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Mental representation of logical connectives

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Logical connectives, such as "AND", "OR", "IF . . . THEN", and "IF AND ONLY IF" are ubiquitous in both language and cognition; however, reasoning with logical connectives is error-prone. We argue that some of these errors may stem from people's tendency to minimize the number of possibilities compatible with logical connectives and to construct a "minimalist" one-possibility representation. As a result, connectives denoting a single possibility (e.g., conjunctions) are likely to be represented correctly, whereas connectives denoting multiple possibilities (e.g., disjunctions or conditionals) are likely to be erroneously represented as conjunctions. These predictions were tested and confirmed in three experiments using different paradigms. In Experiment 1, participants were presented with a multiple-choice task and asked to select all and only those possibilities that would indicate that compound verbal propositions were true versus false. In Experiment 2, a somewhat similar task was used, except that participants were asked later to perform a cued recall of verbal propositions. Finally, Experiment 3 used an old/new recognition paradigm to examine participants' ability to accurately recognize different logical connectives. The results of the three experiments are discussed in relation to theories of representation of possibilities and theories of reasoning.

Logical connectives, such as "AND", "OR", "IF . . . THEN", and "IF AND ONLY IF" are ubiquitous in both language and cognition. Their role is particularly prominent in propositional reasoning, for which outcomes often depend on how logical connectives are construed. For example, a golf club's reputation as a "place for the rich and famous" may leave a wealthy but obscure person wondering whether or not she would fit into the club.

This prominence notwithstanding, reasoning with logical connectives is error-prone, with errors often exhibiting systematic patterns (see Evans, Newstead, & Byrne, 1993; Johnson-

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Laird, 1999; Johnson-Laird & Byrne, 1991, for reviews). In particular, participants have been shown to erroneously infer unwarranted conclusions from conditional premises. For example, when presented with propositions *If employment rates soar then inflation will occur* and *Inflation occurred,* participants tend to erroneously conclude that *Employment rates soared* (see Evans et al., 1993; Johnson-Laird & Byrne, 1991). Furthermore, these errors occur both in the course of deliberate reasoning (Evans et al., 1993) and in the course of on-line comprehension (Rader & Sloutsky, 2002). In general, propositions connected by OR (i.e., disjunctions) or IF . . . THEN (i.e., conditionals) more often generate reasoning errors than proposition connected by AND (i.e., conjunctions; see Evans et al., 1993; Johnson-Laird & Byrne, 1991; Taplin, Staudenmayer, & Taddonio, 1974). Why and where in the course of processing do these errors occur?

It has been argued that the reasoning process consists of several phases, including the construction of the initial representation, the derivation of a putative conclusion, and the search for counterexamples (Johnson-Laird & Byrne, 1991; Johnson-Laird, Byrne, & Schaeken, 1992), with the former two phases occurring primarily on-line, and the latter phase occurring in the course of deliberate reasoning (Rader & Sloutsky, 2002). Each of these phases can elicit reasoning errors, and the focus of current research is the initial representation of logical connectives as a potential source of reasoning errors.

It has been argued that logical connectives are represented analogically, and details of these representations have been specified within the mental model theory of reasoning (Johnson-Laird & Byrne, 1991; Johnson-Laird et al., 1992). According to this theory, the conjunctive statement *Ben is in Chicago and Karl is in Chicago* should be represented as a co-occurrence of the two possibilities:

Ben   Karl

The conditional statement *If Ben likes Russian food then he lives in New York* should be represented in the following manner:

Russian food   New York
  . . .

where the first model makes explicit the possibility in which both liking Russian food and living in New York co-occur, and the second model (ellipsis) corresponds to those possibilities in which the antecedent of the conditional is false. The disjunctive statement *Ben is in Chicago or in Paris* is represented as follows:

Chicago
        Paris

where different lines indicate that the two possibilities do not co-occur. Hence, according to the mental models theory, conjunctions and conditionals are represented similarly, whereas disjunctions are represented differently.

