

Running Head: MENTAL REPRESENTATIONS

MENTAL REPRESENTATION OF ELEMENTARY AND RELATIONAL PROPERTIES
OF PROPOSITIONAL LOGIC ARGUMENTS

Vladimir M. Sloutsky

and

Aaron S. Yarlas

The Ohio State University

September 5, 2000

PAPER IN PROGRESS

Please address correspondence to:

Vladimir M. Sloutsky

21 Page Hall

1810 College Avenue

The Ohio State University

Columbus, OH 43210

Phone: (614) 688-5855

Fax: (614) 292-0321

Email: sloutsky.1@osu.edu

Abstract

Three experiments examined the manner in which logic novices (i.e., college undergraduates) process and represent elementary and relational properties of propositional logic arguments. These experiments used an old/new recognition procedure under conditions in which participants had ample (Experiment 1) or limited time (Experiments 2 and 3) to encode these arguments. Results of these experiments indicate that participants (1) represented both elementary and relational properties of logical arguments, (2) processed these properties in a serial manner, with elementary properties encoded and accessed prior to relations, and (3) exhibited a element-relation response competition. These findings generally replicate those previously obtained using a similar procedure with arithmetic problems (Sloutsky & Yarlas, 2000; Yarlas & Sloutsky, 2000), indicating that processing of elementary and relational properties might be based upon domain-general computation of these two types of properties. Implications the theory of processing and representation of stimuli properties are discussed.

MENTAL REPRESENTATION OF ELEMENTARY AND RELATIONAL PROPERTIES OF PROPOSITIONAL LOGIC ARGUMENTS

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 properties of these entities can be considered elements of these arrangements, the manner in which elements are arranged can be considered relational aspects of arrangements. Although there is a large body of research examining people's processing of elements and relations in perception, similarity judgment, and problem solving (Biederman, 1987; Gentner, 1983; Goldstone & Medin, 1994; Goldstone, Medin, & Gentner, 1991; Palmer, 1978; Treisman & Gelade, 1980), it is not self-evident as to what constitutes an elementary or a relational property. With the exception of perception, where elementary properties could be defined as those detected by special populations of neurons, there could be multiple ways of construing elements (Palmer, 1978). For example, each element of a visual scene (e.g., each individual object) could be further decomposed into more specific perceptual attributes, such as color, shape, or size. In short, what counts as element depends on the processing system, such that a relational output of the sensory system could serve as an elementary input of the perceptual system, and a relational output of the perceptual system could serve as an elementary input of a higher-order conceptual system. For example, a letter may constitute a relational entity in a letter recognition task, but it constitutes an element in a lexical decision task. Similarly, a word may constitute a relational entity in lexical decision, but as demonstrated by Ratcliff & McKoon (1989) it constitutes an element in a sentence comprehension task.

Although it is often difficult to determine *a priori* whether a property is elementary or relational, there are several theoretical proposals arguing for a separate psychological status for

elementary and relational properties, based upon evidence indicating differential processing of elements and relations (Goldstone, et al. 1991; Medin, Goldstone, & Gentner, 1990; Goldstone & Medin, 1994; Ratcliff & McKoon, 1989). For purposes of the present analysis, an “elementary property” will be used to refer to a value on any single separable attribute of multidimensional stimuli. For example, a color of an object, an object in a scene, a term in an equation, a word in a sentence, or a sentence in a text could be considered elements of object, scene, equation, sentence, or text respectively. At the same time, “relational property” will be used to refer to an arrangement of several elements. For example, *the color of object A is brighter than the color of object B*, *object C is the same size as object D*, or *object M plays the same role in scene X as object N plays in scene Y*. Thus, elements could be construed as predicates taking one argument, while relations could be construed as predicates taking more than one argument (see Goldstone, Medin, & Gentner, 1991; Palmer, 1978, for related discussions). For example, the red color of a ball is an elementary property expressed as RED (Ball) whereas the position of the ball above a square is a relational property expressed as ABOVE (Ball, Square). Note that while elementary and relational properties can be readily expressed in predicate calculus, we make no claim that elements and relations are represented in the cognitive system in the predicate calculus format.

It should be noted that while some relational properties, such as “ABOVE” or “BETWEEN”, are perceptually detectable, many others are not. For example, suppose that a participant is presented with two pictures, (a) a wolf attacking a rabbit and (b) a rabbit foraging for cabbage, and is then asked "What does the rabbit in the first picture correspond to in the second picture?" Participants can rely on the correspondence of elements of the two scenes, in which case the rabbit in the first picture corresponds to the rabbit in the second picture. Alternatively, they can rely on correspondence of relational aspects of the two scenes (i.e. “X is food of Y”), in which

case the rabbit in the first picture corresponds to cabbage in the second picture. Of course, “X is food of Y” is a non-perceptual relation, and it is these types of relations that are the focus of the present research.

The fact that relational properties require the processing of more than one element has several important implications for a theory of mental representation of relations. In particular, relations could be represented as holistic entities that are computed in parallel, or they could be represented as composite entities that are computed serially from elementary properties. For example, some “configural” relational properties, such as symmetry or identity, were argued to be processed holistically (e.g., Bamber, 1969; Garner, 1978), whereas other relational properties, such as corresponding spatial positions of an object in two scenes, were argued to be processed serially (Goldstone & Medin, 1994). The focus of the current research is non-perceptual relations, for which existing theoretical analyses and empirical evidence suggests that they are computed serially from elementary properties (e.g., Goldstone & Medin, 1994; Goldstone, Medin, & Gentner, 1991; Sloutsky & Yarlas, 2000; Yarlas & Sloutsky, 2000).

There are several studies directly examining processing of elementary and relational properties in the domain of arithmetic (Sloutsky & Yarlas, 2000; Yarlas & Sloutsky, 2000). These studies used an old/new recognition procedure, in which college undergraduates were initially presented with arithmetic equations that comprised particular levels of elementary properties (e.g., all numbers were between 1 and 9) and relational properties (e.g., the commutative principle). In the recognition phase, participants were presented with a set 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 properties with the study

equations but not the relational properties (E+/R-), whereas others shared relational but not elementary properties (E-/R+).

It was found that when participants were given an ample amount of time to view arithmetic equations in the study phase, they accurately rejected both E-/R+ and E+/R- foils, and they were faster to reject E- foils than to reject E+ foils. These findings suggest that participants (a) encoded both elementary and relational properties, and (b) processed properties of arithmetic equations in a serial manner, with elementary properties being encoded prior to relational properties (otherwise, E+ and E- foils should have yielded comparable latencies).

