

What It Means to Be "the Same": The Impact of Relational Complexity on Processing Efficiency

James K. Kroger (KROGER@LIFESCI.UCLA.EDU)

Department of Psychology

Brain Research Institute

Keith J. Holyoak (HOLYOAK@LIFESCI.UCLA.EDU)

Department of Psychology

University of California, Los Angeles

Los Angeles, CA 90095-1563, USA

Abstract

The fundamental relations that underlie cognitive comparisons -- "same" and "different" -- can be defined at multiple levels of abstraction, which vary in relational complexity. We compared reaction times to decide whether or not two sequentially-presented perceptual displays were the same at three levels: perceptual, relational, and system (higher-order relations). For both 150 msec and 5 sec inter-stimulus intervals, decision time increased with level of abstraction. Sameness at lower complexity levels contributed to decisions based on the higher levels. Relations at multiple levels of complexity can be abstracted and compared in working memory, with higher complexity levels requiring more processing time. Multiple levels can cooperate to reach a decision.

Introduction

Perhaps the most fundamental psychological relation is *sameness*. The capacity to recognize that two objects, situations, or events are the same with respect to a certain criterion underlies object recognition, categorization, and analogical reasoning. It is apparent that the concept of sameness can vary enormously in abstraction. At an implicit level, all vertebrates (and many invertebrates as well) can treat distinct but similar entities as the same (e.g., as prey). More complex comparisons can be made by explicitly identifying dimensions of variation, making it possible to treat objects as the same based on multiple criteria. A monkey, for example, can select which object is the same as another on the basis of shape (ignoring location) or on the basis of location (ignoring shape). An adult human is capable of far more abstract comparisons, such as recognizing that *West Side Story* has the "same" relational structure as *Romeo and Juliet*, despite the considerable surface differences. It has been suggested that human capacity to recognize sameness at abstract levels is closely linked to the evolution of prefrontal cortex (Holyoak & Kroger, 1995). Increasing ability to detect sameness of entities based on similar relationships among their components occurs as species' cortical development becomes

more advanced, and as humans mature from childhood into adulthood.

Defining the levels of abstraction at which sameness can exist involves variations in *relational complexity*. A number of theorists have proposed variants of a three-level taxonomy of relational complexity based on the predicate-argument structure of propositions (Gentner, 1983; Halford, 1993; Holyoak & Thagard, 1995; Premack, 1983). Gentner distinguished sameness at the levels of attributes (one-place predicates), first-order relations (multi-place predicates with objects as arguments), and higher-order relations (multi-place predicates with at least one argument in the form of a proposition). Halford (1993) linked relational complexity to working-memory capacity. Premack (1983) proposed that a more abstract level of sameness distinguishes the reasoning ability of chimpanzees trained in manipulation of symbolic tokens from that of their untrained conspecifics. Holyoak and Thagard (1995) extended Premack's analysis to account for the further gap that separates the reasoning ability of symbol-trained chimpanzees from that of humans.

Consider a basic comparison task such as match-to-sample (e.g., Fuster, 1989). If an apple is presented as the sample, a monkey can be trained to select an apple (rather than a hammer) as the match; if the sample is then varied, the animal will continue to select the alternative that is the same shape as the sample. This task can be performed by making a *perceptual* match between two objects.

Premack (1983) describes a pairwise version of the match-to-sample task, in which the sample is a pair of objects (e.g., apple-apple), and the alternatives are also pairs (e.g., hammer-hammer versus shoe-flower). Only symbol-trained chimpanzees are able to choose the "same" alternative in the pairwise task. This task is more complex because the match must be made on a relation, rather than directly between physical objects. That is, it is necessary to code apple-apple as "same objects", or *O-same*, and to recognize that hammer-hammer is also *O-same*, whereas shoe-flower is *O-different*. The task thus requires a *relational* match.

Holyoak and Thagard (1995) observed that a further increment in relational complexity is required to represent sameness of relations so that analogical matches can be

recognized. The match-to-sample task can be further generalized to items based on *pairs* of pairs. The relation between apple-apple (O-same) and that between hammer-hammer (O-same) are themselves the same relation, or *R-same* (a higher-order relation between relations). Recognizing this abstract sameness would allow a match to shoe-flower (O-different) and bottle-bell (O-different), as the relation between the latter relations is again R-same, even though there is no overlap either of objects or first-order relations. This deeper level of sameness requires a *system* match.