We argue that findings in reasoning and adjacent fields provide strong indications that mental model representations may be further constrained by the tendency to minimize the number of considered possibilities, often constructing a one-possibility representation. Such tendencies were demonstrated in reasoning with conditionals (Evans, Ellis, & Newstead, 1996), in quantified and syllogistic reasoning (Johnson-Laird, Byrne, & Tabossi, 1989; Newstead, Handley, & Buck, 1999; see also Klauer, Musch, & Naumer, 2000, for related arguments), in abductive reasoning and problem solving (Bindra, Clarke, & Shultz, 1980; Fay & Klahr, 1996), and in concept formation (Bourne, 1966; Bruner, Goodnow, & Austin, 1956).

For example, in a truth assignment task with conditionals (Evans et al., 1996, Exp. 2), it was found that participants were much more likely to select a single possibility as indicating that the conditional was true: If the conditional was *If an object is blue it is a square*, the most likely choice was a blue square.

In quantified reasoning, existential quantifiers compatible with multiple possibilities, such as *Some are*, were found to generate more errors than universal quantifiers compatible with a single possibility, such as *None are* (Johnson-Laird & Byrne, 1991; Johnson-Laird et al., 1992; Johnson-Laird et al., 1989). These errors stemmed from participants' tendency to construct a one-possibility representation of the existential quantifier *Some are*.

Similar tendencies have been observed in abductive reasoning of children and adults. In particular, Fay and Klahr (1996) presented preschool age children with several boxes containing various shapes. One shape was contained in only one box (the problem was compatible with a single possibility), whereas other shapes were contained in several boxes (the problem was compatible with several possibilities). Experimenters presented a child with one shape at a time, and the child had to determine from which box the shape had been taken. Findings indicate that while few children had difficulties with problems of the first type, when the problem was compatible with a single possibility, many more children had difficulties with problems of the second type, when the problem was compatible with multiple possibilities. In particular, children interpreted the latter problems as if they corresponded to a single possibility and had a unique solution. Bindra, Clarke, and Shultz (1980) have also demonstrated that when inferring causes from observed outcomes, children, adolescents, and adults were more likely to commit an error when an outcome was compatible with several causes than when it was compatible with one cause. Participants of this study also tended to interpret multicausal outcomes as if they were compatible with a single cause, but not single cause outcomes as if they were multicausal. Other researchers also reported similar findings (Byrnes & Overton, 1986; Scholnick & Wing, 1988).

In categorization, concept formation, and classification learning, concepts that are compatible with multiple possibilities (e.g., disjunctive, conditional, or relational concepts) are more difficult to learn than conjunctive concepts compatible with a single possibility (Bourne, 1966; Bruner et al., 1956; Estes, 1994; Haygood & Bourne, 1965; Staudenmayer & Bourne, 1977).

We believe that there is a commonality underlying all these findings: Whenever a problem is compatible with multiple possibilities and thus is indeterminate, people tend to eliminate indeterminacy by selectively focusing on a single possibility. Often this single possibility is the one that matches their hypothesis or prior beliefs (Fay & Klahr, 1996; Kuhn, Garcia-Mila, Zohar, & Andersen, 1995; Mynatt, Dohetry, & Tweney, 1977; Wason, 1977). We term this tendency "minimalization". Because minimalization seems to be present in different domains of thinking, we hypothesize that it may be a general default characteristic of untrained people's representation of indeterminate problems (see Klauer et al., 2000, for related arguments).

If this hypothesis is correct, it is reasonable to expect that the minimalization should be present in untrained people's mental representation of logical connectives. However, while predicting a single possibility representation for logical connectives, minimalization does not specify this possibility. Because people are more likely to represent information that is explicitly mentioned (e.g., Johnson-Laird & Byrne, 1991), it seems that a conjunction of mentioned atomic events would be a good candidate for a one-possibility representation. For example, if "*" stands for any connective, proposition TRUE (*P* * *Q*) is likely to be represented as *P & Q*, whereas the proposition FALSE (*P* * *Q*) is most likely to be represented as *not-P & not-Q*.

