane et al., 1994; Gentner, 1983, 1989; Gentner & Markman, 1997). On this view, the comparison process seeks a structurally consistent match between two domains. First, the comparison process finds identical attributes and relations in each domain. For example, there are above(x,y) relations in the two representations shown in Figure 1c. Potential matches are examined to ensure that they are structurally consistent.

Structural consistency comprises the constraints of *parallel connectivity* and *one-to-one mapping*. Parallel connectivity says that if an attribute or relation in each domain is placed in correspondence, then their arguments must also match. For example, if the above(x,y) relations are placed in correspondence then the first arguments to that relation (i.e., the things on top) must be matched as must the second arguments (i.e., the things on the bottom). One-to-one mapping requires that each element in one representation match to at most one element in the other. Thus, if the square in the left-hand configuration is matched to the circle in the right because both are on top, then the square on the left cannot also be matched to the square on the right because of their similarity in shape. In cases such as the configure in Figure 1a in which there is some ambiguity about how the objects should be placed in correspondence, the structural alignment process may yield more than one structurally consistent match (Markman & Gentner, 1993b). The structural alignment process has been implemented in a number of computational models using both symbolic (Falkenhainer et al., 1989; Keane et al., 1994) and connectionist (Holyoak & Thagard, 1989; Hummel & Holyoak, 1997) architectures.

The structure-mapping model is much more intensive computationally than spatial or featural models. The calculation of parallel connectivity requires checking each correspondence among relations to ensure that the arguments of those relations also match. In addition, enforcing one-to-one mapping may require a number of comparisons among potential matches.[1] The benefit of this increased complexity is that structural alignment provides a more adequate model of similarity than the prior models.

First, the model's assessment of degree of similarity matches the human phenomena. For example, rated similarity tends to increase with the number of commonalities of a pair and to decrease with the number of differences (Markman &

Gentner, 1993). Furthermore, subjective similarity tends to be higher when people focus on relational commonalities than when they focus on object-attribute commonalities (Gentner, Rattermann, & Forbus, 1993; Markman & Gentner, 1993b). This is especially true if the relations form a system governed by common higher-order relations (Clement & Gentner, 1991; Gentner, Rattermann & Forbus, 1993).

Second, the structure-mapping model provides an account of directionality in similarity that fits human data. Bowdle and Gentner (1997) found that people preferred to see comparisons in the direction from a well-structured, systematic situation to a less well-structured situation. For example, people's knowledge about a familiar domain is usually better structured than is their knowledge about an unfamiliar domain, which leads to an asymmetry in a comparison, so that people prefer the comparison "Scanners are copiers" to the reverse.

Third, structure-mapping predicts inferences that follow from a comparison (Clement & Gentner, 1991; Gentner & Markman, 1997). People spontaneously project new information that is connected to the common structure, but which is not yet present in the target.

Fourth, this account of similarity makes novel predictions about the types of commonalities and differences that emerge from comparisons. As in featural models, commonalities are matching elements. For example, the left and right representations in Figure 1c might be seen as similar, because there is an above(x,y) relation in each. Unlike other models, structure-mapping predicts two kinds of differences that emerge from comparisons. First, elements connected to the common structure may participate in the perception of differences. For example, seeing that one figure is *above* another in each representation leads to noticing that there is a *square* on the top in one configuration and a *circle* on the top in the other. Differences like this that are noticed because of the way the representations were matched are called *alignable differences* (Markman & Gentner, 1993a). Alignable differences can be contrasted with *nonalignable differences,* which are aspects of one representation that are not connected to the common structure and have no correspondence in the other. For example, the triangle in the right-hand configuration is not part of the above relation and has no correspondence in the other configuration, and thus is a nonalignable difference.

The distinction between alignable and nonalignable differences goes beyond what is predicted by featural models. For example, Tversky's (1977) contrast model assumes that the commonalities and differences that emerge from comparisons are independent. The structural alignment approach predicts that alignable differences are fundamentally related to commonalities, though nonalignable differences are not.

Considerable evidence has been gathered to support the distinction between alignable and nonalignable differences. This evidence suggests both that alignable differences are related to commonalities and that alignable differences tend to be favored over nonalignable differences in comparisons. Two lines of evidence support the relationship between commonalities and differences. First, pairs for which people can list many commonalities are also those for which they can list many alignable differences. Second, alignable differences tend to be conceptually related to commonalities, but nonalignable differences do not (Gentner & Gunn, 2000, 2001; Markman & Gentner, 1993a, 1996).

There have also been a number of demonstrations that alignable differences are more focal (or salient) than nonalignable differences in comparisons. For example, in free property listing tasks, more alignable differences tend to be listed than nonalignable differences (Markman & Gentner, 1993a). People find it easier to list a difference for similar pairs (which have many alignable differences) than for dissimilar pairs (which have few alignable differences; Gentner & Gunn, 2001; Gentner & Markman, 1994). Further, carrying out a similarity comparison renders differences more available. Finally, following a similarity comparison of a pair of pictures, an object that was an alignable difference serves as a better retrieval cue than does an object that was a nonalignable difference (Markman & Gentner, 1997; Stilwell & Markman, 2001).

Types of similarity and their use

This review of similarity models reveals two critical dimensions along which models differ. First is the expressive power of the models. Spatial models provide a scalar measure of similarity that is influenced by the similarities or the differences of a pair, but not both. Featural models provide a measure of similarity that is influenced by both commonalities and differences and that can output independent sets of common and distinctive features. Only the structure-mapping model captures both commonalities and differences, as well as the more precise (and psychologically important) distinction between alignable and nonalignable differences. The model also captures the relation between alignable differences and the commonalities of a pair. Further, it is the only one of the three approaches that provides an account of which inferences will be drawn from a comparison.

The second dimension along which models of similarity can be evaluated is computational complexity. The expressive power of structural alignment comes at a computational cost. Ensuring that matching relations in two domains also have matching arguments and that the entire correspondence obeys the constraint of one-to-one mapping is a complex process. In contrast, comparing two points in a multidimensional space and finding correspondences within a set of features are both fairly simple processes to carry out. Thus, the greater complexity of structural alignment requires more time and effort than do the simpler spatial and featural processing models.

