PAPER IN PROGRESS

Representation of Elements and Relations across Informational Structures: Evidence for General Cognitive Mechanisms of Feature Processing

Aaron S. Yarlas (yarlas.1@osu.edu)
The Ohio State University, Center for Cognitive Science, 21 Page Hall, 1810 College Road
Columbus, OH 43210 USA

Vladimir M. Sloutsky (sloutsky.1@osu.edu)
The Ohio State University, Center for Cognitive Science, 21 Page Hall, 1810 College Road
Columbus, OH 43210 USA

Abstract

Previous studies using a categorical recognition task (Sloutsky & Yarlas, 2000a, 2000b; Yarlas & Sloutsky, 2000) elicited three reliable findings in feature processing of arithmetic equations: 1) participants were capable of representing both elementary and relational features of equations, 2) elements and relations were processed serially, with elements processed prior to relations, and 3) participants exhibited an element-relation response-competition, such that responses took longest to recognition items for which elements but not relations were similar to study items. The two reported experiments examined whether these findings would replicate for other types of informational structures (i.e., propositional logic and spatial arrangements) to determine the generality of these phenomena.

Introduction

The processing of elementary and relational features has important implications for understanding the general cognitive mechanisms that determine how people represent the informational structure of the environment. When we perceive, think, or act, we encounter a world consisting of entities that are connected spatially, temporally, or conceptually into larger arrangements. While individual entities or separable features of these entities can be considered elements of these arrangements, the manner in which elements are arranged can be considered relational aspects of arrangements. These relations among elements can take many forms, such as spatial (e.g., “above” or “below”), temporal (e.g., “before” or “after”), quantitative (e.g., “more” or “less”), or conceptual (e.g., “giver” or “taker”).

There are several theoretical proposals arguing for a separate psychological status for elementary and relational features, based upon evidence indicating differential processing of elements and relations among elements (Goldstone, Medin, & Gentner, 1991; Medin, Goldstone, & Gentner, 1990; Goldstone & Medin, 1994; Ratcliff & McKoon, 1989). These proposals are based on findings indicating that elementary features are encoded and processed prior to relations among elements.

Additional regularities in structure processing have been established in a series of studies by Sloutsky and Yarlas (2000a, 2000b; Yarlas & Sloutsky, 2000). These studies directly examined processing of elementary and relational features in the domain of arithmetic. These experiments introduced a categorical old/new recognition procedure, in which mathematics novices were initially presented in a study phase with arithmetic equations that were comprised of particular levels of elementary features (e.g., all numbers were between 1 and 9, all equations had 5 or 6 addends) and relational features (e.g., the associative and commutative principles). In the recognition phase, subjects were presented with a number of equations: some that were Old targets that had been presented earlier in the study phase, and some that were new foils. Some of these foils shared elementary features with the study equations but not relational features (E+/R-), whereas others shared relational but not elementary features (E-/R+). Additionally, some foils shared neither elementary nor relational features (E-/R-), while others shared both types of features but were not actual equations shown in the study phase (E+/R+). This last foil is particularly important in assessing a fundamental assumption of this procedure, that subjects will have categorical memory for the study items rather than a specific-item memory. If this assumption is correct, then there should be high confusability between E+/R+ foils and Old targets. Indeed, across all of these studies, the proportion of subjects’ “Old” responses for these two types of items have been statistically equivalent.

