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Deductive Reasoning

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During the past several years, the senior investigator has been attempting to develop a unified theory of human reasoning. This research has proceeded along two major fronts, one involving the formulation of a subtheory of inductive reasoning, the other involving the formulation of a subtheory of deductive reasoning. ~~We discuss in~~ this article discusses work ~~we have~~ done on deduction. Although the theory of deductive reasoning is not yet completely formulated or tested, ~~but~~ work on the theory is far enough along to merit a pro- (cont over)

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Deductive Reasoning

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During the past several years, the senior investigator has been attempting to develop a unified theory of human reasoning. This research has proceeded along two major fronts, one involving the formulation of a subtheory of inductive reasoning, the other involving the formulation of a subtheory of deductive reasoning. We plan to discuss here work we have done on deduction.

The theory of deductive reasoning is not yet completely formulated or tested, but work on the theory is far enough along to merit a progress report. So far, we have formulated and tested models of deduction for the three main kinds of syllogisms that have been investigated by students of human reasoning: categorical, conditional, and linear syllogisms. We will summarize the theory and data for each of the three kinds of syllogisms below. Then we will draw some conclusions, and mention the directions in which our current research is going.

Categorical Syllogisms[1]

The Nature of Categorical Syllogisms

A categorical syllogism comprises three declarative statements, each of which describes a relation between two sets of items. The first two statements, called the major and minor premise respectively, are givens. The third statement, called the conclusion, follows with logical necessity from the premises. Categorical syllogisms are of two basic types. In the first type, both the major and minor premises express relations between two sets of objects, one of which overlaps between premises. The conclusion expresses a relation between the nonoverlapping sets of objects. An example of such a syllogism is "All _B_ are _C_. All _A_ are _B_. Therefore, all _A_ are _C_." In the second type of syllogism, the major premise expresses a relation between two sets of objects, and the minor premise expresses a relation between a particular item and one of the two sets of objects. The conclusion expresses a relation between that member and the other set. An example of such a syllogism is "All A are B. X is an A. Therefore, X is a B." We will consider in this part of the article only the first, more widely studied type of syllogism.

The Transitive-Chain Theory of Categorical Syllogistic Reasoning

Representation of information. Figure 1 names the five possible set

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Insert Figure 1 about here

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relations, and shows how these relations are represented in both conventional Euler-diagram format and in the symbolic format we propose. Each symbolic representation consists of two distinct components, one (at the left) indicating how many members of Set A are also members of Set B, the other (at the right) indicating how many members of Set B are also members of Set A. In this notation, lowercase letters stand for disjoint, exhaustive partitions of a set. Thus, for example, lowercase a_1 and a_2 are mutually exclusive and exhaustive with respect to Set A. Uppercase letters refer to whole sets, and the arrow relation indicates that the partition to the left of the arrow is a proper subset of the set to the right. Components can be referred to by the order of the terms within them. Thus, all left-hand components in the table are AB components, and all right-hand components are BA components.

Let's consider a couple of examples to see how the notation works. Consider first set equivalence (identity). Note that both partitions of A, a_1 and a_2, are proper subsets of B, and both partitions of B, b_1 and b_2, are proper subsets of A. Thus, all a's are B's and all b's are A's, as is the case for set equivalence. Consider now the second set relation, set-superset. Notice at the right that although all a's are B's, only some b's are A's: In the component at the right, b_2 is a proper subset of not A, rather than of A. This relation, then, indicates that B is a superset of A. To summarize, the basic idea is that each set relation can be represented by a notation indicating the relative number of a's that are B's and b's that are A's.

Combination of representations.[2] Figure 2 shows how two simple inferen-

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Insert Figure 2 about here

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tial rules can be applied to the symbolic representations of set relations to effect the combination of any two representations. The proposed representation has the advantage of permitting combination to occur via the two rules. None of the alternative theories of syllogistic reasoning that have been proposed specify comparable rules by which Euler diagrams or other forms of representation can be combined.

The first rule states that if a partition x_i is a proper subset of Y and a partition y_j (where j may but need not equal i) is a proper subset of Z, then x_i is a proper subset of Z. This rule applies when the two middle terms match in polarity, that is, are both affirmative. It is from this rule that the transitive-chain theory derives its name, since elements are combined by forming simple transitive chains.

The second rule states that if a partition x_i is a proper subset of not Y and a partition y_j (where j may but need not equal i) is a proper subset of Z, then x_i may be a proper subset of either Z or not Z; one can't tell for sure. This rule applies when the two middle terms do not match in polarity, that is, the first is negative and the second affirmative. In this case, one cannot form a transitive chain.

Consider an example in which these two rules are applied to combining two representations, one in which B is a subset of A and the other in which C is a superset of B. There are two ways in which transitive chains might be formed from the two sets of components: first by combining AB with BC (since the middle terms match), and second by combining CB with BA (again since the middle terms match).

First, let's combine the AB component with the BC component. Rule 1 can be applied twice: We can form a first transitive chain by linking a_1 to B with b_1 to C, yielding a_1 to C; we can form a second transitive chain by linking a_1 to B with b_2 to C, again yielding a_1 to C. We write the two a to C relations in the first row to the right of the double arrow. Rule 2 can also be applied twice, since we are unable to form a transitive chain from a_2 to C via either b_1 or b_2. Rather than writing two redundant rows to the right of the double arrow, we simply write the result once: a_2 can be linked to either C or not C.

Next, let's combine CB with BA. Through Rule 1, the c_1 partition can be linked to A through either b_1 or b_2; the two c_1 to A relations are indicated at the right of the double arrow. Through Rule 2, we find that c_2 can be linked to either A or not A, also as indicated at the right of the double arrow. We have now completed the combination process, ending up with two AC and two CA representations.

There's just one more step left. You'll remember that each original representation consisted of an AB component and a BA component. Similarly, each final representation must consist of an AC component and a CA component. But our representations as they now stand consist of either two AC or two CA components. Our final step, therefore, is to rearrange the components into canonical form. There are four ways in which this rearrangement can be realized: by combining AC_1 with CA_1, AC_1 with CA_2, AC_2 with CA_1, or AC_2 with CA_2.

In this particular example, each of these rearrangements yields a unique final representation, although this need not be true in general. Note that by using the two simple rules of inference, we have discovered four possible final representations that can result from combination of the two original ones: _C_ and _A_ equivalent, _C_ superset of _A_, _C_ subset of _A_, and _C_ and _A_ overlapping.

Information-processing model. The description of the transitive-chain theory up to now has been for the ideal subject--one who can process information without making errors. Subjects do make errors, of course, and the transitive-chain theory specifies the processes that give rise to these errors.

In the transitive-chain theory, as in other theories of syllogistic reasoning, there are four basic stages of processing: encoding, during which the premises are read and interpreted; combination, during which information from the premises is integrated; comparison, during which the combined representation is compared to possible labels for the representation (such as "All _A_ are _C_" and "Some _A_ are _C_"); and response, during which the subject communicates a response. According to the transitive-chain theory, encoding and response are error-free. Erroneous responses result from errors made in combination and comparison.