It is typical when evaluating research to pick one model as the best one. We want to take a different tack here. As we discuss below, there are different similarity processes that make different tradeoffs with respect to complexity and expressive power. We suggest that there are two modes of similarity processing (Forbus, Gentner & Law, 1995;

Gentner, Rattermann & Forbus, 1993). The first – the one we have discussed so far – is based on structural alignment, and provides slower more effortful judgments and also yields access to the commonalities and differences (particularly the alignable differences) of a pair. This process is useful in cognitive processes that can be carried out over a period of many seconds (as opposed to milliseconds) or those that involve a small number of comparisons that require access to commonalities and differences. The second is based on the principles embodied in the spatial and featural views, and provides fast judgments of the degree of similarity of a pair, but does not take the structure of the representations into account. This fast process is most useful when judgments are required quickly or when many similarity comparisons must be made in parallel, as when accessing long-term memory.

One piece of evidence in favor of this dichotomy comes from research on analogical reminding. Much research suggests that remindings show much less influence of structure than do analogy comparisons. In one study, Gentner, Rattermann, and Forbus (1993) asked people to read a set of stories. For example, one story was about a hawk that gives feathers to a hunter to use in his arrows in exchange for the hunter's agreement not to shoot the hawk. A week later, the same people read new stories and were asked to recall any stories from the previous week that were similar to the new story. When given new stories that involved similar characters (e.g., an eagle), people were likely to recall the original story. This reminding happened even when the new story had a very different plot from the original. In contrast, when given a story with different characters (e.g., countries) and an analogically similar plot (e.g., one country gives computers to the other to guide its missiles in exchange for an agreement not to shoot the missiles at them), people were unlikely to recall the original story. This finding suggests that retrieval—which requires making a comparison of the cue against the contents of memory—uses a computationally simple form of similarity (see Holyoak & Koh, 1987; Reeves & Weisberg, 1994; Ross, 1989; and Wharton, Holyoak, Downing, Lange, & Wickens, 1991; for related studies).

Although structure was not important for retrieving analogs in the study by Gentner et al. (1993), it was important in people's judgments of similarity when they were given the same pairs of stories to compare. When people were shown pairs of stories together, the highest similarity ratings were given to stories that shared the same plot, even if they had different characters. In contrast, stories with similar characters and a different plot were judged much less similar. In fact, rated similarity showed a reverse pattern to that of memory reminding. Thus, when people were making only a single comparison (with no time pressure) their judgments strongly relied on structural overlap, but retrieval from memory showed little effect of common structure.

This distinction between types of similarities led Forbus and Gentner to hypothesize that the initial retrieval stage in similarity-based remindings are a cheap parallel search for possible matches. This hypothesis is embodied in a computational models of analogy and analogical reminding (Forbus, Gentner, & Law, 1995; Thagard, Holyoak, Nelson, & Gochfeld, 1990). For example, in Forbus, Gentner, & Law's (1995) MAC/FAC (Many are Called/Few are Chosen) model, analogical retrieval begins with a parallel sweep to find items in memory that share similar representational elements without regard to the structure of the representations. Once a small candidate set of remindings is found, a second stage makes a structural comparison between the cue and the items retrieved in the first pass. The best structural matches to the cue are retained and explained.

Similarity and metacognition

Here we propose to extend the notion of fast and efficient similarity estimation processes. A computationally simple form of similarity that calculates the degree of similarity could operate all the time searching for similarities among items in the environment as well as between items in the environment and background knowledge. This process could serve as the basis of metacognitive judgments of where to spend processing effort. That is, a pair that has some initial overlap is likely to yield a better return on processing effort than is a pair that has little overlap.

This proposal would explain why the feeling of similarity is so accessible. Similarity theorists have rarely considered why people are able to make judgments of similarity so easily, or why similarity is such a compelling part of conscious experience.

The view we outline here suggests that the initial assessment of similarity is used as a guide for the allocation of attentional resources (see Markman, 2001 for a related discussion). It provides a reliable guide for further processing. On this account, much of the process of accessing and computing similarity comparisons may not be consciously accessible; indeed, unconscious outputs may drive further cognitive processing. It should be clear that explicit similarity judgments and numerical ratings (like those often collected in the lab) may not reflect the range of ways in which similarity processes can influence cognition and behavior.

Another instance of rough, nonstructural similarity processing may occur early in processing a comparison. Even when a comparison is explicitly presented – removing the need for a reminding from long-term-memory – the early stages of similarity and analogy processing appear local and unstructured. This is captured in SME (described below) by an initial stage that creates a multitude of local matches, with no regard for structural consistency; overall structural consistency emerges later in processing (Falkenhainer, et al., 1989; Forbus, et al., 1995).

Findings with metaphors underscore the idea of an initial rapid similarity process followed by a slower, more detailed process. An early study by Glucksberg, Gildea, and Bookin (1982) asked people to judge whether sentences were literally true or false in a timed task. Some of the literally false sentences were metaphors (e.g., "Some jobs are jails."). People were slower to reject these metaphoric sentences than to reject false sentences that had no interesting semantic overlap; indicating that metaphoric processing begins before literal processing is complete (e.g., "Some dogs are birds."). Wolff and Gentner (2000) further found that people were equally slow to reject reversed metaphors (e.g., "Some jails are jobs"). There are three salient points here. First, the fact that the interference effects are independent of the order of the terms, suggests that the initial stages of metaphor processing are symmetric. Second, metaphoric interference is far greater for high-similarity metaphors like “Some soldiers are pawns” than for low-similarity metaphors like “Some senators are pawns,” regardless of whether the metaphors occur in forward or reversed order. Third, these interference effects occur early in processing; by 1100 - 1200 msec, the metaphors are detected as (literally) false and rejected. These results are consistent with an early, rapid symmetrical similarity process.

Wolff and Gentner also verified that the metaphors were directional when processed to completion. This is a crucial point because metaphors are known to be strongly directional: for example, people greatly prefer “Some jobs are jails” to “Some jails are jobs” (Ortony, 1979). Further, according to the structure-mapping model, the initial alignment process is followed by directional projection of inferences. Thus metaphoric directionality should emerge if people are allowed to complete the comprehension process. Consistent with this prediction, when new subjects were given the same metaphors as in the prior studies and asked to indicate whether the metaphor was comprehensible, they showed strong directional preferences: 75% of the forward metaphors were judged comprehensible, as against 37% of the reversed metaphors. Further, forward metaphors were faster to comprehend than reversed metaphors (*M* = 1644 ms for forward, *M* = 1778 ms for reversed). Also, as predicted, high-similarity metaphors were more likely to be judged comprehensible than low-similarity metaphors. In sum, the results indicate that early processing of metaphors, as tapped in the interference effect, is symmetrical; but that when full processing is allowed, there is a strong directional advantage for forward metaphors. Overall, the pattern fits the structure-mapping claim of initially symmetric processing followed by later directional projection of inferences.