These studies found that when given an ample amount of time (i.e., 10 seconds) to view arithmetic equations in the study phase, subjects accurately judged both E- foils and E+/R- foils to be “New”. Data also indicated that subjects were faster to reject E- foils than to reject E+/R- foils and to accept Old targets and E+/R+ foils. These findings suggest that subjects (a) are capable of encoding both elementary and relational features, and (b) process features of arithmetic equations in a serial manner, with elementary features being encoded prior to relational features (otherwise, E+ and E- foils should have yielded comparable latencies). Evidence from other studies supported that elements are encoded prior to relations. These studies found that when the amount of encoding time in the study phase was reduced dramatically (i.e., when equations were presented for only 1 second each, rather than for 10 seconds), accuracies for E- foils remained near ceiling, while accuracies for E+/R- foils were severely attenuated (Sloutsky & Yarlas, 2000b; Yarlas & Sloutsky, 2000), which suggests that there is a time threshold at which elements are encoded but relations are not. A third important finding from these studies was that mathematics novices took a longer amount of time to correctly respond to E+/R- foils than for all other foils and Old targets. The significantly delayed response to E+/R- foils may be indicative of an element-relation response competition for novices, with the competition occurring between the tendency to accept a foil sharing elementary features with study items and the tendency to reject the foil that does not share a relational feature. This response competition is a by-product of serial processing: because elementary features are accessed prior to relational features, the initial tendency to accept the attractive E+/R- foil is prompted by fast detection of the presence of an elementary feature. However, as processing continues, the tendency to reject the foil is prompted by the slower detection of the absence of a relational feature. Therefore, to correctly reject the E+/R- foil, participants might need to suppress the initial tendency to accept the foil, and this suppression would require additional time to elicit a correct response.

While these studies have allowed for a tentative description of the nature of feature processing, there are still several issues that are left unresolved. One crucial issue that is the focus of the current paper is the generalizability of these findings in explaining processing and representation of elements and relations. In particular, it is unclear whether these phenomena would also be found during feature processing in other, radically different, types of informational structures. For example, would these regularities hold in knowledge-lean domains (e.g., propositional logic) and knowledge-independent domains (e.g., spatial arrangements)? If this is the case, it would provide evidence that the findings in arithmetic were not limited within that particular information structure, or just to knowledge-rich structures, but that they are indicative of domain-general cognitive mechanisms underlying feature processing.

The current studies therefore apply the categorical recognition procedure to these new structures to allow for a better understanding of whether these previous findings point to general cognitive tendencies in the processing and representation of elements and relations. Two experiments using the categorical recognition procedure are described here, the first examining representation of features for propositional logic, and the second for spatial arrangements among objects.

Experiment 1

Method

Participants Participants included 24 undergraduates in an introductory psychology course at a large Midwestern university who participated for partial course credit. This sample had an average age of 22.0 years (SD = 6.1 years), with 6 women and 18 men.

Materials and Procedure All participants were run individually with stimuli presented on a personal computer using SuperLab Pro software (Cedrus Corporation, 1999).

The experiment used the categorical recognition procedure, which consists of three phases: the study phase, the distraction phase, and the recognition phase. In the study phase, participants were presented one at a time with 30 propositional logic arguments consisting of two premises and a conclusion, which they had been instructed to memorize. All 30 arguments incorporated the logical form of Modus Ponens, and posited that if a specific number on one side of a card was found, then a specific number should be on the other side of the card (e.g., *If there is a 7 on the front, then there is a 1 on the back. There is a 7 on the front. Therefore, there is a 1 on the back*). All numbers used in these study arguments ranged from 0 to 9. Each argument was centered and presented in black type on a white background for ten seconds, with a two-second interval between each argument during which only the white background was seen. The order in which arguments were presented was randomized.

A distraction phase followed the study phase for the purpose of clearing participants' short-term memory. For the distraction task, participants were presented with 90 letters, for which they had been instructed to indicate whether the letter was a vowel or a consonant by pressing an appropriate key on the keyboard.

Immediately following the distraction phase was the recognition phase. Participants were instructed that they would be presented with a number of arguments, some which had been presented to them earlier and others that had not been presented earlier. They were further instructed to indicate whether each argument had been presented earlier or not (i.e., if the argument was "New" or "Old") by pressing an appropriate key on the keyboard.