Additionally, it was found that participants took a longer amount of time to reject E+/R- foils than to accept Old Targets. The significantly delayed response to E+/R- foils may be indicative of a element-relation response competition between the tendency to accept a foil containing an elementary property and the tendency to reject the foil that does not contain a relational property. This response competition is a by-product of serial processing: because elementary properties are accessed prior to relational properties, the initial tendency to accept the attractive E+/R- foil is prompted by fast detection of the presence of an elementary property. However, as processing continues, the tendency to reject the foil is prompted by a more slow detection of the absence of a relational property. Therefore, to correctly reject the E+/R- foil, the participant had to suppress the initial tendency to accept the foil, and this suppression may have required additional time. Of course, it could be counter argued that (at least in visual discrimination) “same” responses for identical stimuli are generally faster than “different” responses to highly similar stimuli (see Farrell, 1985 for a review). These differences in latencies were explained by an “identity reporter” that generates a fast “same” response after comparing stimuli based on holistic cues (Bamber, 1969). However, the “identity reporter” explains the comparison of concurrently

presented stimuli, and it is unclear if and how it could explain the differences among latencies in recognition judgement when a recognition item is compared to an item stored in memory.

When the amount of presentation time of equations in the study or recognition phases of these arithmetic experiments was significantly reduced, however, accuracy for E-/R+ foils remained high, but accuracy for E+/R- foils dropped significantly (Yarlas & Sloutsky, 2000). In particular, E+/R- foils became significantly more confusable with Old Targets, with participants mostly responding "Old" to E+/R- foils. These findings provided additional evidence that elementary properties were encoded prior to relational properties. This pattern of serial encoding of elementary and relational properties is consistent with previous research indicating different time course for elementary and relational properties (Goldstone & Medin, 1994; Ratcliff & McKoon, 1989).

In short, previous research indicates that participants encoded elementary and relational properties in a serial manner, with elementary properties encoded prior to relations. If relational properties had been processed holistically (rather than computed serially from elementary properties), there should have been no difference in latencies of responses to E- and E+ foils. These findings also suggested that while under the ample presentation condition participants encoded both elementary and relational properties of arithmetic equations (with elementary properties being processed prior to relational properties), under the limited time conditions they encoded elementary properties only. Processing models under the ample time and limited time conditions are depicted schematically in Figures 1 and 2, respectively.

The goal of the present research is to examine whether the models presented in Figure 1 and 2 accurately depict processing of elements and relations across other domains of knowledge or whether these models are limited to describing processing only in the domain of elementary

arithmetic. According to these models, elementary and relational properties are computed in a serial manner, with elementary properties processed prior to relational properties. Under ample time conditions, whenever a recognition item shares an elementary property with the study item, there is an anticipation of “Old” response. If the recognition item also shares a relational property, the participant responds “Old,” in accordance with the anticipation. However, if the recognition item does not share the relational property with the study item, the participant has to suppress the anticipation and answer “New.” Therefore, the participant experiences a response competition between a formed tendency to answer “Old” and a tendency to suppress this response. This response competition results in delayed responses to E+/R- items. At the same time, under the reduced time presentation conditions, participants base their responses solely on the basis of presence or absence of an elementary property.

One domain where there might be a relatively clear distinction between elementary and relational properties is propositional logic. For example, the content of the premises and the conclusion of an argument, expressed by common words, could be construed as an elementary property CONTENT (Premise₁), CONTENT (Premise₂), CONTENT (Conclusion). At the same time, the validity of the argument could be construed as a relational property, as it takes more than one argument: FOLLOWS (Conclusion, Premise₁, Premise₂). When processing logical arguments, participants may encode elementary properties, relational properties, or both types of properties. Of course, content is not a primitive elementary property, and, therefore, similar to a word that is an element relative to a sentence, but a relation relative to a letter, content is an element only relative to a higher-order relational property of the validity of an argument.

If our theoretical considerations are correct, then under an ample time presentation condition, participants’ processing of properties of logical arguments should conform to the model

presented in Figure 1. At the same time, under the limited time conditions, their processing should conform to the model presented in Figure 2. In particular, when there is sufficient time to compute relational properties, and to encode both types of properties, they should answer "Old" whenever the recognition item shares both elementary and relational properties with study items. At the same time, they should answer "New" whenever the recognition item has different elementary or relational properties from study items. Finally, whenever the recognition item shares elementary but not relational properties, they should exhibit response competition evidenced by a delayed response to E+/R- foil. However, limited time conditions should result in processing of elementary but not relational properties. If this is the case, then whenever an elementary property is present in a recognition item, they should respond "Old," whereas whenever the elementary property is absent, they should respond "New," regardless of the presence or absence of relational properties. Of course, this failure to encode or access the relational property should result in a reduction or elimination of the element/relation response competition. These predictions were tested in the three reported experiments.

If relations are computed from elements, then there should be some constraints on what relations can be computed and encoded. This is because the number of binary, tertiary, and n -ary relations among a set of n objects could be approximated by the expression $(n + 2)! / (3 * 2^n)$ (see Berge, 1971). Because the expression grows exponentially with n , the total number of relational properties becomes intractable even when n is moderate. For example, 3 elementary properties afford 5 relations among them, whereas 8 elementary properties afford 4725 relations. Therefore, it is quite unlikely that all possible relations are being computed. Because there is no theory that specifies which relations are computed, it seems necessary to ascertain empirically that relations under study are being computed. This issue was examined in a preliminary

experiment, with the goal of establishing that college undergraduates, who comprised our samples in the three presented experiments, are capable, in principle, of noticing relational properties in question.

PRELIMINARY EXPERIMENT

Eighteen undergraduates were presented with a forced-choice similarity judgment task. For each trial of compared stimuli, each participant was presented with three cards at a time on a computer screen: a Target card and two Test cards, each which had printed on it a logical argument. Participants were instructed to match the argument on the Target card to one of the Test arguments with which they believed a logic “expert” would think was more similar. Each of the two test arguments shared one property with the target argument and differed on the property that the target shared with the other test argument, with all other properties held constant. There were a total of 30 trials.

All Target arguments incorporated the valid logical form of Modus Ponens (i.e., *If P then Q. P. Q.*). Test arguments that shared a relational property with the Target also incorporated the valid logical form of Modus Ponens, but used different content (i.e., *If A then B. A. B.*). Test arguments that shared an elementary property (i.e., similar content) with the Target did not incorporate the form of Modus Ponens, but rather were based on a close, though not logically valid, form (e.g., *If P then Q. Possibly P. Q.*).