Carrying these findings to the next logical step, Wolff and Gentner (in preparation) gave subjects a task in which they received sentences like the above – including forward or reversed metaphors, literal similarity statements, and anomalous sentences that were clearly false -- and had to say whether they were comprehensible before a deadline passed. As expected, at long deadlines (1800 ms), the forward metaphors are rated as comprehensible far more often than the reversed. However, at short deadlines (1200 ms), the forward and reversed metaphors are indistinguishable. Importantly, both are more comprehensible than the anomalous sentences at fast deadlines, indicating that they have attracted some early processing attention.

These results fit with our conjecture that an early rapid similarity assessment is used to guide the allocation of processing resources. Here the early similarity comparison process identifies sentences that share semantic overlap – both the forward and reversed metaphors. As indicated by the results of the full comprehension studies, once such a semantically overlapping sentence is identified, a more elaborate process of structural alignment and inference projection takes place, such that some of these initially promising sentences will be accepted and others rejected.

Research on sentence verification is also consistent with this proposal. For example, Smith, Shoben, and Rips (1974) examined the speed with which people could verify sentences like "A dog is an animal." Of particular interest to them was the finding that people were very fast to respond to false sentences like "A dog is a bird," but slower to respond to false sentences like "A bat is a bird." They suggested that people are using the initial similarity of bat and bird as a guide to processing. In contrast the absence of similarity between dog and bird is a reliable indication that dogs are not birds.

In the results so far, we have focused on cases where the detection of similarity leads to the allocation of more attentional resources. However, there are cases where the effect of similarity is to allocate *fewer* resources. We will return to this point when we consider infant habituation studies in the next section.

While the feeling of similarity may be consciously accessible, the basis of this judgment may not be consciously accessible. One way to see this point is that associations between words increase people's similarity ratings for a pair, even though these associations do not increase the number of commonalities of a pair (Bassok & Medin, 1997; Gentner & Brem, 1999; Wisniewski & Bassok, 1999). For example, coffee and milk are rated as more similar than coffee and lemonade, even though they do not share more properties, because of their strong co-occurrence association.

This observation could be taken to suggest that similarity and relatedness are psychologically intertwined, or that they are simply two different aspects of the same process. However, Gentner and Brem (1999) suggest that it is sometimes difficult to tell the difference between two different ‘cognitive sensations:’ the sense of similarity that results from comparing items and discovering commonalities, and the sense of associative linkage that results from retrieving a stored association[2]. Indeed, one could ask whether similarity and association result from the same process (e.g., Bassok & Medin, 1997; Sloman, 1996). One piece of evidence for there being different underlying processes despite this confusion, is that there are two patterns of results over the same materials. When asked to choose which is most similar to a *dart*, some people choose *bullseye* as more similar than *javelin*. However, if people are given a word extension task – e.g., they are told that darts are called ‘blickets’ in a certain language – they virtually always extend the new term to the similar item (*javelin*) and never to the associate (Gentner & Brem, 1999). Thus, even though the “cognitive sensations” engendered by comparison activity and by retrieval of associations may be difficult to distinguish explicitly, the processes may have separate courses and separate implicit outcomes.

From the perspective of this chapter, if we postulate a set of early signals used to guide the allocation of attentional resources, then it makes sense to include associative retrieval as well as a sense of similarity in this set, because associations are another good indication that additional processing would be fruitful. The early sense of "something interesting happening" may be difficult to distinguish (or perhaps even identical) for finding a stored association and computing a new similarity.

The presence of a metacognitive process that makes use of the output of similarity judgments to guide future processing has important implications for cognitive processing. One that we explore in the rest of this chapter is that the presence of similarities among items will influence cognitive processes that operate on those items. Thus, the nonintentional perception of similarities between items that occurs during the normal course of processing will have unintended effects on the output of other cognitive processes.

Nonintentional Similarity

In this section, we explore the implications of using similarity processing – whether or not it is explicitly coded as similarity – to allocate attentional resources. We begin with a discussion of information that infants and children are able to extract from repeated presentations of a similar pattern. Then, we turn to research on adults that demonstrates that people process information differently when items are similar than when they are dissimilar. This work comes from studies of conceptual combination, decision making, and person perception. Finally, we broaden the discussion to consider some influences of similarity that occur when people are induced to make comparisons during processing.

Similarity and comparisons in development

It is generally assumed that infants' cognitive processing is less strategic than that of adults. Thus, influences of similarities on the cognitive abilities of infants can be viewed as evidence that nonintentional similarity affects the output of cognitive processes. We begin by describing some influences of similarity on infant cognition and then turn to data from older children.

Many studies of infant cognition make use of the habituation paradigm. Habituation studies with infants rely on the observation that repeated presentations of a set of items eventually lead to a decrease in attention (e.g., Baillargeon, Spelke, & Wasserman, 1985, Eimas, 1971). The general technique is to expose the infant to an event and then repeat the event until the infant’s looking time to the event decreases. In this case, similarity is leading to a *reduced* allocation of resources; intuitively, infants act as though they are bored. At this point, test events are given. If the infant's looking time remains the same, then the experimenter infers that this event is treated by the infant as similar to the one they saw before. If the infant's looking time to the test event increases (i.e., they dishabituate), then the experimenter infers that the current event is seen by the infant as different from the habituation event.

In these studies, the stimuli need not be identical on each trial. For example, when 7-month-old infants are presented with a series of pictures of members of a particular category (e.g., cats) their looking time will decrease over trials (e.g., Cohen & Younger, 1983). Thus, in this case, the assessment of similarity is being used to suggest that additional resources need not be expended. Often these studies include a test phase in which a new item is presented. If infants look longer at a test trial than they did to trials at the end of the habituation phase, this is interpreted as evidence that they noticed a difference between the test trial and the habituation trials. What is important for the present purposes, however, is that a feeling of similarity can be used to drive the allocation of resources.