Errors during the combination stage arise from limitations in the ability of working memory to hold all possible combinations. A standard classical syllogism can require as few as one or as many as sixteen pairs of set relations to be combined. For example, in the syllogism, "No _B_ are _C_. No _A_ are _B_," each premise can be represented by only one set relation, meaning that only one combination need be performed. In the syllogism, "Some _B_ are _C_. Some _A_ are _B_," however, each premise can be represented by four set relations, meaning that sixteen (four times four) combinations need to be performed.

According to the theory, subjects combine a maximum of four set relations.

Moreover, there is a three-tier preference hierarchy that places some constraints on the order in which set relations are combined. In particular, equivalence relations are combined before non-equivalent symmetrical ones (overlap and disjoint sets), which in turn are combined before asymmetrical ones (set-superset and set-subset). This ordering reflects the ease with which relations of each kind are stored and manipulated in working memory. Symmetrical relations are those for which the polarities of the elements of the left-hand side of each component match the polarities of the elements of the right-hand side of each component. A quick glance back at Figure 1 will reveal symmetry of polarities only for equivalence, overlap, and disjoint relations. Four parameters of information processing arise from the combination stage--p_1, p_2, p_3, and p_4--representing the respective probabilities that exactly 1, 2, 3, or 4 pairs of set relations are combined.

Errors during the comparison stage arise from simplifying heuristics subjects use to facilitate selection of a label for combined pairs of representations. If no label is consistent with all of the combined set relations generated during combination, the subject labels the relationship between A and C indeterminate, choosing "None of the above" as an answer. If only one label is correct, then the subject chooses that one. But sometimes two labels are consistent with the representation generated during the combination stage. For example, the final set relation A subset of C can be represented either as All A are C or as Some A are C. In this case, some basis is needed for choosing between labels.

Whenever two labels are consistent with all set relations generated during the combination stage, one of these labels will be stronger than the other, and one of the labels (but not the other) will match the atmosphere of the premises. The stronger of two labels is the label with fewer possible set relations in its representation. For example, All A are C is stronger than Some A are C, because the universal statement can be represented by only two set relations (equivalence and set-superset), whereas the particular statement can be represented by four set relations (equivalence, set-superset, set-subset, set overlap). The atmosphere of two premises is determined by the standard rules: It is particular (leading to the choice of a particular conclusion) if at least one premise is particular, and negative (leading to the choice of a negative conclusion) if at least one premise is negative.

The bases for choosing a label when two labels are possible take into account strength and atmosphere of the premises. It may be that each of the two possible labels meets one of the two criteria, or that one of the two labels meets both. Suppose the former is true: Each label meets one criterion. When one label is weaker than the other label, but matches the atmosphere of the premises, it is chosen with probability β_1, and the stronger label is chosen with probability $(1 - \beta_1)$. Suppose the latter is true: One of the two labels meets both criteria. When one label is both the stronger label and matches the atmosphere of the premises, it is chosen with probability β_2, and the other label is chosen with probability $(1 - \beta_2)$.

There is one more source of error in the comparison stage. This arises when the final set relations generated during the combination stage have different initial components. In the example described in Figure 2, for example, two of the pairs of components have a_1 and a_2 both linked to C, and two have a_1 linked to C but a_2 linked to not C. In such cases, subjects are hypothesized occasionally to mistake this discrepancy as indicating the indeterminacy of the conclusion. When this happens, the subject mistakenly labels the relationship between A and C as indeterminate with probability c.

<u>Alternative Theories of Categorical Syllogistic Reasoning</u>

The constraints of space unfortunately permit only the briefest description of the alternative information-processing models to which we compared the transitive-chain information-processing model. Details can be found in the original papers, and in two of our own papers (Guyote & Sternberg, Note 1; Sternberg & Turner, Note 2).

In the transitive-chain model, errors occur during combination and comparison, but not during encoding. In the complete-combination model of Erickson (1974), errors occur during encoding and comparison but not during combination. In the random combination model of Erickson (1974), errors occur during encoding, combination, and comparison. The atmosphere model of Woodworth and Sells (1935) is essentially one of alogical information processing. Subjects encode, combine, and compare only the quantification (universal or particular) and polarity (affirmative or negative) of the premises. And in the conversion model of Chapman and Chapman (1959), errors in syllogistic reasoning, due to conversion of premises, occur during the encoding and comparison stages of processing.

The numbers of parameters estimated differed widely across models, an inevitable consequence of the different information-processing assumptions the models make. Thus, the transitive-chain model involved estimation of seven free parameters, the complete and random combination models involved estimation of thirteen free parameters apiece, and the atmosphere and conversion models each involved estimation of one free parameter. We were not particularly concerned with the differing numbers of parameters, however, for three reasons. First, our major concern was with comparing the historically important models in a way that did full justice to the initial conceptualizations, and these conceptualizations differ widely in their complexity and completeness. Second, we always estimated large numbers of data points (at least 100) in comparing models, thus minimizing the opportunity for capitalization upon chance variation in the data. Third, the fits of the models showed little correspondence to numbers of parameters in the models, suggesting that number of parameters was not an important determinant of fit.

Empirical Tests of the Models

Method. Three experiments were conducted with Yale undergraduates that are relevant to distinguishing the theories noted above.

In a first experiment, subjects received pairs of premises with abstract content, and had to choose the best of five possible conclusions, for example, "All B are C. All A are B. (a) All A are C. (b) No A are C. (c) Some A are C. (d) Some A are not C. (e) None of the above." Half of 38 syllogisms had at least one valid conclusion from among options (a) to (d), the other half did not. Each of 49 subjects received all of the syllogisms.

In a second experiment, subjects received pairs of premises with concrete content, and again had to choose the best of five possible conclusions. Content could be either factual, for example, "No cottages are skyscrapers. All skyscrapers are buildings;" counterfactual, for example, "No milk cartons are containers. All containers are trash cans;" or anomalous, for example, "No headphones are planets. All planets are frying pans." Note that anomalous premises could be either factually correct (as was the major premise of the example) or incorrect (as was the minor premise of the example): In either case, though, the subject and predicate of the premise were semantically unrelated (or close to it). Each of 20 syllogism types was presented to each of 50 subjects once with each type of content. Items were not blocked by content type. Subjects in this experiment were given the verbal reasoning, spatial visualization, and abstract reasoning tests of the Differential Aptitude Test. The tests were subjected to a principal-components analysis, yielding two orthogonal components, a verbal one and a spatial-abstract one.

In a third experiment, premises were again presented with abstract content. This experiment differed from the first experiment, however, in that (a) the subject's task was to indicate whether a single presented conclusion was definitely, possibly, or never true, and (b) subjects might receive either a single premise or a pair of premises. Sixteen subjects received each of four premises, such as "All _A_ are _B_", with each of four possible conclusions, such as "Some _A_ are not _B_," and had to determine the truth value of each conclusion; sixteen other subjects received 15 pairs of premises such as "All _B_ are _C_. All _A_ are _B_," and had to determine the truth value of the conclusion.[3] Eleven premise pairs had at least one valid conclusion; four did not. This decomposition of the task permitted us to test assumptions of the models regarding encoding of single premises separately from assumptions of the models regarding combination of pairs of premises.

Results. Three sets of results are of primary interest: fits of the models to the data, parameter estimates for the preferred model, and relationships of parameter estimates to ability test scores.