In determining participants’ ability to detect relational properties, we used the following criteria. If a participant made at least one relation-based choice and accompanied this choice with an explanation that describes the shared relation, we could conclude that the participant is (in principle) capable of detecting the relational property. The results indicated that almost 80% of participants (14 out of 18) made at least a single explanation-consistent relational choice.

Furthermore, 61% of participants (11 out of 18) made explanation-consistent relational choices on at least half of all trials. Because a choice accompanied by an appropriate explanation could not be arrived at by chance, we concluded that most college undergraduates are capable of detecting the logical relation in question.

EXPERIMENT 1

The goal of Experiment 1 was to test the predictions of the process model presented in Figure 1. To achieve this goal, Experiment 1 uses an old/new recognition procedure. In the study phase, participants were given a set of arguments that all incorporated the same relational property: the logical form of Modus Ponens. In addition, these arguments, all of which involved a rule regarding numbers on the front and on the back of cards, all used consistent levels of an elementary property. In particular, all arguments used numbers ranging from 0 to 9 (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*).

In the recognition phase, in addition to 'Old' arguments, four types of 'New' arguments were presented as foils. Half of these foils, which we refer to as 'Elementary +' (E+) foils, maintained the same levels of the elementary property as used in the study phase (i.e., included numbers ranging from 0 to 9), while the other half of the foils, which we refer to as 'Elementary -' (E-) foils, violated this category (i.e., included numbers greater than 9). Also, half of the foils, which we refer to as 'Relational +' (R+) foils, maintained the use of Modus Ponens, while the other half, which we refer to as 'Relational -' (R-) foils, did not use the form of Modus Ponens or any other logically valid form, thus violating the logical relation FOLLOWS (Conclusion, Premise₁, Premise₂).

The two levels of the two kinds of properties (i.e., elementary properties being either + or -, and relational properties being either + or -) were fully crossed, thus creating four foils:

Elementary + / Relation + (E+/R+), Elementary + / Relation - (E+/R-), Elementary - / Relation + (E-/R+), and Elementary - / Relation - (E-/R-). The patterns of recognition responses across these foils are indicative of which properties of arguments are represented and which properties are not.

A crucial assumption of this recognition procedure is that participants will not store the specific arguments presented in the study phase, due to the fact that these arguments are not highly differentiable from each other. Rather, it is expected that participants will exhibit a categorical memory for these arguments based on the arguments' elementary and/or relational properties, such that in the recognition phase they will reject arguments (i.e., judge arguments as "New") that violate the categories of properties that they encode and accept arguments (i.e., judge arguments as "Old") that do not violate these categories. The accuracy of this assumption would be evidenced by findings that participants do not differentiate E+/R+ foils from Old targets.

If participants process properties in a serial manner in accordance with the model presented in Figure 1, then each additional step in processing should lead to increases in response latencies. We can therefore derive testable predictions from the processing model in Figure 1. According to this model, if participants encode both elementary and relational properties, with elementary properties being encoded first, E- foils should generate faster responses than E+ foils. Further, should they experience response competition, then latencies should adhere to the following pattern: E-/R+ = E-/R- < Old targets < E+/R-.

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 software (Cedrus Corporation, 1999). The experiment consisted 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 logical 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 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 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 (by pressing the "Z" key on the keyboard) or a consonant (by pressing the "M" key). Each letter was centered and presented in black type on a white background. This phase took approximately three minutes.

Immediately following the distraction phase was the recognition phase. Participants were instructed that they would be presented with a number of arguments, some of which had been presented to them earlier and some which had not been presented earlier. They were further instructed to indicate whether each argument had been presented earlier or not by pressing the “Z” key on the keyboard if the argument had been presented earlier, or the “M” key if it had not been presented earlier.

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 properties 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 properties 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 properties 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 properties 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 false alarms were the dominant response for the E+/R+ foil ($\chi^2(1) = 34.7, p < .001$), latencies for incorrect responses for this foil were used in the analyses.

Percentages of "Old" responses are presented in the left-hand side panel of Figure 3. 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 $t_s(23) > 3.2, p_s < .05$ for differences. Thus, participants gave the fewest "Old" responses for foils in which elementary properties were absent, and were significantly less likely to give "Old" responses when either elementary or relational properties were absent than when both elementary and relational properties were present. These findings are consistent with predictions of the proposed model (Figure 1), indicating that participants encoded both elementary and relational properties of arguments and used both of these properties in their recognition judgments.

Effect sizes (i.e., Cohen d 's) of the two types of properties on responses were computed to determine the degree to which elementary properties and relational properties contributed to participants' recognition judgments. This analysis yielded a very large effect size due to elementary properties ($d = 1.48$) and a small, but substantial, effect size due to relational

properties ($d = .35$). Thus, while elementary properties had a much larger effect on participants' recognition judgments, relational properties had a non-trivial effect on their responses as well.

The right-hand side panel of Figure 3 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 $t_s > 4.45, p_s < .01$. At the same time, responses to E+/R- foils were significantly slower than Old targets, $t = 3.52, p < .02$.

This pattern of latencies (E+ foils being slower than E- foils) support predictions of the proposed processing model (Figure 1), indicating that participants processed elementary and relational properties in a serial manner, with elementary properties 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 an elementary arithmetic task (Sloutsky & Yarlas, 2000) might be a general phenomena, such that untrained participants experience this response competition across domains.

In general, these data support the proposed model (Figure 1) of property processing, as participants clearly based their responses on the presence and absence of both elementary and relational properties. When elementary properties were absent (E-/R- and E-/R+ foils), participants produced fast and accurate "New" responses; however, when elementary properties were present, participants did not always produce "Old" answers. Rather, participants' responses were mediated by the presence or absence of relational properties. In particular, when both elementary and relational properties were present (Old targets and E+/R+ foils) participants generally responded "Old". These responses were slower than those for E-/R- and E-/R+ foils.

Finally, when elementary properties were present but relations were absent (E+/R- foils), participants more often correctly responded “New,” and responses for these correct rejections were significantly slower than responses to Old targets. These findings indicate that, as for the elementary arithmetic task, when elementary properties are present in a logic task, participants might experience an element-relation response competition. In this case, the delay indicates that participants might need to inhibit the salient elementary property to correctly reject the attractive foil that shares elementary properties with Old Targets, but does not share relational properties.

Experiment 1 corroborated predictions stemming from the processing model presented in Figure 1. Indeed, under the ample presentation time condition participants encoded both elementary and relational properties, and exhibited the predicted response competition. Therefore, we deemed it necessary to test predictions of the model pertaining to the limited time conditions presented in Figure 2. These predictions were tested in Experiments 2 and 3.