In one set of studies, Baillargeon (1991) examined infants' ability to reason about the properties of a hidden object. First, subjects in the study were habituated to an event in which a screen that was initially flat on a table rotated backward through a 180° arc. After habituation, a box was placed on the table in front of the subject, and then the screen was again rotated. In the possible event condition, the screen rotated back until it reached the angle at which it touched the top of the box and stopped. In the impossible event condition, the screen rotated back so that it would have passed through the top 50% or the top 80% of the box's height. When given this task alone, 6.5-month-old infants dishabituated to the 80% violation, but not the 50% violation, and 4.5-month-old infants remained habituated to both of these impossible events.

A subsequent experiment demonstrated the importance of similarity on this type of physical reasoning. During the test event, two boxes of the same height were used. One was in the path of the screen and the other was not, so that the second box would always be visible to the infant. Furthermore, the perceptual similarity of the two boxes was varied, so that they were identical, similar, or dissimilar. When the boxes were identical, both 4.5- and 6.5-month-old infants dishabituated to the 50% violations. When the boxes were highly similar but not identical (i.e., same size and shape but different color), the 6.5-month-olds, but not the 4.5-month-olds, dishabituated to the 50% violation. Finally, neither group of infants reliably dishabituated to this violation when the boxes were dissimilar. This finding suggests that infants would spontaneously use the visible box as a kind of standard to help them calibrate the height of the occluded box only when there was considerable perceptual similarity (even though the relevant comparison involved only the height dimension). The younger the infant the greater the degree of perceptual similarity required in order to align the standard with the box and of the box when occluded.

Other findings suggest that infants may be able to use similarities in a set of stimuli to generate representations of relational information in stimuli. As one demonstration of this point, Marcus, Vijayan, Bandi Rao, and Vishton (1999) played 7-month-old infants a sequence of novel three-syllable utterances. These training utterances followed one of two patterns, either ABA (e.g., *ga ti ga*) or ABB (e.g., *ga ti ti*). At test, the infants heard examples of the same pattern they had heard during training or examples of a different pattern. Importantly, the test utterances used a new set of syllables from those in the training utterances (e.g., *wo fe wo* or *wo fe fe*). In this work, the dependent measure was the infant's looking time at a light flashing over a speaker from which the syllables were played. Infants looked reliably longer at the source when the utterances violated the abstract pattern heard during training than when the new utterances followed the training pattern, suggesting that they were dishabituating to the new pattern. A similar result was obtained by Gomez and Gerken (1999) with 12-month-olds using a more complex artificial grammar.[3]

A model of the influence of repeated comparisons on this task was developed by Gentner, Kuehne and Forbus (in preparation; Kuehne, Gentner and Forbus, 2000). This model made use of the SEQL architecture, a model of category learning by abstraction over exemplars that uses the Structure-mapping Engine (SME; Falkenhainer, Forbus, & Gentner, 1989) to carry out its similarity computation and to derive its abstractions (Skorstad, Gentner, & Medin, 1988). Briefly, SME is a computational model that takes as input structured representations of the two items being compared. For example, the relation that the first and third syllables in an utterance are the same might be represented as SAME(wo1, wo3). The output of SME is a set of correspondences between the items that satisfies the constraints on analogy described above (e.g., structural consistency and systematicity). SEQL extends this model by making repeated comparisons. Each comparison yields a set of commonalities, which are retained and used in comparison with the next input item. Over time, the abstraction comes to contain the relational commonalities that reoccur across the items in the input. Importantly, these comparisons are made automatically, and are not under strategic control, making this process appropriate for modeling infant habituation.

In the domain of utterances, repeated comparisons among utterances with a common relational structure allow the model to abstract away the relational commonalities from a set of items, leaving few if any surface (i.e., phonological) properties. When the model is given the same sequence of input utterances (with each syllable represented with 12 phonetic features) as the infant and tested on the same test patterns, it finds the new patterns markedly less similar to its abstraction than the old ones.

There are two types of similarities that infants are likely to use to create relational representations of the novel utterances. First, within each utterance there are some similar elements (i.e., the first and last syllables in the ABA utterances and the repeated syllables in the ABB utterances). These repetitions are a form of internal regularity that may be salient for infants as it is for adults (Ferguson, 1994; Kubovy, 1995; Leyton, 1992). In addition, because utterances following the same pattern are repeated, infants may compare *across* patterns in the manner described above to notice relational similarities.

The idea that repeated comparisons can facilitate children's ability to represent more abstract relational systems can also be seen in a study with pre-school children done by Kotovsky and Gentner (1996). In this study, 4-year-old children given a similarity choice task in which they were shown a standard and were asked to determine which of two comparison figures showed the same abstract pattern. The standard and comparison figures were configurations of three geometric shapes in a line. The shapes in a configuration were the same except for one dimension: size or darkness of color. In the standard, the configuration either had the pattern ABA (symmetry) or ABC (monotonic change). One comparison figure had a configuration with the same abstract relation either along the same dimension or along a different dimension from the standard. The other configuration had the same three shapes in an arbitrary pattern (e.g., ABB on a symmetry trial or ACB on a monotonic change trial). Children chose whichever alternative they felt was most similar to the standard; they were given no feedback beyond general encouragement.

The 4-year-olds given this task were reliably above chance at this task on trials where the standard and comparison figures varied along the same dimension (e.g., all varied in size or all varied in darkness) and when the polarity of the relation was the same (e.g., when *little-big-little* was matched to *little-big-little*), but not when the polarity was reversed (e.g., *little-big-little* to *big-little-big*). These children were also unable to perform cross-dimensional matches, where the standard varied along a different dimension than the comparison figures (e.g., *dark-light-dark* vs. *big-little-big*). Thus, 4-year-olds required substantial perceptual similarity to support the abstract match.

Kotovsky and Gentner (1996) suggested that repeated simple comparisons might lead to abstracting structural regularities that would enable children to learn to do the more difficult cross-dimensional matches. To test this possibility, the comparisons were given in a blocked fashion. First, a block of within-dimension trials were given. Within this block, children first saw configurations that only varied in size (which they tend to find easy) and then configurations that only varied in color (which they tended to find more difficult). Only after this block were they given cross-dimensional trials that involved changes in both size and color. Children who responded correctly to the initial within-dimension trials were able to perform the cross-dimensional matches reliably as well.

In order to rule out a simple practice effect, a second group was initially given the same number of within-dimension trials as the above group, but they only saw triads involving the size dimension. These children performed well on within-dimensions trials but were not able to do the cross-dimension trials successfully. This result suggests that repeated within-dimension comparisons support the creation of more abstract relational representations that were then useful in performing the cross-dimensional matches. Obviously, this study involved comparisons that were part of the experimental task rather than spontaneous comparisons, but these findings are consistent with the Marcus et al. data described above.