Fits of the alternative models of categorical syllogistic reasoning to the response-choice data are shown in Table 1. Model fits are expressed in terms of

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Insert Table 1 about here

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proportion of variance in the data accounted for by each model (R^2), and of root-mean-square deviation of observed from predicted values (RMSD).

The results of the experiments, considered either singly or as a whole, are unequivocal: The transitive-chain model gave a better account of the response-choice data than did any competing model. And the results of the third experiment show that the assumptions of the transitive-chain model are plausible both for encoding considered alone and for encoding and combination considered jointly. Viewed by itself without regard to the other models, the transitive-chain model also did very well: R^2 was greater than .9 for all but one data set (in which it was .89).

Although the fits of the transitive-chain model to the data are most respectable, it is important to note that the model could be rejected at the .05 level or better in every case. Thus, although the transitive-chain model is the best of the competing models, and shows respectable fits when considered just on its own, it is not the true model. The most likely source of inadequacy seemed to us to be the assumption that encoding is always complete and correct. We therefore tried relaxing this assumption, estimating parameters for errors in encoding. Generally, this bought us about .02 or .03 points of R^2, and in about half of the data sets resulted in nonrejection of the model. But the small increases in R^2 did not seem to justify the increase by over 50% in the number of parameters, and so we did not modify the theory.

Table 2 shows values of parameter estimates in each of the various experiments. *Parameters* p_2, p_3, and p_4 were highly correlated, and were therefore

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Insert Table 2 about here

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combined. In general, the parameter estimates make good sense.

Consider first the p parameters. The value of p_1 is particularly low for syllogisms with factual content, suggesting that the working memory or other processing limitations that restrict the number of set relations a subject can combine are lessened when the subject is dealing with concrete, factual content.

The value of β_1 is always considerably greater than .5, indicating that given a choice between a stronger label and a label that matches the atmosphere of the premises, subjects prefer the label that matches the atmosphere of the premises. One would expect β_2 to be quite close to 1, since it represents subjects' preferences for conclusions that both are stronger and match the atmosphere of the premises. In fact, β_2 is quite close to 1 in each data set. Finally, we can see that when the representation for combined premises contains nonidentical first components, subjects did show pronounced tendencies (indicated by nontrivial values of the c parameter) to label the final representation as indeterminate.

We next consider the relationship between the parameters of the transitive-chain model and scores on the orthogonal verbal and spatial-abstract principal components. Means of parameter estimates in Experiment 2 were calculated for subjects high (that is, above the median) and low (that is, below the median) on the two components. The results are shown in Table 3, and can be

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Insert Table 3 about here

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summarized briefly. High and low verbal subjects did not differ significantly on any of the parameters. High and low spatial-abstract subjects, however, did differ significantly on the p_1 (and hence $p_2+p_3+p_4 = 1-p_1$) parameter. Thus, subjects higher in spatial-abstract ability were better able to combine more set relations, presumably because of their ability to visualize more representations or the same representations more clearly than did the lower spatial-abstract subjects. There was no reason to expdct any differences in the parameters of the comparison stage, and none occurred.

It is obviously not possible to describe here all the data analyses we performed and presented in the original reports of our results. Worth noting, however, is the fact that we formulated a response latency model from the assumptions of the transitive-chain theory, and tested it in Experiment 1, the only one of the three experiments in which latency data were collected. The model accounted for 80% of the variance in the latency data, indicating that even with response latencies as long ($\overline{X}$ = 43.59 sec) and as variable (S = 5.34 sec) as those obtained for syllogism data, it is possible to obtain a good fit of observed to predicted times.

Summary. To summarize, we have presented a new theory of categorical syllogistic reasoning, the transitive-chain theory, which we have tested on a variety of syllogism contents and response formats. The theory accounted very well for the response-choice (and latency) data. The parameter estimates were sensible and informative, and an analysis of individual differences in parameter estimates shed some light on the kind of ability that may distinguish good from poor deductive reasoners.

Conditional Syllogisms[4]

The Nature of Conditional Syllogisms

A conditional syllogism comprises three declarative statements. The first statement, called the major premise, expresses a relation between two events, for example, "If *A*, then *B*." The second statement, called the minor premise, asserts the truth or falsity of either the antecedent (first term) or consequent (second term) of the major premise, for example, "Not *B*." The third statement, or conclusion, is either the affirmation or negation of the term not appearing in the minor premise, for example, "Not *A*."

An interesting parallel exists between conditional syllogisms and categorical syllogisms of the second type, which were mentioned earlier but not further discussed. Consider the syllogism, "All A are B. X is not a B. (Therefore,) X is not an A." If A is taken to be the set of states of the world in which event A is true, B is taken to be the set of states of the world in which event B is true, and X is taken to be a particular state of the world, then the conditional and categorical syllogisms become structurally isomorphic. Indeed, the transitive-chain theory assumes that categorical syllogisms of the second type are represented and processed in the same way as conditional syllogisms.

The Transitive-Chain Theory of Conditional Syllogistic Reasoning

The transitive-chain theory applied to conditional syllogisms (and categorical syllogisms of the second type) is very similar to the theory applied to standard categorical syllogisms. First, the subject encodes both premises completely, using the same format for storing information as was described earlier. Then the subject attempts to construct a transitive chain involving the representations of the second premise and one of the components in the first premise. Because all major premises are universal in problems of these types, there are a maximum of two possible representations of the first premise (see Figure 1), and hence two sets of components. If the first rule for constructing transitive chains that was described earlier permits formation of a transitive chain, then the subject forms it and completes solution. If the first rule does not apply, the subject has two choices. He or she can apply the second rule, reason that no definite conclusion exists, and respond that the given conclusion is logically invalid. Or the subject can use indirect proof, trying to form a transitive chain integrating the negation of the conclusion with one of the components in the representation of the major premise. If such a transitive chain can be formed, and if the result contradicts the representation of the second premise, the subject can respond that the conclusion is valid. Otherwise, the conclusion is deemed invalid. The probability of a subject's using indirect proof and thus being able to form a second transitive chain (given that the first rule does not apply in the subject's initial attempt to combine the two premises) depends upon the number of negations in the first premise. Parameter t_0 applies when there are no negations in the first premise, t_1 when there is one negation, and t_2 when there are two negations.

Empirical Tests of the Model

Method. An experiment was conducted with 50 adults from the New Haven area. The stimuli were 64 syllogisms, half of which presented conditional relations and half of which presented categorical relations isomorphic to the conditional relations. The 32 syllogisms of each type were constructed according to a 2^5 design that was exhaustive with respect to the possible item types. In these syllogisms, (a) the first term of the major premise, (b) the second term of the major premise, (c) the single term of the minor premise, and (d) the conclusion were each either affirmative or negative, and (e) the single term of the minor premise was the same (disregarding polarity) as either the first or second term of the major premise. The subject's task was to label each syllogism as having either a valid or an invalid conclusion. The content in each syllogism was abstract (with the letters A and B used as terms). All subjects received all syllogisms blocked by syllogism type, and also the verbal reasoning, spatial visualization, and abstract reasoning sections of the Differential Aptitude Test.