There were a total of 60 arguments presented in the recognition phase. Each argument was centered and presented in black type on a white background. The order of arguments presented in this phase was randomized. These arguments fell into five categories, with 12 exemplars for each category. The first category contained "Old targets", which consisted of arguments that had been randomly selected from those that had been presented earlier in the study phase. The remaining four categories were foils, in that they contained new arguments that had not been presented in the study phase. One type of foil consisted of E+/R+ arguments that used elementary features from the same categories as the study arguments (i.e., numbers between 0 and 9) and incorporated the relation of Modus Ponens (e.g., *If there is a 5 on the front, then there is a 3 on the back. There is a 5 on the front. Therefore, there is a 3 on the back*). A second type of foil consisted of E+/R- arguments that used elementary features from the same category as the study arguments but did not include the relation of Modus Ponens. These foils instead incorporated an invalid argument (e.g., *If there is a 9 on the front, then there is a 7 on the back. There is a 7 on the front. Therefore, there is a 9 on the back*). A third type of foil consisted of E-/R+ arguments that used elementary features that violated the category used in the study arguments (i.e., numbers greater than 9) but still incorporated the relation of Modus Ponens (e.g., *If there is an 18 on the front, then there is a 15 on the back. There is an 18 on the front. Therefore, there is a 15 on the back*). A fourth type of foil consisted of E-/R- arguments that used elementary features that violated the category used in the study arguments and did not incorporate the relational form of Modus Ponens (e.g., *If there is a 16 on the front, then there is a 14 on the back. There is a 14 on the front. Therefore, there is a 16 on the back*).

Results and Discussion

In this section, we will compare participants' "Old" responses and latencies across the foil types. Note that for all foils except E+/R+, we compared latencies for correct responses only. Because, as predicted, false alarms were the dominant response for the E+/R+ foil (χ^2 (1, N = 24) = 34.7, $p < .001$), latencies for incorrect responses for this foil were used in the analyses.

Percentages of "Old" responses are presented in Figure 1. A one-way repeated measures ANOVA points to significant differences among foils, F (4, 92) = 89.1, $MSE = .04$, $p < .001$. Paired-samples post-hoc t-tests with Bonferroni adjustments indicated the following order of "Old" responses across foils: E-/R+ = E-/R- < E+/R- < E+/R+ < Old targets, all ts (23) > 3.2, ps < .05 for differences. Thus, participants gave the fewest "Old" responses for foils in which elementary features were absent, and were significantly less likely to give "Old" responses when either elementary or relational features (or both) were absent than when both elementary and relational features were present. These findings are consistent with those found in the arithmetic experiments, indicating that participants encoded both elementary and relational features of arguments and used both of these features in their recognition judgments.

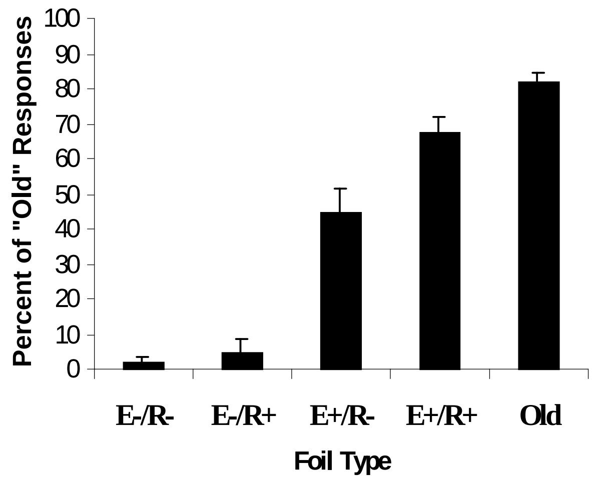

Figure 1. Percentage of "Old" responses across foil types in the recognition phase of Experiment 1. Error bars represent Standard Errors of the Mean.

Figure 2 presents participants' latencies across the foil types. These measures were also subjected to a one-way repeated measures ANOVA, which indicated significant differences among the foils, F (4, 76) = 28.57, $p < .001$. Paired-samples post-hoc t-tests with Bonferroni adjustments indicated that E+ foils and Old targets were significantly slower than E- foils, all ts > 4.45, ps < .01. At the same time, responses to E+/R- foils were significantly slower than Old targets, t (20) = 3.52, $p < .02$. This pattern of latencies (E+ foils being slower than E- foils) indicate that, as in the arithmetic studies, participants processed elementary and relational features in a serial manner, with elementary features being processed first.