It important to note that minimalization should not be confused with other tendencies found in reasoning research, such as "matching bias" (Evans, 1972; Evans et al., 1993; Oaksford, 2002). One variant of matching bias is a tendency to select values named in a proposition. In particular, for propositions, such as (1) *P* * *Q*, (2) *P* * *not-Q*, (3) *not-P* * *Q*, and (4) *not-P* * *not-Q*, matching bias predicts the selection of *P & Q*. Matching bias is more likely to be found in falsification tasks than in verification tasks (Evans, 1972), and it is more likely to be found for conditionals than for disjunctions (Evans & Newstead, 1980). In addition, matching bias predicts the selection of affirmations over negations (Evans & Lynch, 1973). This matching bias has been referred to as Matching_1, whereas the tendency to match the entire clause has been referred to as Matching_2 (Oaksford, 2002). In particular, for propositions, such as (1) *P* * *Q*, (2) *P* * *not-Q*, (3) *not-P* * *Q*, and (4) *not-P* * *not-Q*, matching bias predicts the selection of *P & Q*, *P & not-Q*, *not-P & Q*, and *not-P & not-Q*, respectively.

Although under some conditions, matching bias (both Matching_1 and Matching_2) and minimalization yield similar predictions, there are two principal differences between minimalization and matching bias. First, minimalization and matching bias make similar predictions for verification tasks, but not for falsification tasks. In addition, minimalization is not limited to conditionals, and it makes predictions for disjunctions and conjunctions as well. Therefore, if confirmed, minimalization would represent a tendency that is different from matching bias.

Of course, content often dissuades people from constructing a one-possibility representation (Janveau-Brennan & Markovits, 1999; Newstead, Ellis, Evans, & Dennis, 1997; Quinn & Markovits, 1998; see also Evans et al., 1993, for a review). For example, sometimes a disjunction could imply alternation, such as *Ben is in Chicago or in Paris* (a person cannot be in both places at the same time). Similarly, deontic content of the conditional *If you are over 16*, *you can drive a car* may imply the converse *If you are under 16*, *you cannot drive* (Evans et al., 1993), whereas causal content referring to multiple causes may lead to an increase in correct responding to the conditional (Janveau-Brennan & Markovits, 1999). In present research, however, content effects were eliminated: We randomly paired atomic statements and randomly assigned connectives to these pairs.

Note that it was previously found that disjunctions *P or Q* are often construed as exclusive disjunctions *P or Q, but not both* (Brain & Rumain, 1981; Evans & Newstead, 1980). However, sizable proportions of participants (ranging from 50% to 75%) construct an inclusive interpretation of disjunctions (see Evans et al., 1993, for a comprehensive review). The exclusive interpretation of OR may stem from a "scalar implicature" or a tendency to attribute the speaker reasons to avoid a more informative connective, such as AND (see Noveck, 2001, for a discussion of scalar implicatures in other reasoning tasks). Therefore, we deemed it necessary to block these implicatures, thus eliminating variance due to different interpretation of disjunctions. To block these putative implicatures, we explicitly indicated that disjunctions were inclusive by presenting them in the form *P or Q, or both*. However, it is possible that under different conditions, the exclusive interpretation may prevent people from constructing a one-possibility representation, and we return to this issue in the General Discussion.

If our theoretical considerations are correct, then people should more frequently err when connectives correspond to multiple possibilities, and these errors should exhibit a particular pattern—people should construct minimalist representations, truncating the number of alternatives compatible with a problem. Therefore, the fully determinate connective AND that corresponds to exactly one possibility should elicit the smallest number of representational errors. In short, the following hypotheses were tested in presented studies:

1. People construct the "minimalist" representation of logical connectives, truncating the number of alternatives compatible with a connective.
2. As a result, they construct mostly correct representations of the one-possibility conjunction, while frequently erring with connectives corresponding to multiple possibilities: Logical forms that are compatible with (but not exhausted by) conjunction are often represented as conjunction, thus exhibiting a "conjunction bias".
3. Because these tendencies characterize representation of logical connectives, they should be present in representation-related processes, such as recall and recognition.