Results. Three sets of results are again of primary interest: fits of the model to the data, parameter estimates for the model, and relationships of parameter estimates to ability test scores. It is also of interest to note that the correlation across the 32 item types for the two kinds of syllogisms was .97, suggesting that the processes used to solve syllogisms of the two types probably were quite similar, if not practically identical.

The transitive-chain model provided an excellent fit to the response-choice data for both conditional and categorical syllogisms. For the conditional problems, R^2 was .95 and RMSD was .10; for the categorical problems, R^2 was .97 and RMSD was .07. As in the earlier experiments, however, the fit of the model to each set of data could be rejected at the .05 level, indicating that the transitive-chain model, although a close approximation to the true model, is not identical to the true model.

Parameter estimates for the conditional syllogisms were .36 for p_1, .64 for p_2, .52 for t_0, .48 for t_1, and .15 for t_2. (Parameters p_3 and p_4 are irrelevant in this type of syllogism, because there are never more than two possible set relations to combine; parameters β_1, β_2, and c are irrelevant, because the presentation of only a single conclusion in this experiment obviates the need for a comparison stage.) Parameter estimates for the structurally isomorphic categorical syllogisms were .43 for p_1, .57 for p_2, .60 for t_0, .61 for t_1, and .16 for t_2.

Comparison of the value of p_1 in this experiment with that of p_1 in the first experiment with categorical syllogisms of the first kind reveals that with content type held constant, subjects combine more representations for problems of the types used in this experiment than for problems of the type used in that experiment. This result is a most sensible one, since the representation of the minor premise in problems of the present types is simpler than the representation of the minor premise in problems of the previous type. In the present problems, the minor premise consists merely of a single term (conditionals) or indication of set membership (categoricals), whereas in the previous problems the minor premise consisted of a quantified relation between two sets.

We assume that subjects have a fixed amount of processing capacity that they can devote to each problem, and that increased consumption of processing capacity for one kind of operation results in decreased processing capacity left over for other kinds of operations. Using this reasoning, we had expected the values of t_0, t_1, and t_2 to be successively smaller: The increased processing capacity allocated to comprehension of negations in the major premise was expected to leave decreased processing capacity to allocate to forming a second transitive chain from the negation of the conclusion. Instead, the values of t_0 and t_1 were approximately equal, whereas the value of t_2 was indeed considerably lower. Apparently, double negations cause considerably more difficulty for subjects relative to single negations than do single negations relative to straightforward affirmations.

Next, we turn to comparison of the orthogonal verbal and spatial-abstract principal component scores for high and low verbal subjects and for high and low spatial-abstract subjects. Our general expectation was that parameters reflecting processing capacity (those relevant to the combination stage) would differ in value across ability groups, whereas those parameters merely reflecting biases in response choice (those relevant to the comparison stage) would not differ in value across ability groups. Because the representation of information combined is assumed to be symbolic, our particular expectation was that larger differences would be obtained between the two spatial-abstract groupings than between the two verbal groupings. The results of the previous experiment confirmed both the general and specific expectations, and the results of the present experiment do as well. As in the previously described experiment, the values of p_1 for high and low verbal subjects--.38 and .43--did not differ significantly; the values of p_1 for high and low spatial-abstract subjects--.35 and

.52--did differ significantly. Similarly, the values of the t parameters (which are combination-stage parameters) did not differ significantly across high and low verbal subjects--.54 and .55 for t_0, .50 and .55 for t_1, and .16 and .17 for t_2; they did differ significantly across high and low spatial-abstract subjects--.66 and .43 for t_0, .63 and .42 for t_1, and .22 and .11 for t_2. The results of both experiments thus confirm that (a) parameters measuring processing capacity vary with spatial-abstract ability, whereas parameters not measuring processing capacity do not vary with this ability, and (b) no parameters vary with verbal ability. These results provide further support for the kind of symbolic representation and for the identification of processes proposed by the transitive-chain theory.

As in Experiment 1 for categorical syllogisms of the first type, a response-latency model was formulated on the basis of the transitive-chain theory. The values of R^2 for this model were .91 for conditional syllogisms and .84 for categorical syllogisms of the second type. The model thus provides a good fit to the latency data.

Summary. To summarize, we have presented an extension of the transitive-chain theory to conditional syllogisms and to categorical syllogisms of the second type. The two problems were proposed to be structurally isomorphic, and the high correlation between response-choice data supports a claim of psychological as well as structural isomorphism. The transitive-chain theory well accounted for response-choice (and latency) data. The parameter estimates again shed light on the ways in which subjects process information, and the analysis of individual differences in parameter estimates provided indirect support for representational and processing assumptions of the transitive-chain theory.

Linear Syllogisms[5]

The Nature of Linear Syllogisms

A linear syllogism comprises two premises and a question. Each of the premises describes a relation between two items, with one of the items overlapping between the two premises. The subject's task is to use this overlap to determine the relation between the two items not occurring in the same premise. Determination of this relation enables the subject to answer the question. In the linear syllogism, "C is not as tall as B; A is not as short as B; Who is shortest?" the subject must determine that B is the overlapping term, and that since B is shorter than A and B is taller than C, C is shorter than A. Hence, C is shortest.

Whereas subjects show a rather wide range of responses in their solutions to particular categorical and conditional syllogisms, they show little variation in their response choices for linear syllogisms. In four experiments where subjects were told to emphasize accuracy of response (Sternberg, Note 3), 99% of the responses to the questions were correct. Hence, the priorities in modeling linear-syllogism data are reversed from those of categorical and conditional syllogisms. The primary goal is to model response latency, and the secondary goal to model errors.

A Mixture Theory of Linear Syllogistic Reasoning

Representation of information. According to the proposed theory, two types of representations are used in the solution of linear syllogisms (and hence the name "mixture theory"). First, subjects are hypothesized to decode the premises of the syllogism into a linguistically-based, deep-structural proposition of the type originally proposed by Chomsky (1965). A premise such as "John is taller than Mary," for example, would be represented as (John is tall+; Mary is tall) (see Clark, 1969). Next, subjects are hypothesized to recode the deep structural representation into a spatial array that functions as an internal analogue to a physically realizable array. In such an array, John would be placed above Mary, $\begin{matrix}\text{John}\\ \text{Mary}\end{matrix}$.

According to the mixture theory (as proposed by Sternberg, Note 3, and modified by Sternberg, Note 4), as many as 10 component processes may be required to solve linear syllogisms of various kinds. These processes will be illustrated with reference to the example problem cited above (C is not as tall as B; A is not as short as B; Who is shortest?).

1. Premise reading (mandatory). The subject reads each of the two premises, "C is not as tall as B" and "A is not as short as B," comprehending their surface structure.

2. Linguistic decoding of comparative relation (mandatory). The subject decodes the surface-structural form into a deep-structure proposition relating the two terms of the premise. Decoding of a premise with a marked adjective (such as short) is assumed to take longer than decoding of a premise with an unmarked adjective (such as tall). In the example, the first premise is decoded into the form (C is tall+; B is tall); the second premise is decoded into the form (A is short+; B is short). Note that at this point, only the comparative and not the negative has been processed, so that the deep-structural propositions do not accurately represent the content of the premises.