Note that E+/R- foils elicited the slowest responses. These increased latencies point to the fact that the element-relation response competition found in the elementary arithmetic task (Sloutsky & Yarlas, 2000a, 2000b; Yarlas & Sloutsky, 2000) might be a general phenomena, such that untrained participants experience this response competition across domains.

In general, these data exhibit similarities with those found in the arithmetic studies. First, participants clearly based their responses on the presence and absence of both elementary and relational features. When elementary features were absent (E-/R- and E-/R+ foils), participants produced fast and accurate "New" responses. However, when elementary features were present, participants did not always produce "Old" answers. Rather, participants' responses were mediated by the presence or absence of relational features. In particular, when both elementary and relational features were present (Old targets and E+/R+ foils) participants generally responded "Old", but when elementary features were present but relational features were absent (E+/R- foils), participants more often responded "New." Second, responses for E+ foils and Old targets were slower than those for E- foils, which points to a longer processing time needed for relational features than for elements. Finally, when elementary features were present but relations were absent (E+/R- foils), responses for correct rejections were significantly slower than responses to Old targets. These findings indicate that, as for the elementary arithmetic task, when elementary features are present in a logic task, participants might experience an element-relation response competition.

Experiment 2 again used the categorical recognition task to examine feature processing, this time for elements and relations in spatial structure.

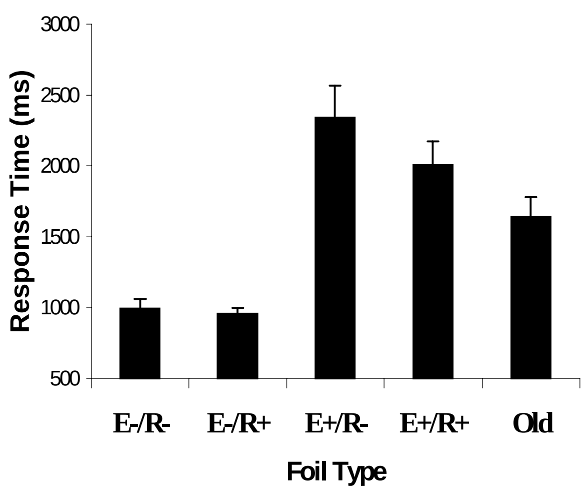

Figure 2. Latencies (in milliseconds) across foil types in the recognition phase of Experiment 1. Error bars represent Standard Errors of the Mean.

Experiment 2

Method

Participants Participants included 29 undergraduates in an introductory psychology course at a large Midwestern university who participated for partial course credit. This sample had an average age of 18.7 years (SD = 0.8 years), with 24 women and 5 men.

Materials The materials in the current experiment consisted of object arrangements, with three objects in each arrangement. All objects were colored shapes. In the study phase, all object arrangements followed an "a-b-a" arrangement, such that the same shape appeared on the left and right sides, with a different shape between them (e.g., a graphical representation of "circle-triangle-circle"). All 30 arrangements in the study phase incorporated simple shapes and colors from among a set of six shapes and colors. The shapes used in the study phase were circles, triangles, crosses, ovals, trapezoids, and parallelograms, while the colors included beige, light blue, gray, red, pink, and yellow. Shapes and colors varied independently. The color of each shape for each object arrangement was randomly assigned, with the constraint that no color was repeated within each object arrangement. Each shape was approximately 1" by 1" in size, with approximately a .5" space between each shape, and all arrangements were centered on top of a white background. The ordering of the 30 arrangements in the study phase was randomized.

In the recognition phase, there were again 60 items, with 12 exemplars from 5 categories of arrangements. The first category consisted of Old targets, which were arrangements randomly selected from among the study items. The remaining four categories were foils, consisting of novel arrangements. The first type of foil consisted of E+/R+ arrangements that used elementary features from the same categories as the study arrangements (i.e., colors and shapes taken from the same set) and incorporated the relation of a-b-a. The second type of foil consisted of E+/R- arrangements that used elementary features from the same category as the study arrangements, but instead of following the a-b-a relation, these foils used the spatial relation of a-b-b (e.g., "yellow oval - beige cross - light blue cross"). The third type of foil consisted of E-/R+ arrangements that followed the a-b-a relation, but used shapes and colors from a different set. The shapes and colors for these foils, which again varied independently, were taken from different sets of six shapes and colors, with the set of shapes including pentagons, stars, rectangles, squares, diamonds, and hexagons, and the colors being orange, black, dark blue, brown, purple, and green. Colors and shapes for these items were assigned in the same manner as for the study items. An example of an E-/R+ foil is "orange hexagon – green star – black hexagon". The fourth type of foil consisted of E-/R- arrangements that used colors and shapes from the same set as the previous foils, and also incorporated the spatial relation of a-b-b (e.g., "black diamond – dark blue pentagon – brown pentagon").