The present study introduces a speeded matching task related to these variants of match-to-sample. We compare the time required to make matches between visual displays at either the perceptual, relational, or system level, while holding the physical characteristics of the displays as constant as possible. We hypothesized that higher complexity levels would require more processing time. By varying sameness at lower complexity levels, we also sought to determine whether each type of match is made independently, or whether multiple levels of representation can cooperatively contribute to a decision. We examined the impact of relational complexity on decision time at both short (Experiment 1) and longer (Experiment 2) inter-stimulus intervals.

Experiment 1

Method

Participants Thirty-eight UCLA undergraduates participated in the experiment as part of the requirements of an introductory psychology course.

Materials, Design and Procedure The experiment was controlled by an Apple Macintosh computer with a color monitor. A computer program presented all instructions and stimuli and recorded responses and reaction times (RTs) for each trial. Stimuli consisted of a group of four colored squares (blue, green, red, or gray) arranged as shown in Figure 1, presented against a black background. The overall figure was 1.6" high and 1.5" wide. Participants sat approximately 30" from the screen, with their index fingers resting on the computer keyboard.

Each stimulus remained on the screen until the subject pressed a response key. Participants were instructed to indicate for each figure whether it demonstrated the "designated change" relative to the previous figure (except that no response was made for the first figure). Responses were indicated by pressing the "c" key (change) or "n" key (no change) on the computer keyboard. Two seconds after the response, the figure was replaced by a black screen for 150 msec, after which the next stimulus appeared. One trial consisted of a presented figure and the participant's response, indicating whether or not each figure was changed in a prescribed way from the previous figure. The stimuli were presented in a continuous fashion, so that each figure (after the first) was first compared to the preceding figure on one trial, and then served as the comparison figure for the next trial.

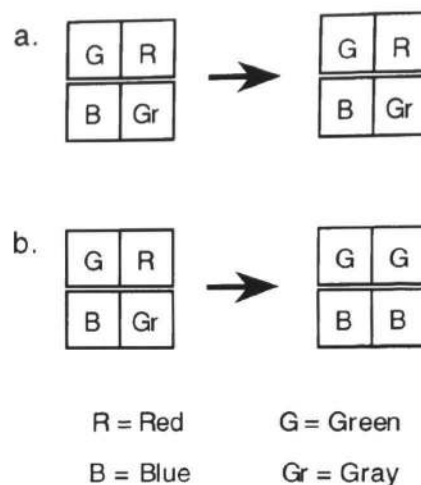


Figure 1. Examples of two trials. Either could occur in any of the complexity conditions. In (a) the second figure is the same as the first at all three levels of complexity. The figures in (b) are different at the perceptual and relational levels but are the same at the system level.

Three kinds of designated change were described to participants, corresponding to three levels of relational complexity. These three decision criteria were used in separate blocks of trials. In the *perceptual* condition, a "change" was defined as any change in the color of one or more squares in the preceding figure (e.g., top left square changing from red to green).

In the *relational* condition, a "change" was defined in terms of the relations between the colors of the squares within each of the two pairs (top and bottom). For example, if both squares in a pair were red (O-same), then a relational change would require that the corresponding pair in the next figure be of different colors, or O-different (e.g., green-blue would define a change, whereas green-green would not). Similarly, if the initial pair were O-different (e.g., red-green), then green-green (O-same) would count as a change, but green-blue (O-different) would not.

In the *system* condition, a change was defined in terms of the higher-order relation between the sameness relations for the two pairs. For example, if the initial figure consisted of red-red (O-same) above green-blue (O-different), then the higher-order relation between these two relations would be R-different. Accordingly, if the next figure presented consisted of red-red (O-same) above green-green (O-same), forming a higher-order relation of R-same, this would count as a change. In contrast, if the next figure were red-gray (O-different) above green-green (O-same), the higher-order relation would remain R-different (i.e., no change).

The program presented animated instructions explaining the designated change for the first condition (including two examples), administered practice trials until five consecutive correct responses were obtained, and executed a block of trials for that condition. This was followed by instructions, practice, and a trial block for each of the two remaining level-of-complexity conditions. Six more blocks of trials

followed, each preceded by a short paragraph indicating the designated change for that block. The nine twenty-trial blocks (three for each level-of-complexity condition) formed a Latin square design that controlled for order effects. Successive trial blocks were separated by a rest period of approximately 15 seconds.

An equal number of Match (no change) and Mismatch (change) trials were randomly ordered within each level-of-complexity condition. In the perceptual condition Match trials, all four squares were the same color as in the previous figure. In the Mismatch trials for the perceptual condition, two randomly chosen squares were of different colors relative to the previous trial. When a square changed colors from one trial to the next, the color was randomly chosen among the other three colors.