3. Decoding of negation (optional). If a premise is a negative equative, that is, one with the relation "not as ___ as," it is necessary to reformulate the deep-structural decoding of the premise to take the negation into account. The roles of the terms in the propositions are reversed, so that the first proposition becomes (B is tall+; C is tall) and the second one becomes (B is short+; A is short).

4. Spatial seriation of comparative relation (mandatory). Having decoded

the premises into deep-structural propositions, the subject is now able to seriate the terms of each premise spatially. A propositional encoding is assumed to be prerequisite for spatial seriation. The subject may seriate the two terms of each premise in either a preferred (usually top-down) or nonpreferred (usually bottom-up) direction. It is assumed that the subject's choice of direction depends upon whether or not the adjective in the original premise was marked or not. The preferred direction is used for unmarked adjectives, the nonpreferred direction for marked adjectives. In the example, *B* and *C* are seriated top-down into one spatial array, $\begin{matrix}B\\C\end{matrix}$. *B* and *A* are seriated bottom-up into a second spatial array, $\begin{matrix}A\\B\end{matrix}$.

5. *Pivot search* (optional). Once the subject has seriated the terms in each of the two premises into two spatial arrays, the subject must locate the middle (pivot) term that will enable him or her to combine the two arrays into a single array. The pivot is assumed to be immediately available if either (a) it appears in two affirmative premises, or (b) it was the last term to be seriated in a negative equative. (The principles behind this availability are described in Sternberg, Note 3.) In the example, the last term to have been seriated was *A* (the tallest term). The subject inquires whether *A* is the pivot. Since it is not, the subject must use additional time locating the pivot, *B*, which is the only term that appears in both premises.

6. *Seriation of the two arrays into a single array* (mandatory). Having found the pivot, the subject is prepared to combine the two separate arrays into a single, integrated spatial array. The subject combines the two single arrays according to the order of the original premises. Combination of these arrays is assumed to be less susceptible to error (although not less time-consuming) if the first term to be combined (which is always the first term in

the final deep-structural proposition describing the first premise) is the term that is most current in working memory, namely, the pivot (from the immediately preceding operation 5).[6] In the example, the subject starts seriation with the *B* term as encoded from the bottom half of the array, $\begin{smallmatrix}B\\C\end{smallmatrix}$, and ends up in the top half of the array, $\begin{smallmatrix}A\\B\end{smallmatrix}$. Thus, the subject links the second pair of terms, *A* and *B*, to the first pair, *C* and *B*, forming the spatial array, $\begin{smallmatrix}A\\B\\C\end{smallmatrix}$.

7. *Question reading* (mandatory). Next, the subject must read the question that he or she will be required to answer. If the question contains a marked adjective, as does the question in the example, it is assumed to take longer to decode, and the subject is assumed to have to search for the response to the question in the nonpreferred end of the array. A marked adjective in the question, therefore, increases response latency. The example question, "Who is shortest?", contains such an adjective.

8. *Response search* (optional). After seriation was completed (Operation 6), the "mind's eye" of the subject ended up either in the top or bottom half of the spatial array. If the question has as its answer the term that is in the half of the array in which the subject's mind's eye ended up, then the response is immediately available. If the answer term is in the other half of the array, however, then the response is not available and must be sought. This search requires additional time. In the example, the subject ended up in the top half of the array, completing seriation with the *A* and *B* terms. The question, however, asks who is shortest. The subject must, therefore, search for the response, finding it in the bottom half of the array.

9. *Establishment of congruence* (optional). The processes described above are sufficient to establish a correct answer, and under some circumstances, a response is immediately forthcoming. If, however, subjects wish to check the accuracy of the response obtained by interrogation of their spatial array, they

have available to them their propositional representation by which they can verify their response.[7] If the linguistic encoding of the proposed response is congruent with the linguistic encoding of the corresponding term of the proposition, then the response immediately passes the congruence check. If the two are incongruent, however, congruence of the response term to the propositional term is established, taking additional time. In the example, _C_, the shortest term, was described as tall (relative to _B_, which was tall+). The question, however, asks who is shortest. Congruence must therefore be established by formulating the question in terms of who is least tall.

10. Response (mandatory). The final operation is response, whereby the subject communicates his or her choice of an answer. In the example, the subject responds with _C_.

Alternative Theories of Linear Syllogistic Reasoning

The mixture theory was compared to two other theories of linear syllogistic reasoning, a spatial theory based upon the theories of DeSoto, London, and Handel (1965) and Huttenlocher (Huttenlocher, 1968; Huttenlocher & Higgins, 1971), and a linguistic theory based upon the theory of Clark (1969). Although the alternative theories as formulated here were based upon previous theories, they were not identical to them. The alternative theories were not specified in a form sufficiently rigorous to permit quantification, and in order to permit precise comparison of theories, additional assumptions had to be made that did enable quantification. Although the alternative theories as presently formulated are not identical to the previous theories, they do seem to capture many of the major intuitions of these previous theories.

The theories to be compared all agree that there are certain encoding, negation, marking, and response operations that contribute to the latency with which a subject solves a linear syllogism. All linear syllogisms contain certain terms and relations to be encoded, and require a response. Only some linear syllogisms contain premises with negations and marked adjectives. Although the theories agree on the presence of these operations, they disagree as to which of the operations are spatial and which are linguistic. The theories also disagree as to what further operations are required. This divergence is particularly important, since it provides the basis for distinguishing among theories. Because the theories are partially nonoverlapping in the operations alleged to be used in solving linear syllogisms, the theories make different latency predictions across item types.

Under certain circumstances (described in Sternberg, Note 3), the mixture theory has one more parameter (seven) than do the spatial and linguistic theories (six).[8] As will be shown, however, the presence of the additional parameter (the optional parameter representing the time to establish congruence) never changes the rank order of the model fits to the latency data.

Empirical Tests of the Theories

Method. Five experiments were conducted with college undergraduates that were designed to distinguish among the mixture, spatial, and linguistic theories. All of the experiments involved presentation of 32 basic types of linear syllogisms with three different adjective pairs (usually taller-shorter, better-worse, and faster-slower). The length of the experiments ranged from one to three sessions, and all experiments included administration to each subject of tests of verbal reasoning, spatial visualization, and abstract reasoning abilities.

In the first experiment, 16 Stanford undergraduates received linear syllogisms such as "Sam is taller than Joe. Joe is taller than Bob. Who is tallest? Joe Bob Sam." Items were presented to all subjects in both of two cueing conditions. In the first condition, subjects received a blank field in the first part of a trial. Subjects indicated readiness to see the item by pressing a foot pedal, and following this indication of readiness the entire item appeared on a tachistoscope screen. In the second condition, subjects received the first two premises of the syllogism in the first part of the trial. Subjects processed the premises as fully as they could, and then pressed the foot pedal, resulting in the appearance of the entire item on the screen.

In the second experiment, the linear syllogisms were presented to 18 Yale undergraduates with the question first: "Who is tallest? Sam is taller than Joe. Joe is taller than Bob. Joe Sam Bob." In this experiment, there were three rather than two precueing conditions. Subjects received either a blank field, just the question, or the question and the two premises in the first part of the trial. They always received the whole item in the second part of the trial.