The idea that comparisons promote the recognition of abstract relational similarities receives additional support from research by Gentner and Namy (1999, Namy & Gentner, 2002) on word learning in 4-year-olds. They examined how children would extend a novel noun that they heard. For one group of children, the noun was applied to a single object (e.g., the experimenter points to a picture of a bicycle and says "This is a dax."). For a second group, the same procedure was followed for a tricycle as standard. A third group was shown both standards (which were always from the same taxonomic category) and invited to compare them; e.g., the experimenter pointed first to a bicycle and then to a tricycle and said "This is a dax, and this is a dax too. Can you see why they’re both daxes?". The child was then shown two test objects. One test object was perceptually similar to the standard(s) but belonged to a different category (e.g., eyeglasses). The second test object was not perceptually similar to the standard(s), but belonged to the same taxonomic category (e.g., a skateboard). The child was asked which of these alternatives should be given the same label as the standard (e.g., "Can you show me another dax?").

When given either of the two standards by themselves, children tended to select the perceptual match (the eyeglasses). When shown both standards *together*, children chose the taxonomic match, despite preferring the perceptual match for *either* of the standards presented singly. That is, carrying out a comparison enabled children to override compelling perceptual commonalities in favor of deeper conceptual ones. This outcome provides critical evidence that carrying out a structural alignment facilitates attention to common functional and causal relations over common perceptual features. Thus, when children are invited to compare a pair of objects, they are much more likely to focus on more abstract properties like those that form the basis of taxonomic categorization.

These results show that engaging in a comparison process can actually shift the basis for categorization from perceptual properties to conceptual relations. This is because as predicted by structure-mapping theory, comparison leads to alignment of common relational structure, thereby promoting the relations' salience. This relational focus is most dramatic in a far analogy, where there are few object commonalities; but common relations are promoted to some degree even in close similarity comparisons. Because relations (even core relations such as internal causal or function relations) tend to be less accessible than object features, this alignment process will render relational commonalities more obvious in the pair than in either of the separate exemplars. In other words, the relations "stand more to gain" from this alignment process than do more obvious object properties.

In this section, we reviewed findings that assess the influence of similarity and comparison on cognitive processing in infants and young children. The presence of compelling similarities in the environment supports complex reasoning. These comparisons also enable children to extract more abstract commonalities of items than they would be able to find when considering a single object. Furthermore, these effects occur spontaneously, but they can also be observed when the task calls for a more explicit comparison. In the next section, we turn to a parallel set of phenomena in research with adults.

Changes in adults' processing with similarity

Cognitive processing in adults is typically more strategic than that of children. There are many instances in which the particular strategy that people adopt is influenced by whether the items being processed are similar. We suggest that this effect occurs because similarity affects the way processing resources are allocated. To demonstrate this point, we begin with some results from studies of conceptual combination. Then, we turn to research on decision making. We end with a discussion of research on person perception. In all of these cases, the influences of similarity are likely to be unintentional, because the goal of the task does not require attention to similarity.

Conceptual combination

Conceptual combination is the study of the way people interpret complex noun phrases such as adjective-noun combinations like *the brown apple* and noun-noun combinations like *the turkey apple*. In the present discussion, we will focus only on noun-noun combinations, which have been the subject of extensive research (Costello & Keane, 2000; Gagne, 2000; Gerrig & Murphy, 1992; Murphy, 1988; Wisniewski & Gentner, 1991; Wisniewski & Love, 1998).

In a noun-noun combination like *goose horse*, the first noun typically modifies the second, and so the first noun is called the *modifier*, and the second is called the *head*. Studies of conceptual combination suggest that there are three dominant strategies that people adopt when interpreting novel noun-noun phrases. The first, called *property mapping*, involves carrying over a property from the modifier to the head. For example, a goose horse could be interpreted as a horse with a long neck, in which case the property long neck is carried from goose to horse. The second strategy called *relational combination*,[4] involves positing a relationship between the two nouns. For example, a goose horse could be interpreted as a horse that lives near geese. Finally, some noun-noun combinations are *hybrids*, which involve combining the two concepts on a massive scale. Often, the definition given by a subject simply specifies that the resulting combination is a mix of the two concepts. For example, a goose horse could be interpreted as a mixture of goose and horse. This definition specifies that the referent is such a complete combination of the concepts that the individual components could not be separated out.

An important observation is that the relative frequency of different kinds of combinations changes as a function of the similarity of the constituents of the noun phrase (Markman & Wisniewski, 1997; Wisniewski, 1996; Wisniewski & Gentner, 1991). In general, the more similar the pair, the more likely that it will be given a property mapping interpretation. For extremely similar pairs, hybrid interpretations also become common. One explanation for this phenomenon is that it is easier to align the representations of similar pairs than of dissimilar pairs. This alignment highlights an alignable differences of a pair – e.g., that geese have longer necks than do horses – which can be carried over from the modifier to the head noun in property definitions. When a pair is very similar, their representations are highly alignable, which makes combining the concepts into a hybrid more attractive. Dissimilar pairs, are less likely to be spontaneously aligned, and hence give rise to fewer property mapping definitions.

As support for this account, Wisniewski and Markman (1993) had people interpret conceptual combinations of noun phrases for which other subjects had listed commonalities and differences. They found that the properties carried over in property mapping definitions were much more likely to be alignable differences of a pair than to be nonalignable differences. This phenomenon demonstrates clearly how similarity can affect cognitive processing in indirect ways.

Decision making

Decision making situations are ones in which people have an unsatisfied goal and at least two different courses of action (where one of those courses of action may be to do nothing or to defer the choice). Decision making is particularly interesting to look at from the perspective of nonintentional similarity because people use many different strategies for making choices (Payne, Bettman, & Johnson, 1993). Thus, it is easy to look at how people's strategies shift with the similarity of the options. In addition, at some level all choices require some form of comparison. Economic models predict that options are evaluated abstractly for their goodness or utility and that only these utilities are compared. However, often choice strategies involve comparison of one or more of the more specific attributes of the options (Medin, Goldstone, & Markman, 1995). There are two general points we make in this section. First, increasing the similarity of the options increases the degree to which people compare specific attributes of those options when making a choice. Second, when people compare the options, they tend to focus on the alignable differences of the options rather than on the nonalignable differences.