EXPERIMENT 2

The current experiment was designed to test predictions stemming from the model depicting processing under limited time (see Figure 2). In particular, according to this model, all E+ foils (and Old targets) should generate mostly “Old” responses, whereas all E- foils should generate mostly “New” responses. To achieve this goal, the amount of time each argument was presented in the study phase was drastically reduced from 10 seconds in the previous experiment to 1.5 seconds in the current experiment.

One concern with this radical reduction of presentation time was that participants would be unable to attend to all propositions within the study argument. We therefore deemed it necessary to conduct a pilot experiment with the goal of ascertaining that participants could encode information from all three propositions in the limited presentation time. For this study, 8

undergraduates were presented in the study phase with the same 30 study arguments as in Experiment 1, with each argument presented on screen for 1.5 seconds. In the recognition phase (following the distraction phase), participants were presented with 60 arguments. Twelve of these arguments consisted of Old Targets, while another 12 were E+/R+ foils. The remaining 36 arguments were all E-/R- foils. Of these 36 foils, 12 of them violated the elementary property (i.e., used a number greater than 9) in only the first premise, 12 of them violated the elementary property in only the second premise, and the remaining 12 violated the elementary property in only the conclusion. If in the limited encoding time participants were unable to encode the entire argument, then the degree to which the different E-/R- foils are judged as “New” should differ. For example, if participants are only able to encode the first premises of study items, then they should be more likely to judge as “New” foils in which elementary properties are violated in the first premise than for foils in which the elementary properties are violated in the second premise or in the conclusion. The results of this pilot experiment indicated that there was in fact no difference among the three types of E-/R- foils, $F(2, 14) < 1$, and that the percentage of “New” judgments for all E-/R- foils were near ceiling (the means ranged from 95.8% to 97.9%). This pilot thus establishes that 1.5 seconds were sufficient for the participant to process all three propositions of the study phase arguments.

Method

Participants

Participants included 23 undergraduates in an introductory psychology course at a large Midwestern university who participated for partial course credit. This sample had an average age of 20.4 years ($SD = 2.2$ years), with 10 women and 13 men.

Materials and Procedure

The materials and procedures for this experiment were identical to those used in Experiment 1, with one critical exception. In the current experiment, each of the 30 arguments in the study phase was presented on the screen for 1.5 seconds, as opposed to 10 seconds as in Experiment 1.

Results and Discussion

As for our discussion of results for Experiment 1, we will compare participants' "Old" responses and latencies across the foil types. For E- foils and Old targets, we compare latencies for correct responses only. Because false alarms were the dominant response for both E+/R- and E+/R+ foils (both $\chi^2(1) > 25.5$, $p < .001$), latencies for incorrect responses for these foils were used in the analyses.

Percentages of "Old" responses for participants are presented in the left-hand side panel of Figure 4. A one-way repeated measures ANOVA points to significant differences among foils for "Old" responses, $F(4, 88) = 152.8$, $MSE = .02$, $p < .001$. 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 $t_s(22) > 10.2$, all $p_s < .001$ for differences. Thus, in contrast to Experiment 1, where participants gave fewer "Old" responses to E+/R- foils than for E+/R+ foils and Old targets, in the current experiment there were not significant differences in the percentages of "Old" responses for these three foils. An independent-samples t-test was conducted to determine whether participants' inaccurate "Old" responses for E+/R- foils increased significantly from levels observed in Experiment 1 due to the reduction in presentation time. This analysis yielded that "Old" responses for this foil dropped significantly in the current experiment as compared to Experiment 1, $t(45) = 2.23$, $p < .05$. Thus, with the shorter presentation time in the study phase, participants were more likely to judge items as "New" when

elementary properties were absent and as “Old” when elementary properties were present, regardless of the presence or absence of relational properties. This pattern of responses is most consistent with predictions of the simpler processing model (see Figure 2).

As in the previous experiment, effect sizes (i.e., Cohen d 's) of the two types of properties on responses were computed to determine the degree to which elementary and relational properties contributed to participants' recognition judgments. This analysis again yielded a very large effect size due to elementary properties ($d = 1.77$), but in contrast to that in Experiment 1, a very small effect size due to relational properties ($d = .15$). Thus, given the shorter encoding time, elementary properties still had a large effect on participants' recognition judgments, while relational properties had a negligible effect on their responses.

The right-hand side panel of Figure 4 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, $F(4, 88) = 17.4$, $p < .001$. Paired-samples post-hoc t -tests with Bonferroni adjustments indicated that latencies for E+ foils and Old Targets were significantly greater than for E- foils, all $t_s > 4.3$, $p_s < .005$, but there was no differences among latencies for E+ foils and Old Targets (all $t_s < 1$). A planned comparison between latencies for correct responses to E+/R- foils and Old targets was conducted to determine whether response-competition persisted for these foils when participants did attend to the absence of the relational property. This test yielded that when participants correctly answered “New” to E+/R- foils, their responses were significantly slower than for correct answers for Old targets, $t(22) = 3.3$, $p < .01$. This finding provides additional support for the element-relation response competition. As in Experiment 1, it appears likely that correct rejections of E+/R- foil required participants to inhibit a salient elementary property and reject the foil.

Taken together, the results of Experiment 2 indicate that property encoding from arguments is a serial process, with elementary properties being encoded prior to relational properties. The results also corroborate findings of Experiment 1 (as well as previous findings with arithmetic equations) that accurate rejection of E+/R- items takes significantly more time than for any other item. Therefore, those participants who encoded both elementary and relational properties during the decreased presentation time exhibited the same pattern of response competition between the "Old" and "New" responses as participants who encoded both types of properties in Experiment 1. In both experiments, to produce the correct "New" response to E+/R- foils, it appears that participants needed to suppress the erroneous "Old" response. This competition between the two responses ("Old" vs. "New") points to a difficulty for participants to suppress the salient elementary property and reject the item.

Having established the order of property encoding, we deemed it important to replicate these findings using a variation of the recognition procedure. This new variation, which is incorporated in Experiment 3, involves limiting the amount of presentation time for arguments during the recognition phase. When recognition items are presented, a participant must (a) encode the recognition item, and (b) compare this item to an accessed representation of properties of study items. Thus, by reducing the amount of time during recognition, we can better understand the nature of both encoding and accessing of elementary and relational properties. It is expected that participants' processing of these properties will conform to that represented in the processing model in Figure 2, such that participants will generally answer "New" for all E- foils, and "Old" for all E+ foils and Old targets.

EXPERIMENT 3

Experiment 3 used the same recognition procedure as Experiment 2, with the exception that the length of presentation of stimuli in the recognition phase, rather than in the study phase, was reduced from an unlimited amount of time to 1.5 seconds.