In the third experiment, the linear syllogisms (with question last) were presented to 18 Yale undergraduates without precueing. However, subjects also received eight basic types of two-term series problems, for example, "Jim is taller than Bob. Who is tallest? Jim Bob."

The fourth experiment was similar to the third experiment, except that each of the 54 Yale undergraduates participating received two-term series problems and linear syllogisms (which are also known as three-term series problems) with just one of the three adjective pairs, rather than with all three as in the previous experiments.

The fifth experiment was also similar to the third experiment, except that the 18 Yale summer session students were encouraged to solve items rapidly, and a bonus was paid to encourage more rapid (and hence less accurate) performance. The speed-accuracy tradeoff manipulation proved to be successful: Mean solution latencies decreased by about a second (from approximately seven to approximately six seconds), and mean error rates increased from 1% in the previous experiments to 7% in this experiment.

Results. As in the previous analyses, we shall be concerned with fits of the quantified models to the data, parameter estimates, and relations between parameter estimates and ability test scores. Because of space limitations, we shall present only model fits for the zero-cue condition (blank field in the first part of the trial).

Table 4 presents model fits (in terms of R^2) for the latency data from each of the five experiments. In each experiment, the mixture theory is clearly

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Insert Table 4 about here

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superior to either the linguistic or spatial theory: The differences in R^2 between the mixture theory and the second best theory (the linguistic theory in four of the five experiments) were .213, .148, .155, .240, and .237 in Experiments 1, 2, 3, 4, and 5 respectively. Thus, regardless of whether the question came before or after the premises, of whether or not precueing was part of the experimental design, of whether different adjectives were presented within or between subjects, and of whether subjects emphasized speed or accuracy, the mixture theory best accounted for the data. The optional parameter for establishment of congruence was relevant to performance in Experiments 3, 4, and 5. With this parameter deleted, the values of R^2 for the mixture theory were .765, .832, and .761 in Experiments 3, 4, and 5 respectively. Thus, even without the optional parameter, the mixture theory was clearly superior to its competitors. Moreover, this superiority held up in every comparison for every adjective, session, and with precueing conditions included in the analysis. It should be noted, though, that the mixture theory could be rejected relative to the true theory in all but the first experiment: The unexplained variance was statistically significant in four of the five experiments. Thus, the mixture theory, although the best available approximation to the true theory, is not identical to it.

Table 5 presents parameter estimates for the various operations that could be separated in each of the five experiments. The ENC+ (encoding plus) parame-

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Insert Table 5 about here

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ter includes a combination of times for between-premise seriation, incremental seriation of marked adjectives in the nonpreferred direction, premise reading, and encoding of unmarked adjectives. The first two processes are hypothesized to be spatial, and to account for most of the estimated time. The second two processes are hypothesized to be linguistic. $ENC+_1$ differed significantly from 0 in both experiments in which it was estimated (1 and 2), and was estimated at about 4650 msec. $ENC+_2$, comprising slightly fewer operations, was estimated at about 3050 msec in the experiments with standard speed-accuracy tradeoff. It seems unlikely that the small difference in the composition of $ENC+_1$ and $ENC+_2$ (see Sternberg, Note 3) could account for the large difference in estimated values. Rather, it seems more likely that encoding operations were performed more rapidly in Experiments 3 and 4, where $ENC+_2$ was estimated (under standard speed-accuracy tradeoff), than in Experiments 1 and 2, where $ENC+_1$ was estimated (also under standard speed-accuracy tradeoff). The obtained difference is exactly as predicted by the mixture theory, according to which encoding should be more rapid and less careful in experimental paradigms leading to the use of the optional operation for the establishment of congruence. In Experiments 1 and 2, the use of precueing presumably encouraged subjects to encode the premises fully before indicating readiness to see the question and solve the problem. In Experiments 3 and 4, there was no precueing in which subjects could take as long as they needed to get a sharp spatial encoding. Hence, subjects are likely to have encoded the items more quickly and less sharply, at the expense of needing the extra check for congruence at the end.

It was possible to estimate unconfounded durations of negation, marking, pivot search, and response search times in all five experiments. Estimates (for standard speed-accuracy tradeoff) of negation time center around 350 msec, of marking time around 400 msec, of pivot search time around 1100 msec, and of response search time around 500 msec. Question reading time (plus confounded operations) could be estimated only in the second experiment, and appears to be about 400 msec. Response time is about 800 msec.

For the most part, the group parameter estimates are reasonable and in close agreement across data sets. The two exceptions (for standard speed-accuracy tradeoff) are that negation time was inexplicably low in Experiment 3, and response search time was inexplicably low in Experiment 1.

Correlations between parameter estimates and composite ability test scores for the first four experiments are shown in Table 6. Data from the fifth experiment were excluded because the unique speed-accuracy tradeoff in this experiment rendered parameter estimates noncomparable to parameter estimates in the previous experiments.

Insert Table 6 about here

The encoding parameter (ENC+) was significantly correlated with scores on all three types of ability tests. This pattern is consistent with the mixture theory, according to which the ENC+ parameter includes both linguistic and spatial-abstract processes. A strictly linguistic or spatial theory would have difficulty accounting for this pattern. Although ENC+ contains a mixture of operations, the predominant operation, according to the mixture theory, is spatial seriation between premises. This mixture theory therefore predicted that the spatial-abstract correlations will be higher than the verbal correlations, and this was in fact the case.

The negation parameter (NEG) showed significant correlations with the spatial and abstract composite scores but not with the verbal composite. This pattern of correlations was inconsistent with the prediction of the mixture theory, according to which negation was supposed to be a linguistic operation. It now appears that negation is accomplished spatially by reversing the positions of the two relevant terms in a within-premise spatial array.

The marking parameter (MARK) showed some relationship to all three composite ability scores, as predicted by the mixture theory but neither the spatial nor linguistic theories. It thus appears that marked adjectives are both linguistically more difficult to encode and spatially more difficult to seriate in an array.

Pivot search (PSM) was significantly correlated with the spatial and abstract composites but not with the verbal composite. This pattern of correlations was consistent with the mixture theory, according to which pivot search is a spatial-abstract operation.

Response search (RS) was significantly correlated with all three composite scores. The significant correlation with verbal ability came as a surprise, since response search is postulated by the mixture theory to be a spatial operation. A possible explanation of the correlation with the verbal composite is that subjects may differ in the rates at which they read off names from a spatial array, resulting in individual differences along a verbal dimension.

Search for congruence (NCON) was significantly correlated with the verbal composite, but with neither the spatial nor the abstract composites. This correlational pattern is as predicted by the mixture theory, which, like the linguistic theory, postulates that the search for congruence is a linguistic operation.

Finally, response (RES+) was significantly correlated with the verbal composite but not with either the spatial or abstract composite. Response was a confounded parameter containing mostly linguistic operations (see Sternberg, Note 3), and hence this pattern of correlations was consistent with the theory.

Generally speaking, the results of the individual-difference analysis were consistent with the predictions of the mixture theory, according to which particular operations should show patterns of individual differences along either verbal, spatial-abstract, or both lines. The two exceptions to the predictions suggest a need for slight reconceptualization, which in the present analysis was of necessity ad hoc.