As one demonstration that similarity of options affects the way people make choices, Johnson (1984) asked people to make choices between options that were comparable (e.g., two toasters) or noncomparable (e.g., toaster and a smoke alarm) at the level of their specific features. For comparable choice sets, people describing their choice process mentioned specific attributes of the options. For example, when choosing between toasters, they might mention the number of slots or the number of heat settings. In contrast, when choosing between noncomparable choice sets, people tended to use abstract attributes like utility. For example, when deciding between a toaster and a smoke alarm, the choice involved which item they needed more. Specific attributes of the products did not enter into the choice. This finding suggests that when the options are comparable, people spontaneously access the commonalities and differences of the options. In contrast, when the options are difficult to compare, other strategies are brought to bear to make the choice.

Ease of comparison also influences the attributes people use to make choices. In a simple demonstration of this point, Tversky and Kahneman (1986) gave people choices between the pairs of gambles shown in Table 1. In these gambles, people would be paid an amount that depended on the color of a marble drawn from a basket. Some people chose between A and B, and others chose between C and D. Gamble A is clearly better than Gamble B, because the green marble has a higher payoff and the blue one a lower loss for Gamble A than for Gamble B. Consistent with this analysis, everyone in the group given this pair of gambles selected gamble A. Gambles C and D are equivalent to A and B. Gamble C is created from Gamble A by merging the green marble into the set of red marbles. Gamble D is created from Gamble B by merging the blue marble into the set of yellow marbles. Despite the fact that Gamble C is strictly better than Gamble D in the same way A is to B, 58% of the people given the choice between Gambles C and D chose D. This choice is based on the fact that a comparison of the outcomes of C and D makes salient the loss of $10 versus the gain of $30 associated with the green marble. Thus, people appear to be focusing on the attributes that are easy to compare rather than calculating the expected value of the gamble, which is a more general measure of a gamble's goodness.

From the standpoint of structural alignment, strategies that involve property comparisons are particularly interesting, because decisions must focus on the differences among options. Some research has explored whether people spontaneously use alignable differences among options rather than nonalignable differences. In a classic set of studies, Slovic and MacPhillamy (1974) found that people making judgments about which of a pair of students would have a higher GPA were more likely to make use of scores on a test that both had taken (i.e., an alignable difference) than scores on a test that only one of them had taken (i.e., a nonalignable difference). More generally, it has been observed that people tend to discount dimensions for which one option has a missing value relative to dimensions for which all options have a value (Markman & Medin, 1995; Ross & Creyer, 1992; Sanbonmatsu, Kardes, & Herr, 1992).

In one set of studies, Zhang and Markman (1998) looked specifically at the use of alignable and nonalignable differences in choice. A series of three novel brands of microwave popcorn were introduced across two experimental sessions. In the first session, subjects were exposed to a description of one brand of popcorn which was described by 10 attributes. In the second session, the initial brand was shown again followed by descriptions of two other brands that also were described by 10 attributes. Across the set, four of the attributes were commonalities of all of the brands. Three of the attributes were alignable differences. Finally, three of the attributes were nonalignable differences. People were better able to recall the alignable differences than the nonalignable differences. In addition, the alignable differences had a bigger impact on people's preferences than did the nonalignable differences. This finding suggests that people spontaneously compared the attributes of the new brands to the attributes of the brand learned first in the course of forming their preferences (though see Zhang & Markman, 2001 for a discussion of boundary conditions on the use of alignable differences).

Two central conclusions can be drawn from this research on decision making. First, the ease with which options can be compared affects what kind of information is available for choice processing. When the options can be compared easily, then their attributes are used to make a decision. When the options cannot be compared easily, choice strategies that involve more abstract evaluations of the options are brought to bear. Second, when the choice sets are comparable, the alignable differences among options are often more important to people's decisions than are nonalignable differences. These effects occur despite the fact that there is no explicit direction to compare the attributes of the options. Comparisons occur as a byproduct jointly considering the two alternatives, and strongly influence choice processing.

Situation perception and person perception

One influence of comparisons that we have not yet addressed involves the way that known information influences the way that new items are represented. People spontaneously make comparisons between background knowledge and new situations that affect how those situations are perceived. The background knowledge that gets used may be general schemas or it may involve specific instances. In this section, we start with influences of remindings in physical arena. Then we move to effects of comparisons on person perception.

Comparisons of new situations to known situations are common in cognitive processing. One area where this has been explored in some detail is in research on analogy and metaphor. Analogies and metaphors are often used to help people structure their knowledge about a new domain by carrying over the relations from a known domain. In one extended analysis, Gentner and Gentner (1983) examined the way people reasoned about the flow of electricity based on whether they conceptualized it as being like the flow of water or like the movement of a crowd. Some aspects of electricity are reasonably easy to conceptualize using either analogy. For example, both analogies help people to differentiate current from voltage. However, these analogies are not equally good at explaining all aspects of electricity. For example, in the moving-crowd model it is much easier to reason about resistors than about batteries. In contrast, the flowing water model is more transparent for batteries than for resistors. As would be predicted by this analysis, when asked to reason about circuits with combinations of components in series or in parallel, people who held the moving-crowd model were relatively better at reasoning about combinations of resistors than about combinations of batteries, and the reverse was true for people with the flowing water model.

The application of analogical systems also occurs in real life, sometimes with little explicit awareness. For example, Kempton (1986) studied the use of analogies in people's naive theories of home heat control. A thermostat can be conceptualized as being like a switch or as being like an accelerator. The switch model (which is the correct one) suggests that when the temperature in a room cools to a certain point, a switch goes on and the heater starts. The heater continues operating until the temperature exceeds the set point, at which time the heater shuts off and the cycle continues. The accelerator model says that the amount of heat that is produced by the heater is proportional to the difference between the current temperature and the set point, just as pressing down the accelerator of a car further increases the amount of gas that reaches the engine and hence the speed of the engine. People who hold this incorrect model tend to change their thermostats more times each day and tend to use more energy to heat their homes.

As a further example, historians have examined the influence of analogies such as the domino theory on political decisions (Glad & Taber, 1990). Before the United Nations intervened in the Korean War, the political situation was often framed using an analogy of falling dominos in a line, where the fall of a single domino causes the entire line to collapse. On this analogy, communism was an external force pressing on the governments of countries. If one government fell, then many others would follow soon after. As a consequence of this analogy, the communist insurgency in Korea was viewed as coming from the outside, and thus the United Nations could intervene. Had this same conflict been viewed as a civil war, the United Nations would not have been able to get involved.