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 20.2 years ($SD = 1.5$ years), with 10 women and 14 men.

Materials and Procedure

The materials and procedures for this experiment were identical to those of Experiment 1, with one critical exception. In the current experiment, each of the 60 arguments in the recognition phase was presented on the screen for 1.5 seconds, rather than until the participant made their response. Immediately prior to the recognition phase, participants were instructed that each argument would be presented on screen for a brief time, and that after the argument disappeared, they should indicate whether the argument had been presented or had not been presented earlier in the experiment by pressing a corresponding key on the keyboard. Each argument in the recognition phase was presented on screen for 1.5 seconds, and then replaced on the screen by the following instruction: "Press Z if the item was presented before, or press M if the item was not presented before."

Results and Discussion

Again, in this section, we will compare participants' "Old" responses and latencies across the foil types. As in Experiment 2, for E- foils and Old targets, we compared latencies for correct

responses only, but because false alarms were again the dominant responses for both E+/R- and E+/R+ foils (both $\chi^2(1) > 62.3$, $p_s < .001$), latencies for incorrect responses for these foils were used in the analyses.

Percentages of "Old" responses for participants are presented in the left-hand side panel of Figure 5. A one-way repeated measures ANOVA points to significant differences among foils for "Old" responses, $F(4, 92) = 227.6$, $MSE = .02$, $p < .001$. 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 $t_s(23) > 14.2$, all $p_s < .001$ for differences. This pattern of responses among foils is qualitatively identical to the pattern in Experiment 2. These data indicate that with the shortened presentation time in the recognition phase participants were likely to judge items as "New" when elementary properties were absent and as "Old" when elementary properties were present, regardless of the presence or absence of relational properties. This pattern of responses is most consistent with predictions of the simplified processing model (see Figure 2).

An independent-samples t-test was conducted to determine whether participants' incorrect "Old" responses for E+/R- foils increased significantly from levels observed in Experiment 1 due to the reduction in recognition time. This analysis yielded that "Old" responses for this foil did in fact significantly increase in the current experiment as compared to Experiment 1, $t(46) = 3.63$, $p < .001$. These results indicate that with a 1.5 seconds presentation of arguments in the recognition phase, participants were able to encode and access elementary properties but were less likely to encode and access relational properties.

Effect sizes (i.e., Cohen d 's) of the two types of properties on responses were again computed to determine the degree to which elementary and relational properties contributed to

participants' recognition judgments. This analysis yielded a very large effect size due to elementary properties ($d = 1.83$), but a virtually non-existent effect size due to relational properties ($d = .00$). Thus, given the shorter recognition time, elementary properties still had a large effect on participants' recognition judgments, while relational properties had essentially no effect on their responses.

The right-hand side panel of Figure 5 presents participants' latencies across the foil types. These measures were subjected to a one-way repeated measures ANOVA, which indicated significant differences among the foils, $F(4, 92) = 4.5$, $p < .01$. Paired-samples post-hoc t-tests with Bonferroni adjustments indicated that responses to both E- foils were significantly faster than those for Old targets (both $t_s < -3.2$, both $p_s < .05$) and responses to E-/R- foils were significantly faster than those for E+/R+ foils, $t(23) = -4.1$, $p < .01$, with no other differences significant. As in Experiment 2, a planned comparison between latencies for correct responses for E+/R- and Old targets was conducted to determine whether response-competition persisted for these foils when participants did indicate attention to relational properties. This test again yielded that when participants correctly answered "New" to E+/R- foils, their responses were significantly slower than for correct answers for Old targets, $t(20) = 2.4$, $p < .05$. This finding corroborates that of the previous two experiments, pointing to an element-relation response competition.

The results of Experiment 3 thus corroborate findings of Experiment 2, indicating that property encoding is a serial process, with elementary properties being encoded prior to relational properties. In short, it appears that the model in Figure 2 provides the best overall fit in describing the mechanisms underlying recognition judgments when recognition items are presented for a short time.

General Discussion


The major findings of the three reported experiments are as follows. When logical arguments were presented under the ample time condition (Experiment 1), participants tended to encode both elementary and relational properties of the arguments. However, a correct rejection of an E+/R- foil generated a significantly delayed response. Under limited encoding time either in the study phase or recognition phase (Experiments 2 and 3), participants tended to represent only elementary properties, while mostly not encoding relational properties. Still, when relations were represented by participants under the reduced time conditions, it was also found that correct rejection of an E+/R- foil generated a delayed response.

These results are consistent with those found in similar tasks examining recognition for arithmetic equations under both ample and reduced time conditions (Sloutsky & Yarlas, 2000; Yarlas & Sloutsky, 2000), and thus conform to the models presented in Figures 1 and 2. Under the ample time conditions, participants encoded both elementary and relational properties with relational properties being encoded first (see Figure 1). These participants also experienced an element-relation response competition detected earlier in processing of arithmetic equations (Sloutsky & Yarlas, 2000; Yarlas & Sloutsky, 2000). At the same time, under the reduced time conditions participants' response patterns conformed to the model in Figure 2, such that acceptance and rejection of foils was mediated only by the presence or absence of elementary properties, regardless of the presence or absence of relational properties. Thus, the order of encoding of elementary and relational properties, as well as the element-relation response competition, show across domain generality, indicating that these phenomena are not restricted to arithmetic problems.

These results point to several important regularities. First, encoding of elementary and relational properties of logical arguments is a serial process, with elementary properties being encoded prior to relational properties. This finding is important because it corroborates intuitive construal of relational properties as compositional and computed from more simple elementary properties. Therefore, relational properties may be more difficult to process due to the fact that these properties should be computed from elementary properties, which increases computational demands. If this is true, then the harder the task conditions (e.g., limited exposure to stimuli, response deadlines, or presence of competing tasks), the less likely it is that participants would compute relational properties, while processing of elementary properties would be assumed to attenuate to a lesser degree. For example, suppose that participants are asked which plant grows faster, given the following weekly measurements for Plants 1 and 2. Plant 1: Week₁ = 2 cm, Week₂ = 4 cm, Week₃ = 8 cm, and Week₄ = 16 cm, and Plant 2: Week₁ = 100 cm, Week₂ = 120 cm, Week₃ = 140 cm, and Week₃ = 160 cm. An element-by-element comparison (i.e., Week₁ of Plant 1 vs. Week₁ of Plant 2, Week₂ of Plant 1 vs. Week₂ of Plant 2) should yield a response that the Plant 2 grows faster. At the same time a relational comparison (i.e., $[\text{Week}_{2 \text{ of Plant 1}} - \text{Week}_{1 \text{ of Plant 1}}] / \text{Week}_{1 \text{ of Plant 1}}$ vs. $[\text{Week}_{2 \text{ of Plant 2}} - \text{Week}_{1 \text{ of Plant 2}}] / \text{Week}_{1 \text{ of Plant 2}}$) should yield a response that Plant 1 grows faster. If relational properties are compositional, it could be predicted that (a) a large number of participants would tend to respond that Plant 2 grows faster, and (b) the number of these participants should increase with the introduction of time limits. Of course, these intuitions may or may not be correct regarding all relational properties, but they seem plausible regarding the examined relational properties.