Error rates in the first four experiments were too low to permit analysis. A detailed analysis of error rates in the fifth experiment is presented elsewhere (Sternberg, Note 4), but will not be discussed here.

<u>Summary</u>. The results of five experiments provide strong support for the mixture theory, considered either by itself or in comparison to alternative theories of linear syllogistic reasoning. Parameter estimates for the mixture theory were sensible and generally consistent across experiments, and patterns of individual differences generally supported predictions as to which operations were spatial and which linguistic.

Conclusions and Current Directions

The transitive-chain and mixture theories provide plausible and empirically sound accounts of reasoning with three kinds of syllogisms. Although neither theory is "true" in the sense of accounting for all reliable variance in the data, each theory is superior to any of the currently available competitors. Thus, each theory has an interesting story to tell, but neither story is the final one. These theories will presumably go the way most theories have in the past, and eventually be replaced by better theories.

Our present research is following three principal directions, the first of which is an attempt to show that the transitive-chain and mixture theories are both special cases of a more general theory of deductive reasoning, the second of which is an attempt to extend the theories to prose processing, and the third of which is an analysis of the development of deductive reasoning.

We propose that the transitive-chain and mixture theories are both special cases of a general theory of deduction. We are currently studying two tasks that we believe integrate information processes from the two theories. In both tasks, subjects receive two premises such as "All gleebs are taller than some fricks. Some fricks are taller than all quirps." Note that these premises resemble categorical syllogisms in the use of the quantifiers <u>all</u> and <u>some</u>, but resemble linear syllogisms in the use of linear relational orderings. Like both categorical and linear syllogisms, some of the items involve negations and others do not. Subjects participating in two experiments have to perform either of two tasks. In one task, subjects must answer a question such as "Which are tallest? All gleebs, Some gleebs, All fricks, Some fricks, All quirps, Some quirps, Can't tell." This task is similar to that subjects confront in solving linear syllogisms. The other task presents four conclusions and the possibility of an indeterminacy: "All gleebs are taller than all quirps. All gleebs are taller than some quirps. Some gleebs are taller than all quirps. Some gleebs are taller than some quirps. Can't tell." Subjects choose the best conclusion. This task is similar to that subjects confront in solving categorical syllogisms. We expect that an account of the data from the two tasks will require a generalization including components of both the transitive-chain and mixture theories.

Subjects may reason quite differently when presented with syllogisms in the format of reasoning problems from the way they do when presented with implicit syllogisms embedded in their everyday reading. For this reason, we are investigating subjects' strategies for solving syllogisms when the syllogisms are presented implicitly in the context of articles such as would be found in newspapers or magazines, and when the questions requiring solution of the syllogisms are embedded in the midst of other, more straightforward reading comprehension questions.

Finally, three experiments are underway that investigate the development of categorical, conditional, and linear syllogistic reasoning. Our goal in these experiments is to determine what it is that develops with time. The studies investigate cognitive development within the componential framework outlined in previous work (Sternberg, 1977a, 1977b, in press; Sternberg & Rifkin, Note 5).

Neither the experiments we have done to date, nor those currently planned, exhaust the problem domain of deductive reasoning. We believe, however, that we have made a good, if modest, start toward an understanding of the representations and processes subjects use in solving a variety of deduction problems.

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Footnotes

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[1]The research summarized here is presented in detail in Guyote and Sternberg (Note 1) and in Sternberg and Turner (Note 2).

[2]The combination process is actually somewhat more complex than can be described here. See Guyote and Sternberg (Note 1) for details.

[3]Thirty-two other subjects in this experiment received a slightly different task. See Sternberg and Turner (Note 2) for details.

[4]The research summarized here is presented in detail in Guyote and Sternberg (Note 1).

[5]The research summarized here is presented in detail in Sternberg (Note 3, Note 4).

[6]The differential difficulty of problems in which the pivot is or is not the term current in working memory was previously referred to as linguistic pivot search (Sternberg, Note 3, Note 4).

[7]The precise circumstances under which the optional operation for establishing congruence is used are described in Sternberg (Note 3).

[8]The number of parameters is fewer than the number of component processes because of experimental confoundings of some of the operations.

Table 1

Performance of Models in Predicting

Response-Choice Data for Categorical Syllogisms of the First Type

Experiment	Transitive Chain R^2	Transitive Chain RMSD	Complete Combination R^2	Complete Combination RMSD	Random Combination R^2	Random Combination RMSD	Atmosphere R^2	Atmosphere RMSD	Conversion R^2	Conversion RMSD
1	.97	.05	.77	.15	.57	.18	.40	.23	.43	.22
2F	.91	.08	.55	.19	.24	.24	.29	.26	.36	.23
2C	.92	.08	.54	.19	.39	.22	.27	.27	.32	.25
2A	.89	.09	.50	.20	.28	.23	.28	.27	.31	.25
6E[a]	.96	.19	.82	.41	.81	.43	.73	.41	.96	.19
6C[a]	.96	.16	.89	.28	.84	.33	.53	.51	.92	.26

Note: In Experiment 2, the suffixes F, C, and A refer to factual, counterfactual, and anomalous syllogism contents respectively. In Experiment 6, the suffixes E and C refer to encoding and combination tasks respectively.

[a]Model fits were computed using parameter estimates from Experiment 1.

Table 2

Parameter Estimates for Transitive-Chain Model in Predicting Response-Choice Data for Categorical Syllogisms of the First Type

Experiment	Parameter				
	p_1	$p_2+p_3+p_4$	β_1	β_2	c
1	.54	.46	.81	.92	.37
2F	.29	.71	.67	.95	.37
2C	.49	.51	.73	.94	.48
2A	.47	.53	.70	.92	.48

Note: In Experiment 2, the suffixes F, C, and A refer to factual, counterfactual, and anomalous syllogism contents respectively. Parameter estimates for Experiment 1 were used for Experiment 3, and hence estimates for Experiment 3 were not shown.

Table 3

Parameter Estimates for Subjects High & Low in

Verbal & Spatial-Abstract Abilities:

Categorical Syllogisms of the First Type

	Verbal		Spatial-Abstract	
Parameter	High	Low	High	Low
p_1	.38	.43	.28	.53
$p_2+p_3+p_4$	.62	.57	.72	.47
β_1	.74	.73	.72	.75
β_2	.96	.97	.98	.95
c	.46	.45	.45	.46

Note: Parameter estimates are from Experiment 2.

Table 4

Performance of Models in Predicting

Latency Data for Linear Syllogisms:

Proportion of Variance Accounted For

Exper-iment	Model: Mixture	Linguistic	Spatial
1	.81	.60	.57
2	.74	.59	.59
3	.84	.69	.58
4	.88	.64	.58
5	.84	.59	.61

Table 5

Parameter Estimates for Mixture Theory in Predicting

Latency Data for Linear Syllogisms

Experiment	$ENC+_1$	$ENC+_2$	NEG	MARK	PSM	$\tilde{R}S$	NCON	QR+	RES+
1	4648	----	351	337	1136	380	----	---	----
2	4666	----	366	412	1045	695	----	393	836
3	----	2986	184	307	1154	522	538	---	----
4	----	3124	244	380	1008	656	396	---	----
5	----	1354	143	327	788	485	305	---	----

Note: Parameter estimates are expressed in milliseconds. All estimates are for both cued and uncued data combined.