Since judgments at the relational and system levels of complexity did not depend directly on whether squares were the same color as in the previous figure, it would have been possible to change all the squares' colors on any given trial. However, we wished to induce participants to perform the desired comparisons at greater levels of complexity while keeping the number of actual color changes among the four squares generally consistent with the number of squares changing color in the perceptual trials. Accordingly, a rather complex scheme of color changes was adopted for the two higher complexity conditions so as to implement the designated changes for trials in the higher complexity conditions in a way that counterbalanced the frequency of changes among squares and pairs, while also minimizing the number of squares changing colors on a given trial. The effect of the scheme was to ensure that the number of individual squares changing color from one figure to the next was approximately equated across all complexity levels.

Results and Discussion

As depicted in Figure 2, mean correct RTs increased monotonically with complexity level (means of 1095, 1340 and 1727 msec, respectively, for the perceptual, relational, and system conditions), $F(2, 74) = 63.86$, $MSE = 120556$, $p < .0001$. Errors rates also increased with complexity level (9, 13 and 14 percent, respectively), indicating that the RT pattern cannot be attributed to a speed-accuracy trade-off. Overall, decisions were faster for Match than for Mismatch trials (1282 versus 1493 msec), $F(1, 37) = 48.70$, $MSE = 52034$, $p < .0001$. Trial type interacted with level of complexity, $F(2, 74) = 8.83$, $MSE = 20720$, $p < .001$ (Figure 4), reflecting a smaller difference between Match and Mismatch trials for the perceptual condition.

The increase in decision time as complexity level increased supports the hypothesis that manipulating representations at higher levels of relational complexity places greater demands on processing capacity. It should be noted that this pattern is actually opposite to that predicted by the minimal number of cross-stimulus comparisons required at each level. At the perceptual level a "match" decision requires four comparisons (one for each individual square). At the relational level a "match" decision requires two comparisons (one for each pair, based on the relations O-same or O-different). At the system level a "match"

decision requires one comparison (for the overall higher-order relation between pairs, R-same or R-different). Our results indicate that any reduction in load due to the lesser number of required cross-stimulus comparisons for higher complexity levels is more than offset by the increase in the time required to construct and manipulate more abstract relations.

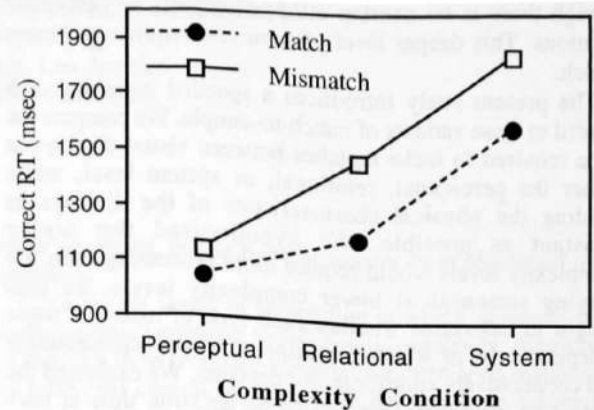


Figure 2. Mean correct RTs for perceptual, relational, and system conditions.

More detailed aspects of the results allow us to test alternative processing accounts of how higher level decisions are made. One possibility is that decisions at each level are independent of one another. At each level, decisions could be based solely on the most abstract relevant code, which in effect summarizes all lower level information. For example, a system decision could be made by deriving the higher-order relation for the first stimulus, doing the same for the second stimulus, and then comparing the two higher-order relations. Alternatively, decisions at the higher levels may be interdependent with those at lower levels. Rather than deciding solely on the basis of the most abstract relevant code, a decision could be based on a mapping between full representations at each level. For example, in an interdependent processing model, a system decision could be made by mapping multiple representational levels, with each stimulus being encoded not only by a single higher-order relation, but also by the first-order relations for each pair, and the color attributes of each individual square.

The independent and interdependent processing models can be distinguished by examining whether or not lower level matches have any effect on the time to assess higher level matches. Such cross-level effects would support an interdependent model in which cooperative processing occurs. For each of the two higher complexity levels, we examined RTs for types of trials that varied in the degree of support provided by lower levels for the correct decision. Note that if all four squares match across figures at the perceptual level, then the figures are necessarily the same at both the relational and the system level. Similarly, if both pairs match at the relational level, then the figures must match at the system level. (Neither converse holds.) Figure 3 presents mean correct RTs for the various item types. The