Another important finding is the element-relation response competition, such that responses are significantly delayed when elementary but not relational properties of a recognition item

match those of study items. Recall that similar response competition has been found when tasks employed elementary and relational properties of arithmetic (Sloutsky & Yarlas, 2000; Yarlas & Sloutsky, 2000). It is hypothesized that this response competition emerges due to participants needing to inhibit a response based solely upon the presence of matching elementary properties in order to account for the lack of matching relational properties in their final response. This response competition is thus a product of the serial processing of these two types of properties. Present findings indicate that the earlier found response competition exhibits generality across domains of arithmetic and logic. However, to ascertain that the phenomenon is truly domain-general, it seems necessary to establish presence of the competition in other domains, such as language comprehension, or perception of spatially arranged stimuli.

Finally, it seems quite important that processing of elementary and relational properties is a serial process. As discussed above, encoding of a relational property requires a computation of this property. When relations are computed, they could be encoded and represented either propositionally (e.g., LEFT-OF (Triangle, Square)) or analogically, such as in a mental model (). In the propositional system, accessing time to elementary and relational properties should be comparable, whereas in an analogical system, relational properties need be recomputed, and therefore should require more time to access than elementary properties, which could be read off directly from an analogical representation. The fact that access to relations is slower than access to elements seems to provide indirect support the second rather than the first possibility. Of course, this issue requires a more direct examination. In particular, it could be predicted that if participants are presented with a display depicting a triangle above a circle, and asked to verify statements describing the display, the following difference should be observed. Verification latencies for the statement “There is a triangle” should be shorter than verification

latencies for the statement “Triangle is above circle,” even when verification latencies are adjusted for differences in reading time. This difference, however should not be found if relations are represented propositionally (see Huttenlocher, 1968; Johnson-Laird, 1983, for relevant discussions).

Present findings may also have important implications for a theory of expertise. For example, Sloutsky & Yarlas (2000) found that mathematics experts (i.e., doctoral students in mathematics) differ from mathematics novices in processing of arithmetic problems. While under the ample time condition, mathematics experts, as did novices, accessed elementary and relational properties in a serial manner, with elementary properties accessed first, experts did exhibit the element-relation response competition. Further, under a reduced presentation time condition (Yarlas & Sloutsky, 2000), experts’ recognition judgments were still mediated by both elementary and relational properties, indicating that mathematics experts either encode relational properties much faster than novices, or that they encode elementary and relational properties in a parallel manner. Preliminary data with logic experts (i.e., doctoral students in Philosophy) mirror performance of mathematics experts, in that under an ample time condition, logic experts do not exhibit the element-relation response competition. Furthermore, under a reduced presentation time condition, logic experts encoded both elementary and relational properties. Therefore, expansion of present research to experts would provide insights into the nature of expertise, eliciting whether or not experts’ processing within domains of their expertise exhibits invariance across knowledge domains.

The studies presented here support differential processing for elementary and relational properties within the domain of propositional logic, corroborating prior evidence of differential processing of elementary and relational properties (Goldstone & Medin, 1994; Ratcliff &

McKoon, 1989; Sloutsky & Yarlas, 2000; Yarlas & Sloutsky, 2000). Further examination of the nature of property processing should examine the reason for these differences. It may be the case that because relational properties are more computationally demanding, it takes a longer time to encode these properties than less demanding elementary properties. However, it may be the case that these differences can be accounted for by differences in saliency between elementary and relational properties with elementary properties being more salient than relational properties. If relational properties were made more salient, such as by explicitly or implicitly directing attention to them, or if elementary properties were made less salient, would the nature of processing be reversed, such that relational properties would be processed prior to elementary properties? Would differences in salience of several elementary properties lead to similar differences in processing as has been found with elementary and relational properties? In other words, are elementary and relational properties processed in a qualitatively different manner, or are they processed in a quantitatively different manner with differences accounted for by the degree of saliency? While answers to these questions will be provided in future research, present research allows us to conclude that novice processing of logical arguments is similar to novice processing of arithmetic equations: both types of problems elicit (a) serial processing, with elementary properties processed prior to relations, and (b) element-relation response competition.

REFERENCES

- Bamber, D. (1969). Reaction times and error rates for "same"-"different" judgments of multidimensional stimuli. Perception & Psychophysics, 6, 169-174.
- Berge, C. (1971). Principles of combinatorics. New York: Academic Press.
- Biederman, I. (1987). Recognition-by-components: A theory of human image understanding. Psychological Review, 94, 115-117
- Farell, B. (1985). "Same"-"different" judgments: A review of current controversies in perceptual comparisons. Psychological Bulletin, 98, 419-456.
- Garner, W. (1978). Aspects of a stimulus: Features, Dimensions, and Configurations. In E. Rosch & B. B. Lloyd (Eds.), Cognition and categorization (pp. 99-133). Hillsdale, NJ: Erlbaum.
- Gentner, D. (1983). Structure-mapping: A theoretical framework for analogy. Cognitive Science, 7, 155-170
- Goldstone, R. L., & Medin, D. L. (1994). Time course of comparison. Journal of Experimental Psychology: Learning, Memory, & Cognition, 20, 29-50.
- Goldstone, R. L., Medin, D. L., & Gentner, D. (1991). Relational similarity and the nonindependence of features in similarity judgments. Cognitive Psychology, 23, 222-262.
- Huttenlocher, J. (1968). Constructing spatial images: A strategy in reasoning. Psychological Review, 75, 550-560.
- Johnson-Laird, P. N. (1983). Mental models. Cambridge, MA: Harvard University Press.
- Medin, D. L., Goldstone, R. L., & Gentner, D. (1990). Similarity involving attributes and relations: Judgments of similarity and difference are not inverses. Psychological Science, 1, 64-69.

Palmer, S. E. (1978). Fundamental aspects of cognitive representation. Hillsdale, NJ: Erlbaum.

Ratcliff, R., & McKoon, G. (1989). Similarity information versus relational information: Differences in the time course of retrieval. Cognitive Psychology, 21, 139-155.