Table 6

Correlations between Parameter Estimates for Linear Syllogisms and Composite Ability Scores

Parameter	Composite Ability Score Verbal	Spatial	Abstract
ENC+	-.25**	-.51***	-.58***
NEG	-.14	-.34**	-.41***
MARK	-.20*	-.36***	-.38***
PSM	-.16	-.25**	-.35***
RS	-.26**	-.35***	-.34***
NCON	-.31*	-.24	-.22
RES+	-.30**	-.09	-.15

Note: Correlations are for data from Experiments 1-4 combined.

*p <.05

**p <.01

***p <.001

Figure Captions

1. Symbolic representation of information in transitive-chain theory of syllogistic reasoning.

2. Inferential rules for transitive-chain theory of syllogistic reasoning, with application to an example of combination of representations.

Figure 1.

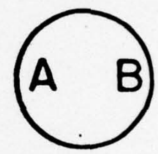
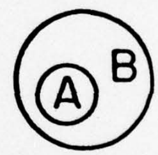
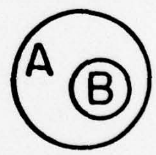
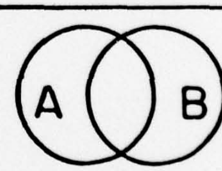
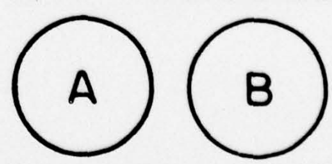
Set Relation	Symbolic Representation	Euler Diagram Representation
Equivalence	$a_1 \rightarrow B \mid b_1 \rightarrow A$ $a_2 \rightarrow B \mid b_2 \rightarrow A$	
Subset-Set	$a_1 \rightarrow B \mid b_1 \rightarrow A$ $a_2 \rightarrow B \mid b_2 \rightarrow -A$	
Set-Subset	$a_1 \rightarrow B \mid b_1 \rightarrow A$ $a_2 \rightarrow -B \mid b_2 \rightarrow A$	
Overlap	$a_1 \rightarrow B \mid b_1 \rightarrow A$ $a_2 \rightarrow -B \mid b_2 \rightarrow -A$	
Disjoint	$a_1 \rightarrow -B \mid b_1 \rightarrow -A$ $a_2 \rightarrow -B \mid b_2 \rightarrow -A$	

Figure 2

INFERENTIAL RULES FOR TRANSITIVE-CHAIN THEORY OF SYLLOGISTIC REASONING

1. <u>Match</u> <u>in</u> <u>Pivot</u> <u>Component</u>

$$x_i \rightarrow Y \;\&\; y_j \rightarrow Z \Longrightarrow x_i \rightarrow Z$$

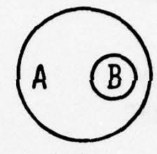
2. <u>Mismatch</u> <u>in</u> <u>Pivot</u> <u>Component</u>

$$x_i \rightarrow -Y \;\&\; y_j \rightarrow Z \Longrightarrow x_i \rightarrow Z \text{ or } x_i \rightarrow -Z$$

APPLICATION OF INFERENTIAL RULES TO COMBINATION OF REPRESENTATIONS

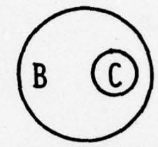
Representation 1

(AB)	(BA)
$a_1 \rightarrow B$	$b_1 \rightarrow A$
$a_2 \rightarrow -B$	$b_2 \rightarrow A$



Representation 2

(BC)	(CB)
$b_1 \rightarrow C$	$c_1 \rightarrow B$
$b_2 \rightarrow C$	$c_2 \rightarrow -B$



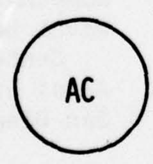
Combine AB with BC:

(AB)	(BC)		(AC_1)	(AC_2)
$a_1 \rightarrow B$	$b_1 \rightarrow C$	$\Longrightarrow$	$a_1 \rightarrow C$	$a_1 \rightarrow C$
$a_2 \rightarrow -B$	$b_2 \rightarrow C$		$a_2 \rightarrow C$	$a_2 \rightarrow -C$

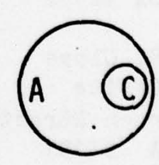
Combine CB with BA:

(CB)	(BA)		(CA_1)	(CA_2)
$c_1 \rightarrow B$	$b_1 \rightarrow A$	$\Longrightarrow$	$c_1 \rightarrow A$	$c_1 \rightarrow A$
$c_2 \rightarrow -B$	$b_2 \rightarrow A$		$c_2 \rightarrow A$	$c_2 \rightarrow -A$

(AC_1)	(CA_1)
$a_1 \rightarrow C$	$c_1 \rightarrow A$
$a_2 \rightarrow C$	$c_2 \rightarrow A$

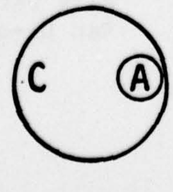


(AC_2)	(CA_1)
$a_1 \rightarrow C$	$c_1 \rightarrow A$
$a_2 \rightarrow -C$	$c_2 \rightarrow A$

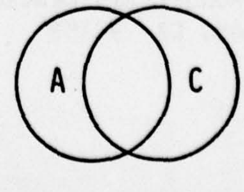


Final Representations

(AC_1)	(CA_2)
$a_1 \rightarrow C$	$c_1 \rightarrow A$
$a_2 \rightarrow C$	$c_2 \rightarrow -A$



(AC_2)	(CA_2)
$a_1 \rightarrow C$	$c_1 \rightarrow A$
$a_2 \rightarrow -C$	$c_2 \rightarrow -A$



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Erratum: Sternberg, R. J., Guyote, M. J., & Turner, M. E. Deductive reasoning. ONR Technical Report #3. This page replaces former page 36.

Table 1

Performance of Models in Predicting

Response-Choice Data for Categorical Syllogisms of the First Type

Experiment	Model									
	Transitive-Chain		Complete Combination		Random Combination		Atmosphere		Conversion	
	R^2	RMSD	R^2	RMSD	R^2	RMSD	R^2	RMSD	R^2	RMSD
1	.97	.05	.76	.14	.59	.18	.57	.18	.78	.13
2F	.91	.08	.67	.16	.34	.21	.29	.23	.46	.20
2C	.92	.08	.69	.15	.54	.18	.52	.18	.69	.15
2A	.89	.09	.66	.15	.53	.16	.46	.18	.61	.16
6E[a]	.96	.19	.86	.37	.86	.37	.73	.41	.96	.19
6C[a]	.96	.16	.89	.26	.84	.32	.53	.51	.92	.26

Note: In Experiment 2, the suffixes F, C, and A refer to factual, counterfactual, and anomalous syllogism contents respectively. In Experiment 6, the suffixes E and C refer to encoding and combination tasks respectively. Experiments 1 and 2 are from Guyote and Sternberg (Note 1). Experiment 6 is from Sternberg and Turner (Note 2).

[a]Model fits were computed using parameter estimates from Experiment 1 of Guyote and Sternberg (Note 1).