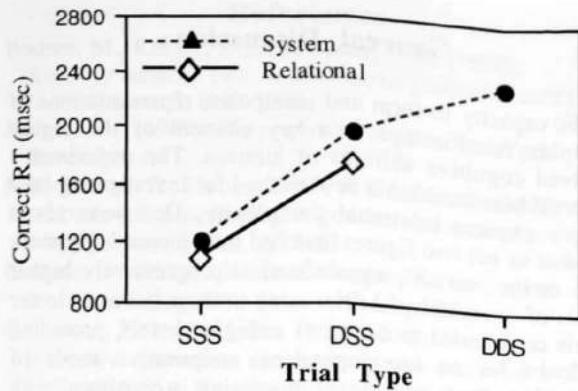


Figure 3. Mean correct RTs for relational condition and system condition Match trials as a function of support from matches at lower complexity levels.

types are described by a three-letter code signifying whether the figures match (S, for "same") or mismatch (D, for "different") at the perceptual, relational and system levels. For example, SSS trials yield a match at all three levels; DDS trials yield a mismatch at the perceptual and relational levels, but a match at the system level.

The results (see Figure 3) provide clear support for interdependent processing. At the relational level, RT was lower for SSS than for DSS trials (1088 versus 1726 msec), $F(1, 31) = 38.80$, $MSE = 167430$, $p < .0001$. In SSS trials, but not DSS trials, a lower-level perceptual match supports the required relational match. Similarly, at the system level RT increased across SSS, DSS, and DDS trials (1207, 1961 and 2371 msec, respectively), $F(2, 70) = 71.36$, $MSE = 175928$, $p < .0001$. Lower level matches led to faster matches at the most abstract level; and when both lower levels of complexity supported a match at the system level, decisions were faster than when only the relational level provided support. It appears that multiple levels of representation operate cooperatively; decision efficiency at the system level increases with the number of lower levels that support the higher level decision.

A more serial processing model might be proposed as an alternative to cooperative processing. Perhaps participants became aware of the conditional implications relating matches at lower levels to matches at higher levels, and adopted a strategy of serially checking for matches from the least to most complex level, responding at the first level that yielded a firm decision. This strategy could be applied for all three types of designated changes. For example, if a match is found at the perceptual level (SSS trials), then a "match" response would be made immediately, regardless of the nominal complexity level. This strategy, rather than cooperative processing at multiple levels, could explain the reduction in RTs observed when a higher level match was supported by lower levels (Figure 3).

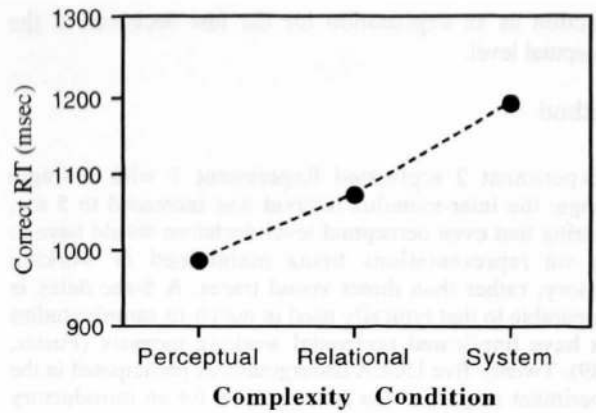


Figure 4. Mean correct RTs across complexity levels for SSS trials, for which a "match" response might always be generated at the perceptual level.

This serial self-terminating strategy predicts that RTs will depend solely on the lowest complexity level that generates a decision. In particular, "match" responses for SSS trials should be equal across complexity levels. But as Figure 4 indicates, RTs for SSS trials increased monotonically with complexity level (986, 1074 and 1194 msec, respectively), $F(2, 72) = 11.83$, $MSE = 33841$, $p < .0001$. Thus, "match" decisions for perceptually identical stimuli varied with complexity level, even though it would have been possible in principle to always generate a "match" response at the perceptual level. The combination of variations in RTs for different trial types *within* complexity levels (Figure 3) and variations in RTs for the same trial type *across* complexity levels (Figure 4) is uniquely accounted for by a cooperative processing model.

An alternative explanation of increasing RT across complexity conditions might focus on the total number across-stimulus *plus* within-stimulus comparisons necessary for each trial, considered with subjects' opportunity to respond in perceptual trials as soon as a difference is detected (which would decrease the number of comparison performed on average). In the SSS trials no such premature termination is possible, and the total number of within-stimulus *plus* across-stimulus comparisons is four per trial in all three conditions. The increase in SSS RTs across conditions can be attributed only to increasing relational complexity of the required comparisons.