Overview of experiments

We employed multiple methods to test the hypotheses outlined above. In Experiment 1, we presented participants with content-based sentences with logical connectives AND (conjunction), OR (disjunction), IF . . . THEN (conditional), and IF AND ONLY IF . . . THEN (biconditional), and with a full ("truth table" type) list of possibilities. For each sentence of the form *A * B*, the list included the following possibilities (1) *A and B*, (2) *not-A and B*, (3) *A and not-B*, and (4) *not-A and not-B*. Participants were asked to select all and only those possibilities that would indicate that the proposition was either true (true condition) or false (false condition). According to the predictions, for all logical forms in the true condition, participants should tend to select only the *A and B* possibility.

In Experiment 2, participants were presented with sentences similar to those in Experiment 1 accompanied with cutout cards with constituent atomic propositions printed on them. For each sentence of the form *A * B*, the following cards were included, (1) *A* (two cards), (2) *not-A* (two cards), (3) *B* (two cards), and (4) *not-B* (two cards). Participants were asked to select all and only those cards that would indicate that the proposition was either true (true condition) or false (false condition). The selected cards were presented later for cued recall. The experiment was administered under two between-subjects conditions: (1) with external aids and (2) without external aids. It was predicted that in the no external aid condition, all logical forms in the true condition should be represented and recalled as conjunctions. The external aid condition, however, was critical to establish reasons for representation and recall errors. First, it is possible that errors stem from participants' poor knowledge of the meaning of logical connectives. Alternatively, it is possible that errors stem from a failure to represent relations among the alternative possibilities denoted by logical connectives. In the latter, but not in the former case, external aids should lead to the improvement of representation and recall of logical connectives.

Finally, Experiment 3 employed an old/new recognition paradigm. First, during the learning phase, sentences with logical connectives were presented to participants. Then, during recognition phase, each sentence was presented under the following conditions: (1) unmodified version, where the sentence was presented exactly as it had been presented in the study phase; (2) different connective versions, where the study phase connective was substituted by other connectives (e.g., AND was substituted by OR and IF . . . THEN); and (3) different noun version, where one of the original nouns of the study phase sentence was substituted with a new noun. It was predicted that participants should accurately recognize conjunctions, accurately reject other connectives substituting original conjunctions, and erroneously accept conjunctive versions of other connectives.

EXPERIMENT 1

The goal of Experiment 1 was to test the posed hypotheses by investigating participants' representations of propositions with various logical connectives. Representations of logical connectives were examined by analysing participants' selections of possibilities compatible with each logical connective.

Method

Participants

Participants were 109 undergraduate students at the Ohio State University (mean age = 22.1 years; 15 men and 94 women). Students were recruited through psychology classes and were given extra credit for participating in the study.

Materials and design

Participants were presented with sentences with logical connectives, one sentence at a time, and with lists of possibilities referring to each sentence. The task was to read each sentence first, then to read a list, and to select all and only those possibilities from the list that make the sentence either true or false. Materials consisted of propositions that were, to avoid systematic effects due to content, randomly conjoined using logical connectives AND, OR, IF . . . THEN, and IF AND ONLY IF. The complete set of materials is presented in the Appendix. Below are examples of propositions:

Conjunction: *This person drinks orange juice in the morning and watches the history channel.*
Disjunction: *This person likes fishing or volunteers in a public school, or both.*
Conditional: *If this person works on weekends, then he supports scientific research.*
Bi-conditional: *If and only if this person is honest he drives a blue minivan.*