To complete this discussion, it is important to recognize that mappings between domains can become conventionalized. For example, Lakoff and Johnson (1980) discuss a number of metaphorical systems in English in which a domain is described in terms initially used by a second (e.g., "He was boiling mad."). We suggest that such systems come about through a process in which repeated comparisons lead to progressive abstraction of metaphorical meanings (much as in the sequential categorization models discussed earlier). This conventionalization process results in the existence of alternative meanings for words that once were active metaphors (Gentner & Wolff, 1997). For example, the verb ‘boil’ now has a metaphorical meaning -- ‘to become emotionally agitated [like a boiling liquid]’ -- as well as its literal meaning.

There are also more global metaphoric systems. For example, Gentner, Imai and Boroditsky (in press; Gentner, 2001) showed that space-time metaphors are comprehended in terms of two different global systems of mappings, rather than on an individual lexical basis. In particular, there are two main spatial metaphors for time. In one, an individual moves through time (e.g., "We are approaching Christmas."). In the other, time moves toward the individual (e.g., "Christmas is approaching.") Gentner et al. showed that people are faster at processing a sequence of temporal sentences if the sentences remain in the same space time metaphor; there appears to be a processing cost for a shift from one of these metaphor systems to the other.

Further, Boroditsky (2000) demonstrated that the mapping is asymmetric: people conceptualize time in terms of space. In one study, people were primed with pictures of individuals moving past objects or of objects moving on a conveyor belt past people. Then, they were given the sentence "Wednesday’s meeting has been moved forward two days," and were asked to state on what day the meeting would occur (McGlone and Harding, 1998).

If space-time priming occurs, the two spatial situations should prime different interpretations of the temporal sentence. A person moving past a set of objects should prime the ego-moving metaphor system. In contrast, objects moving past a person should prime the time-moving metaphor. Consistent with these predictions, people in the moving-person condition considered that moving the meeting forward changed it to Friday, whereas people in the moving-object condition considered that the meeting was moved to Monday. Furthermore, the reverse priming could not be obtained. That is, using different metaphors for time did not influence people's reasoning about space.

The use of background knowledge is also important for forming impressions about people. Theories of social comparison (e.g., Festinger, 1954 ; Goethals & Darley, 1977) have acknowledged the diagnostic advantages of comparisons with standards who are similar in critical ways. Similarity is important in social comparison processes in at least two ways. There is considerable evidence that perceived similarity influences the selection of a standard. Second, the psychological consequences of social comparisons for self-evaluation, affect, and behavior also depend critically on the perceived similarity to the standard (e.g., Brown, Novick, Lord, & Richards, 1992; Catrambone, Beike, & Niedenthal, 1996; Gilbert et al., 1995; Lockwood & Kunda, 1997; Mussweiler, in press) Mussweiler and Gentner (in preparation) found evidence that social comparisons involve a process of structural alignment and mapping. Selection of a standard was sensitive not merely to surface commonalities between the self and the social comparison standard (e.g., being good at sports), but also to higher-order relational structures (e.g., caring enough about mastery in some arena – whether sports or music -- to sacrifice greatly to achieve it). Further, consistent with the framework already presented, making a social comparison appears to render the common information more accessible.

Social comparison is also an important influence on first impressions. When we meet a new individual, we typically have a limited set of interactions with them. Nonetheless, we are quickly able to form impressions about their characteristics and to determine whether this person is someone we want to get to know better. An intriguing set of findings by Andersen and colleagues (Andersen & Cole, 1990; Chen & Andersen, 1999; Chen, Andersen, & Hinkley, 1999) suggests that similarities between new people and particular known individuals affect how the new person is perceived. As a demonstration of this point, subjects in experiments are asked to describe the characteristics of a significant other such as their mother. The same subjects are asked to participate in an unrelated study at another time. They are given descriptions of new people, some of whom have characteristics in common with the significant others they described. People are more likely to attribute other characteristics of their significant other to the new person than are control subjects who did not have this significant other. This finding suggests that similarities of a new person to known individuals have a strong influence on the way the new person is represented (see Chapter xx in this volume).

To summarize, comparisons between new situations and background knowledge have an important influence on the way people represent and reason about the new situation. These comparisons often happen spontaneously. The point of having background knowledge is to enable a reasoner to recognize when they are in a familiar situation and to apply previous strategies to new cases. Initially, the relationship between a new domain and existing knowledge must involve an active comparison between domains. Eventually, however, if a mapping between domains is important enough to reoccur, it may be stored and become part of the background for the domain.

Conclusions

In this chapter, we have examined a number of influences of similarity on cognitive processing. These effects often occur spontaneously in cognitive processing, though some of the experiments we described involved tasks in which people were directed to make comparisons. We discussed four central influences of similarity on cognitive processing. First, comparisons may help people to see more abstract commonalities between situations than they would be able to find if only one domain were explored in isolation. We demonstrated this point with a number of developmental studies involving infants and young children. Second, the presence of similarities between items can influence cognitive processing by making specific properties of the items readily available. In particular, comparable pairs promote access to the commonalities and differences of items, which can then influence processing. Third, the presence of some similarities among items can be used as a signal that additional processing resources should be devoted to exploring a pair. This metacognitive aspect of similarity is evident in demonstrations that similarities influence looking time in infants and response times in adults. The similarity processes that give rise to these metacognitive judgments also appear to incorporate other information like associations between terms that may signal that additional processing would be useful.

Finally, new situations are spontaneously compared back to previous experiences. These comparisons facilitate the representation of the new domain. Comparisons that are made frequently may become stored concepts.

Another important aspect of similarity is the distinction between the full structural alignment process and cheaper kinds of similarity processing. We suggested, first, that a quick, cheap similarity process is used to generate remindings from long-term memory; and, second, that early in any similarity comparison the processing is a kind of free-for-all of local matches. When the process of comparison is carried further, however, it results in the alignment of the representational structures of the two items. These comparisons promote noticing the commonalities and alignable differences of pairs, which can then be used in a variety of cognitive processes such as decision making, reasoning, problem solving, and person perception.