Sloutsky, V. M., & Yarlas, A. S. (2000). Problem representation in experts and novices: Part 2. Underlying processing mechanisms. In L. R. Gleitman & A. K. Joshi (Eds.), Proceedings of the 22nd Annual Conference of the Cognitive Science Society (pp. 475-480). Mahwah, NJ: Erlbaum.

Treisman, A. M., Gelade, G. (1980). A feature-integration theory of attention. Cognitive Psychology, 12, 97-136.

Yarlas, A. S., & Sloutsky, V. M. (2000). Representation of arithmetic principles by novices: Knowledge or attention? Manuscript under review.

Author Note

This research was supported in part by a grant from James S. McDonnell Foundation. Correspondence concerning the manuscript should be addressed to Vladimir M. Sloutsky (sloutsky.1@osu.edu), 21 Page Hall, 1810 College Avenue, The Ohio State University, Columbus, OH 43210.

Figure Captions

Figure 1. Proposed processing model for ample time condition, assuming participants' encoding of both elementary properties and relational properties in the recognition procedure.

Figure 2. Proposed processing model for limited time condition, assuming participants' encoding of elementary properties only in the recognition procedure.

Figure 3. Proportion of participants' "Old" responses and latencies (in milliseconds) across foil types in the recognition phase of Experiment 1. Error bars represent Standard Errors of the Mean. E+/R- = Elementary +/Relation -, E+/R+ = Elementary +/Relation +, E-/R- Elementary -/Relation -, E-/R+ = Elementary -/Relation +, and Old = Old targets.

Figure 4. Proportion of participants' "Old" responses and latencies (in milliseconds) across foil types in the recognition phase of Experiment 2. Error bars represent Standard Errors of the Mean. E+/R- = Elementary +/Relation -, E+/R+ = Elementary +/Relation +, E-/R- Elementary -/Relation -, E-/R+ = Elementary -/Relation +, and Old = Old targets.

Figure 5. Proportion of participants' "Old" responses and latencies (in milliseconds) across foil types in the recognition phase of Experiment 3. Error bars represent Standard Errors of the Mean. E+/R- = Elementary +/Relation -, E+/R+ = Elementary +/Relation +, E-/R- Elementary -/Relation -, E-/R+ = Elementary -/Relation +, and Old = Old targets.