Procedures The procedures in the current experiment were identical to those in Experiment 1.

Results and Discussion

As in the description of Experiment 1, we will again compare participants' "Old" responses and latencies across the foil types. Also, as for the previous experiment, we compared latencies for dominant responses only. This corresponded to the correct response for all foils except for E+/R+, for which, as expected, false alarms were the dominant response (336 out of 348 total judgments for this foil were incorrect "Old" responses).

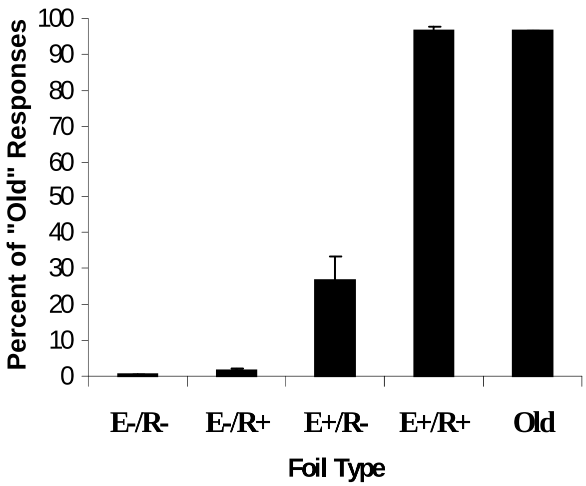

Figure 3. Percentage of "Old" responses across foil types in the recognition phase of Experiment 2. Error bars represent Standard Errors of the Mean.

Percentages of "Old" responses are presented in Figure 3. A one-way repeated measures ANOVA points to significant differences among foils, $\underline{F}$ (4, 112) = 258.01, MSE = .27, $\underline{p} < .001$. Paired-samples post-hoc t-tests with Bonferroni adjustments indicated the following order of "Old" responses across foils: E-/R+ = E-/R- < E+/R- < E+/R+ = Old targets, all $\underline{t}$s (28) > 3.7, $\underline{p}$s < .02, for differences. Thus, as in the previous experiment, participants gave the fewest "Old" responses for foils in which elementary features were absent, and were significantly less likely to give "Old" responses when either elementary or relational features were absent than when both types of features were present. These findings are thus consistent with those found for the arithmetic and propositional logic structures, indicating that participants encoded both elementary and relational features of arguments and used both of these features in their recognition judgments.

Figure 4 presents participants' latencies across the foil types. These measures were again subjected to a one-way repeated measures ANOVA, which indicated significant differences among the foils, $\underline{F}$ (4, 104) = 13.77, p < .001. Paired-samples post-hoc t-tests with Bonferroni adjustments indicated that E+ foils and Old targets were significantly slower than E- foils, all $\underline{t}$s > 3.85, $\underline{p}$s < .02. Also, responses to E+/R- foils were again significantly slower than Old targets, $\underline{t}$ (26) = 2.69, $\underline{p} < .05$. The finding that responses for E+ foils were slower than E- foils once again point to serial processing, indicating that participants processed elementary features prior to relational features.