We suggest that these similarity processes are always active. In particular, the comparison process that influences metacognitive judgments need not be under conscious control, and need not yield products that are consciously accessible. Thus, the presence of similarities among items may have unintended influences on higher-level cognitive processes, because attentional resources may be allocated on the basis of nonintentional similarity comparisons.

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Footnotes

[1] Formally, the process of finding the maximal match between two predicate structures is a variant of the problem of matching two arbitrary directed acyclic graphs. This problem is known to be in the class of NP-complete problems, meaning that the effort required to perform the computation is some exponential function of the size of the representations (see Falkenhainer, Forbus, and Gentner, 1989, for more discussion).

[2] There are of course cases of stored similarity links – such as *horse* and *zebra* – that may be retrieved from memory like other stored associations. What we are contrasting here is newly computed similarities vs. stored associations.

[3] Interestingly, the looking-time measure used in the study by Gomez and Gerken (1999) showed the opposite pattern from that found by Marcus et al. (1999). Infants in this study looked reliably longer at new strings that followed the training grammar than at strings that did not follow the training grammar. The source of this difference is not clear. One possibility is that the materials used by Gomez and Gerken were more complex than those used by Marcus et al., which could lead to a preference for familiar strings (Cohen, 2001).

[4] This terminology is unfortunate, because "relational" combinations actually involve associative relations rather than relational commonalities.

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Table 1. Choice options from Tversky and Kahneman (1986).

	Marble Color				
Option	White	Red	Green	Blue	Yellow
A					
Percentage	90	6	1	1	2
Outcome	$0	Win $45	Win $45	Lose $10	Lose $15
B					
Percentage	90	6	1	1	2
Outcome	$0	Win $45	Win $30	Lose $15	Lose $15
C					
Percentage	90	7	1		2
Outcome	$0	Win $45	Lose $10		Lose $15
D					
Percentage	90	6	1		3
Outcome	$0	Win $45	Win $30		Lose $15

Figure Captions

Figure 1. (a) A geometric configuration used as an example of information that is available in similarity comparisons. (b) A simple feature list describing these configurations. (c) A graph of structured representations that describe the configurations. The ovals in the graph are relations, the bold round rectangles are attributes, and the light round rectangles are entities.

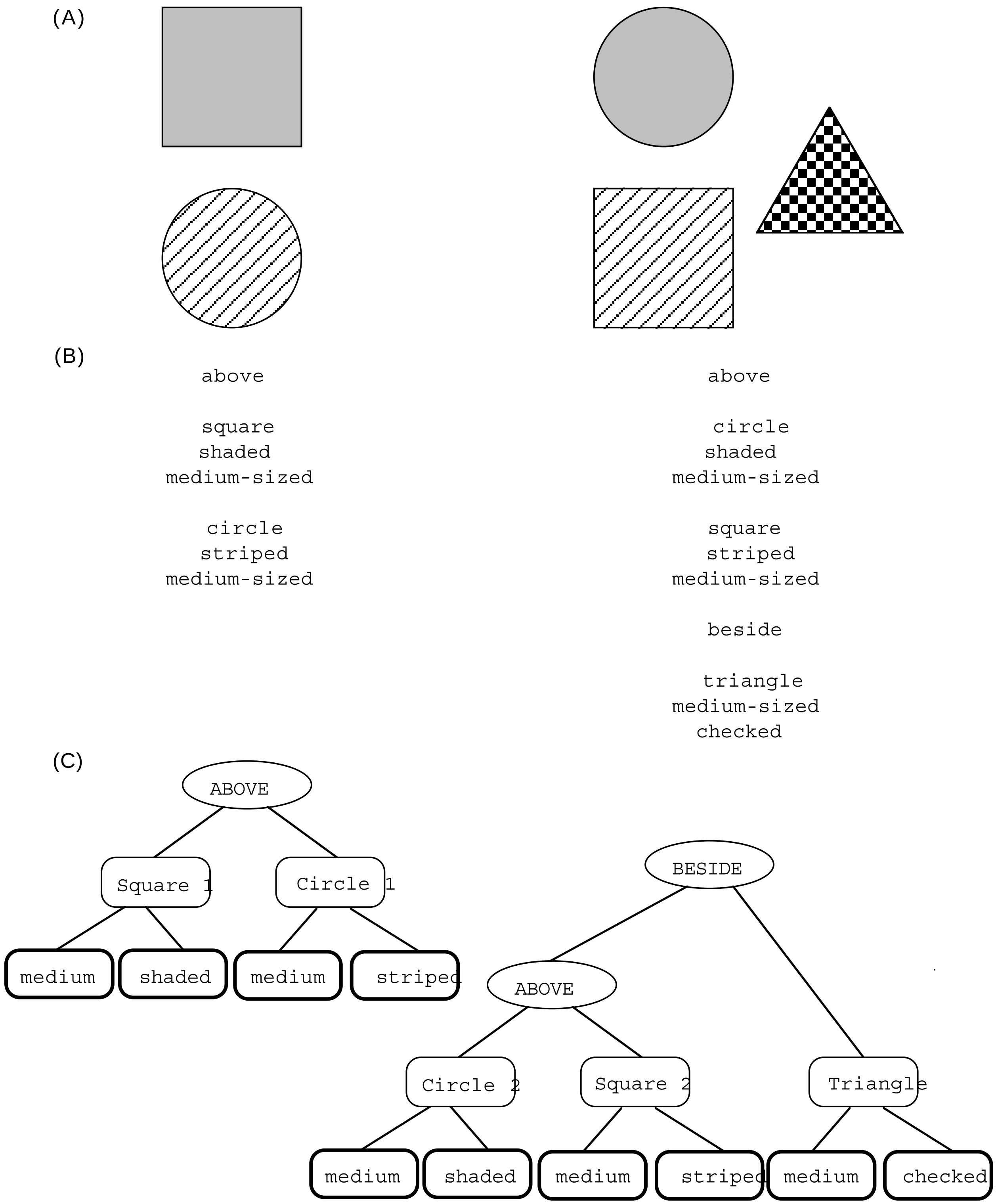
(A)
(B)
above
square
shaded
medium-sized
circle
striped
medium-sized
above
circle
shaded
medium-sized
square
striped
medium-sized
beside
triangle
medium-sized
checked
(C)
ABOVE
Square 1
Circle 1
medium
shaded
medium
striped
BESIDE
ABOVE
Circle 2
Square 2
Triangle
medium
shaded
medium
striped
medium
checked

Figure 1.