Experiment 2

It might be argued that the monotonic increase in RTs across complexity levels observed in Experiment 1 could be partly attributable to some sort of automatic "pop-out" that facilitated detection of changes at the perceptual level. The brief inter-stimulus interval (150 msec) might have allowed iconic memory for the first figure to provide a basis for automatic change detection. As our interest is in the influence of complexity level on deliberate, attentional processing, we wished to rule out automatic change

detection as an explanation for the fast decisions at the perceptual level.

Method

Experiment 2 replicated Experiment 1 with a single change: the inter-stimulus interval was increased to 5 sec, ensuring that even perceptual level decisions would have to rely on representations being maintained in working memory, rather than direct visual traces. A 5-sec delay is comparable to that typically used in match-to-sample studies that have implicated prefrontal working memory (Fuster, 1989). Twenty-five UCLA undergraduates participated in the experiment as part of the requirements for an introductory psychology course.

Results and Discussion

The pattern of results observed in Experiment 1 was fully replicated in Experiment 2. Figure 5 (comparable to Figure 2 for Experiment 1) depicts the monotonic increase in RTs as complexity level increased (1577, 1830, and 2054 msec for the perceptual, relational, and system conditions, respectively), $F(2, 48) = 18.40$, $MSE = 44903$, $p < .0001$. Error rates also increased across levels (12, 17, and 17 percent, respectively). Match trials were significantly faster than Mismatch trials, $F(1, 24) = 27.69$, $MSE = 127183$, $p < .0001$, and the two factors yielded an interaction, $F(2, 48) = 3.55$, $MSE = 44903$, $p < .05$, reflecting a smaller Match advantage at the perceptual level. We also performed analyses of the various trial types across complexity levels as in Experiment 1. These analyses yielded the same patterns as those depicted in Figures 3 and 4. The close replication supports the robustness of the findings. The use of a 5-sec delay in Experiment 2 indicates that the relatively fast decisions in the perceptual conditions are not attributable to automatic visual processes, but rather to deliberative processes applied to working-memory representations of low complexity.

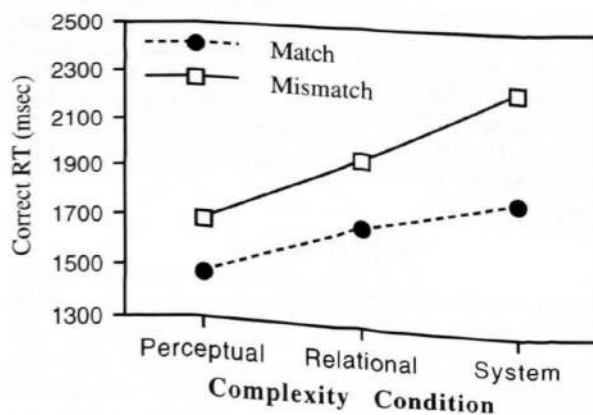


Figure 5. Mean correct RTs for perceptual, relational, and system conditions with a 5 second intertrial delay.

General Discussion

The capacity to form and manipulate representations of complex relationships is a key element of the highly evolved cognitive abilities of humans. The experiments reported here establish a new method for investigating how people process relational complexity. Decisions about whether or not two figures matched took increasingly more time as the "match" was defined at progressively higher levels of complexity. At the same time, matches at lower levels contributed to decisions at higher levels, providing evidence for an interdependent, cooperative mode of processing. Such multi-level processing is consistent with computational models of analogical mapping (e.g., Falkenhainer, Forbus & Gentner, 1989; Holyoak & Thagard, 1989; Hummel & Holyoak, 1997), as well as with interactive models of similarity judgments (Goldstone & Medin, 1994). Our results are broadly consistent with other evidence from tasks based on unspeeded similarity judgments, which also have found evidence that people abstract and use higher-order relations derivable from perceptual displays (Goldstone, Medin & Gentner, 1991; Markman & Gentner, 1993).

The overall pattern of relational processing was virtually identical regardless of whether the inter-stimulus interval was brief (150 msec in Experiment 1) or longer (5-sec in Experiment 2). Responses were about 300 to 500 msec longer when the interval was longer, and accuracy decreased slightly across conditions, consistent with previous findings concerning the effect of delay in match-to-sample studies (e.g., Bodner, Kroger, & Fuster, 1996). Fuster (1989) has argued that humans' highly advanced frontal lobes permit them to use symbolic representations of contingency relationships; the frontal lobes are brought progressively into play when such relationships become complex or must be retained across time in the absence of actual stimuli. It appears from our results that this generalization may be extended to the processing of relational complexity. Relational complexity probably engages some of the same neural architecture that has been the object of match-to-sample research. Our findings suggests that frontal cortex underlies the ability to manipulate relational information at a level of complexity that sets human cognition apart from that of lower primates.

Acknowledgements

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