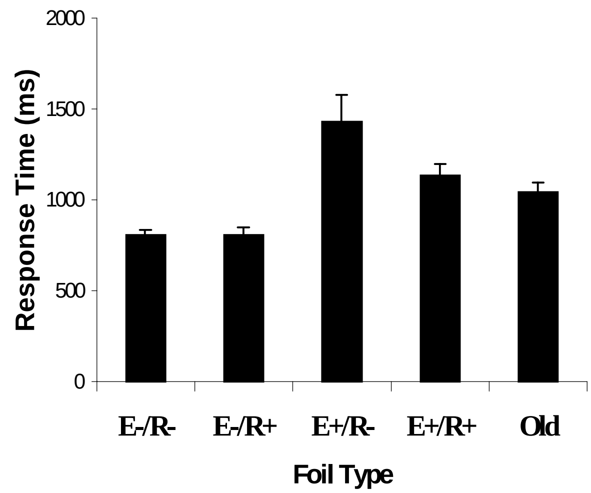

Figure 4. Latencies (in milliseconds) across foil types in the recognition phase of Experiment 2. Error bars represent Standard Errors of the Mean.

Once again, participants were slowest to respond to E+/R- foils, which replicates the data found in both arithmetic and propositional logic structures. The finding of this element-relation response-competition in this knowledge-independent informational structure provides stronger evidence that the element-relation response competition might be a function of general cognitive mechanisms that underlay feature processing.

General Discussion

The data from both experiments replicated several phenomena found in the processing and representation of elementary and relational features for arithmetic problems (Sloutsky & Yarlas, 2000a, 2000b; Yarlas & Sloutsky, 2000). First, participants are capable of encoding both elementary and relational features. In both experiments presented here, participants were significantly less like to accept recognition items as "Old" when either elementary or relational features (or both) were absent than when both types of features were present. Given that participants' recognition was based on categorical matches rather than matches due to specific item memory (as indicated by the fact the false alarms were the dominant response to E+/R+ foils in both experiments), participants should only reject foils that violate an encoded feature category. Thus, the fact that participants in both studies rejected E+/R- items more often than E+/R+ items provides strong evidence that subjects did encode and represent these relations.

Second, patterns of latencies provided indirect evidence that the two types are features are processed serially, with elements processed prior to relations. Both of the reported studies replicated the result found in arithmetic that E- foils were responded to more quickly than E+ foils and Old targets. This pattern of responses is consistent with a decision model in which one first checks whether similar elements are present or absent in making their response prior to checking for the presence or absence of relations for their decision. More direct evidence for this serial processing in arithmetic was described above: the finding that when encoding time was reduced, recognition was based solely on the presence or absence of elements, regardless of the presence or absence of relations. This "limited-encoding" effect was in fact replicated using the same manipulation with propositional logic arguments (Sloutsky & Yarlas, 2000c), providing further evidence that this is a domain-general phenomenon of feature processing (this manipulation has not yet been tested with object arrangements).

Finally, evidence for an element-relation response-competition was found in both of the current experiments. For both propositional arguments and object arrangements, as for arithmetic equations, responses took significantly longer for E+/R- foils than for all other recognition items. This reliable finding may indicate that one must inhibit the tendency to make a decision based solely upon the presence of the more salient elementary feature in order to correctly respond based on the absence of the less salient relational feature. Of course, it could be argued that the increased latencies for these foils are merely a function of similarity: that E+/R- foils exhibit high confusability with the study items. Recent studies by Yarlas and Sloutsky (2001), however, undermine this possibility. In these recent studies, participants were given the same materials and procedures as those presented here, with the crucial exception that instead of making recognition decisions in the final phase, participants were asked to judge the similarity of foils and Old targets with the general class from which study items had been taken (the intention of this class was not described to participants). For both propositional logic arguments and object arrangements, these similarity scores accounted for almost all variance in recognition decisions (R^2 were .89 and .97 for propositional logic arguments and object arrangements, respectively), but accounted for very little variance in latencies for recognition decisions (R^2 were .24 and .12 for propositional logic arguments and object arrangements, respectively). Thus, while categorical similarity judgments appear to account heavily for recognition decisions, they do not account as well for latencies.

The findings of the reported experiments replicate a number of phenomena that had had been previously found, linking all these findings together. The replication of these effects across a number of informational structures, particularly those vary greatly in the degree to which prior knowledge is a factor, provides evidence that the processing and representation of elements and relations may be at least partially based on general cognitive mechanisms.

Acknowledgments

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