Each sentence was followed by a full ("truth table" type) list of possibilities. The list included the following possibilities: *A & B*; *not-A & B*; *A & not-B*; and *not-A & not-B*. These possibilities were randomized for each sentence and were accompanied by two filler items. The filler items were included to lower the chance level, thus providing a clearer distinction between random responding and a systematic pattern. An example of a sentence and subsequent possibilities is as follows:

This person drinks orange juice in the morning and watches the history channel.
1. This person drinks orange juice in the morning and does not watch the history channel
2. This person has running shoes and does not smoke cigars
3. This person does not drink orange juice in the morning and does not watch the history channel
4. This person drinks orange juice in the morning and watches the history channel
5. This person does not drink orange juice in the morning and watches the history channel
6. This person does not have running shoes and smokes cigars

Of course, filler items 2 and 6 could be construed as *not-P & not-Q* cases; however, according to most existing theories of negation (see Oaksford & Stenning, 1992) this possibility seemed unlikely, and participants' responses to filler items in the current study indicate that this was indeed not the case.

The experiment had a mixed design with the truth condition as a between-subject factor and logical form as a within-subject factor. The truth condition had two levels: (1) Select ALL and ONLY those items that indicate that the proposition was TRUE (true condition), and (2) select ALL and ONLY those items that indicate that the proposition was FALSE (false condition). The within-subject factor included four logical forms: conjunctions (*A and B*), disjunctions (*A or B, or both*), conditionals (*If A then B*), and bi-conditionals (*If and only if A then B*). The entire set consisted of 21 items, 12 of which were target items (each of the four logical forms appearing three times with different content), and 9 were filler items. These items were combined in two random orders, with participants randomly assigned to these orders.

Procedure

The participants were presented with booklets that contained 21 items. The instruction asked them to encircle ALL and ONLY those choices that indicate that the proposition was TRUE (true condition) or that it was FALSE (false condition). The participants were instructed to take the task seriously, and they were also asked not to return to previous pages in the booklet once they turned a page. The experiment was conducted in a single 20-min session. Participants were tested in groups ranging from 20 to 60 participants.

Results and discussion

In this section, we consider how participants represented propositions by analysing their choices across conditions. When performing the analyses, we applied the following strategy. First, we compared participants' selections with correct (i.e., truth table) representations of the presented logical forms. These normative responses for the true and false conditions are presented in Table 1. The Table presents four logical forms (conjunction, disjunction, conditional, and bi-conditional) and item selections representing correct and incorrect choices by logical forms and truth conditions. A participant's answer was coded as correct in a given condition if the participant selected all and only the possibilities marked by the plus signs in Table 1. Note that for the true condition, the conjunction form is the only form compatible with a single possibility, while for the false condition, the disjunction and conditional forms are those compatible with only one possibility.

Proportions of correct responses are presented in Figure 1. To compare these proportions across logical forms and truth conditions, we conducted a two (truth condition) by four (logical form) repeated measures analysis of variance (ANOVA). While the main effect of truth condition was not significant, $F(1, 107) < 1$, $p = .36$, the main effect of logical form, $F(3, 321) = 159.02$, $p < .0001$, and the logical form by truth condition interaction, $F(3, 321) =$

TABLE 1
Truth table representations of logical connectives

	Truth conditions and possible card arrangements							
	True condition				*False condition*			
Logical forms	*A & B*	*¬A & B*	*A & ¬B*	*¬A & ¬B*	*A & B*	*¬A & B*	*A & ¬B*	*¬A & ¬B*
Conjunction (AND)	+	–	–	–	–	+	+	+
Disjunction (OR)	+	+	+	–	–	–	–	+
Conditional (IF)	+	+	–	+	–	–	+	–
Bi-Conditional (IFF)	+	–	–	+	–	+	+	–

Note: "+" indicates a card arrangement that correctly represents a choice in a given condition, whereas "–" indicates an incorrectly selected card arrangement. In the rest of the article, the conjunction is also referred to as AND, disjunction will also be referred to as OR, the conditional is referred to as IF, and the bi-conditional is referred to as IFF.