Figure 1

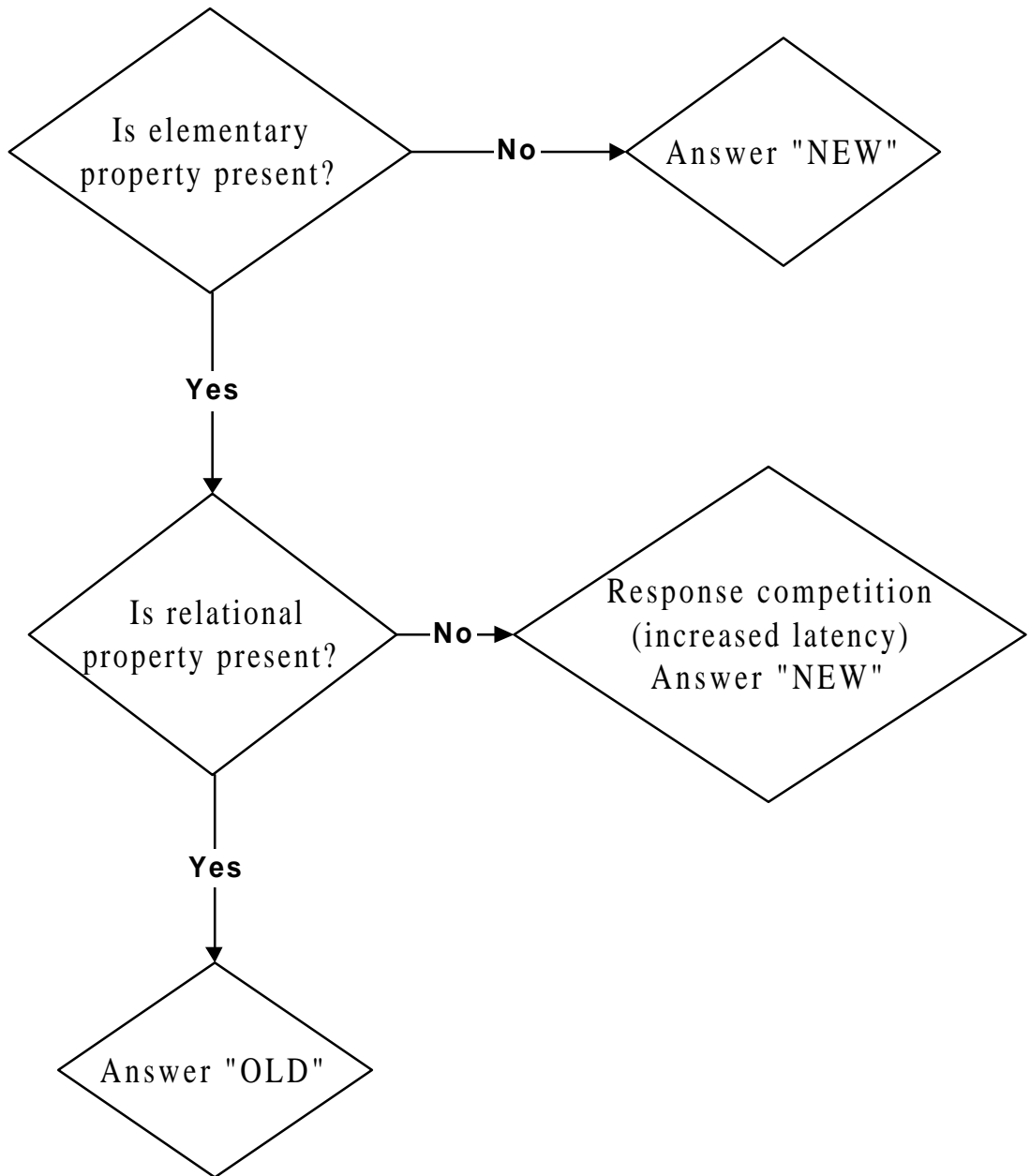


Figure 2

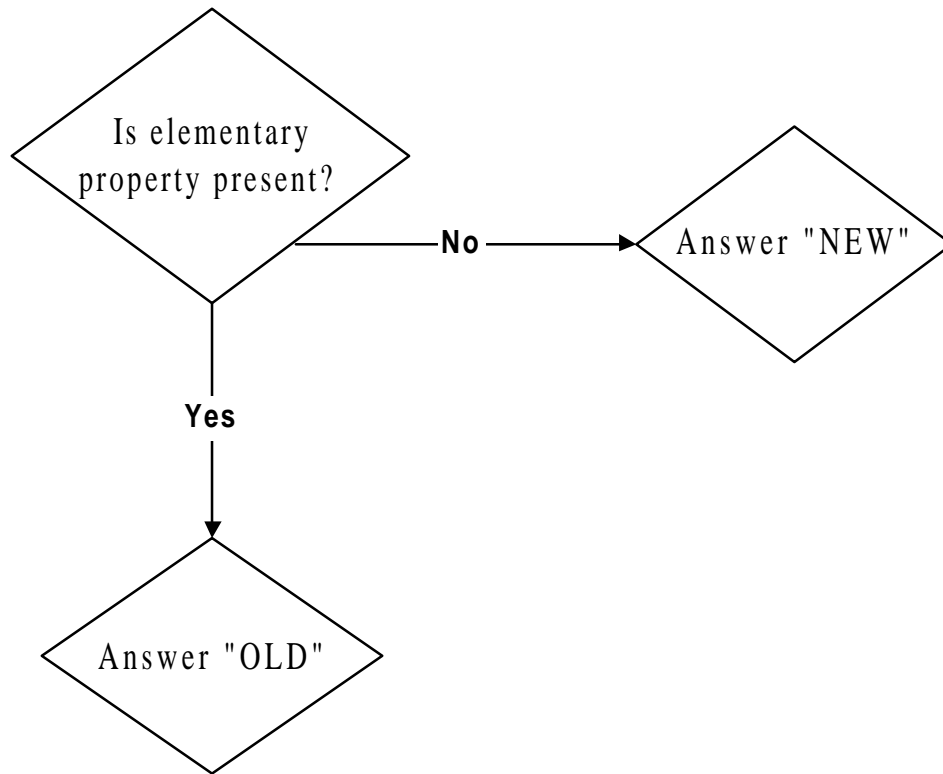


Figure 3

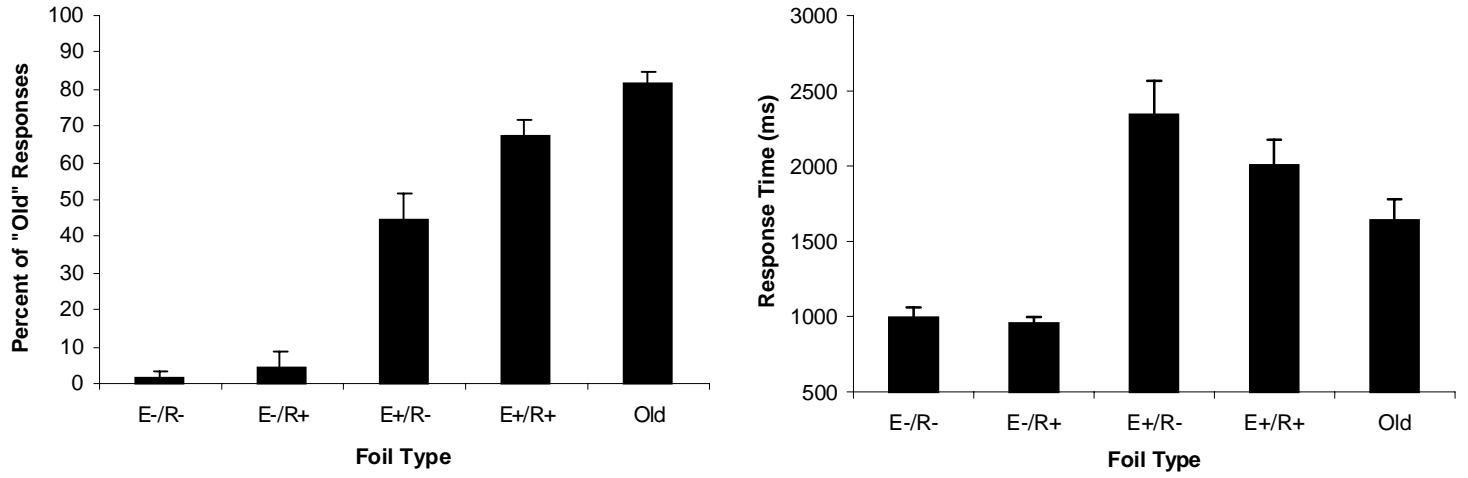


Figure 4

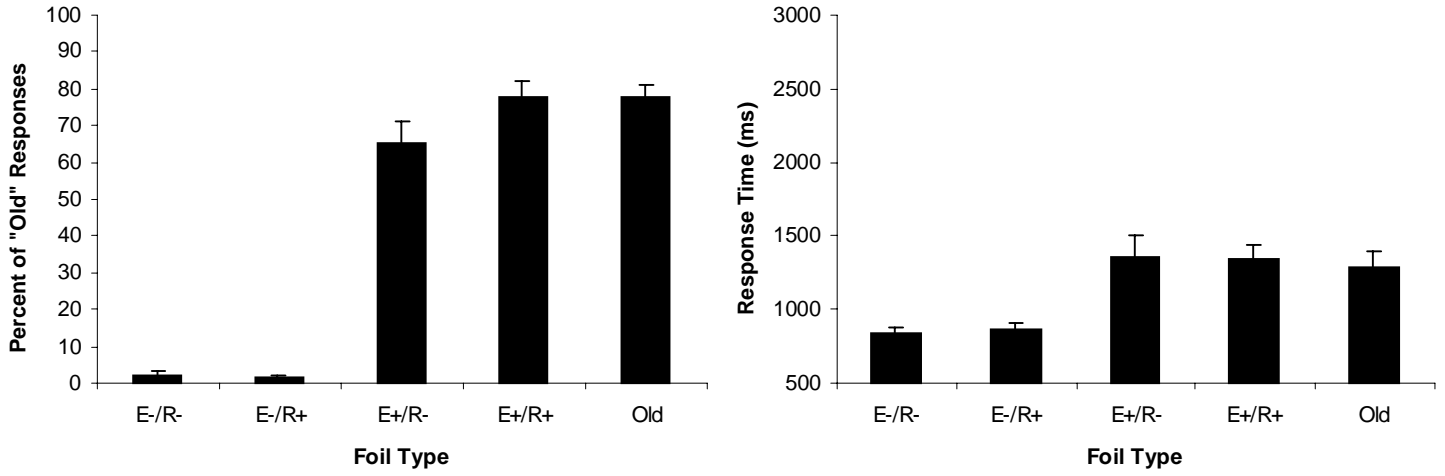


Figure 5