47.23, $p < .0001$, were significant. In the true condition, the likelihood of correct representation was as follows: AND > IFF > IF = OR (all paired sample *t*s > 4.6, all Bonferroni adjusted *p*s < .001 for differences). In the false condition, the likelihood of correct representation was as follows: OR > IF > AND = IFF (all paired sample *t*s > 3.4, all Bonferroni adjusted *p*s < .001 for differences). Therefore, in both true and false conditions, those forms that are compatible with exactly one possibility (i.e., conjunction in the true condition and disjunction and conditional in the false condition) were more likely to be represented correctly than forms compatible with multiple possibilities.

Truth conditions and logical forms differed not only in the proportions of correct responses, but in proportions and types of errors as well. Proportions of responses by the truth and logical form conditions are shown in Table 2 (true condition) and Table 3 (false condition). Because responses to different logical forms were nonindependent, we ran a series of chi-square analyses and the analyses of confidence intervals for each of the logical form within each truth condition. The responses were defined as dominant if chi-squares were significant,

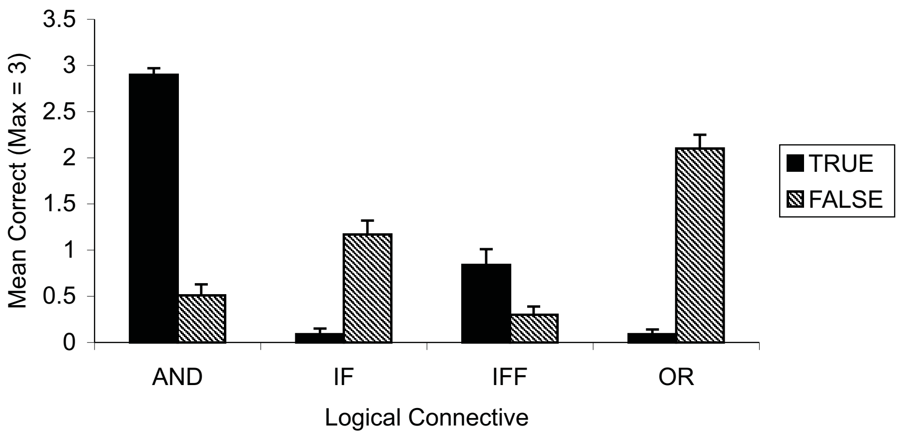

Figure 1. Percentage of correct representations across logical forms in the "TRUE" vs. "FALSE" conditions, Experiment 1.

TABLE 2
Percentage of representation responses in the TRUE condition by logical form in Experiment 1

Representations constructed by participants	*Forms presented to participants*			
	AND	*IFF*	*IF*	*OR*
AND (conversion-to-conjunction)	**96.58***	71.63*	71.75*	91.09*
IFF	0.06	**29.20**	20.33	0.03
IF	0.08	0.04	**0.05**	0.06
OR	0.08	0.07	0.08	**3.63**
Other (incorrect)	3.22	0.06	7.79	5.19

Note: Correct responses are in the diagonal cells (in bold). *Dominant response within the respective column, χ^2s(4) > 220, nonoverlapping confidence intervals, *p*s < .01.

and the confidence interval for a particular response did not overlap with confidence intervals of other responses. Data in Table 2 indicate that in the true condition, for all logical forms, the dominant responses were conversion-to-conjunction responses, all χ^2s(4) > 220, *p*s < .0001. At the same time, data in Table 3 indicate that in the false condition, the one-possibility conjunction of negations was dominant for the conjunction and disjunction, both χ^2s(4) > 90, *p*s < .0001, and this response pattern accounted for a sizeable proportion of responses in the conditional and the bi-conditional (35% and 36%), although not reaching the status of the dominant response.

In short, the analysis of responses point to the following regularities. First, results indicate that in both true and false conditions, participants were more likely to correctly represent those forms that were compatible with a single possibility (i.e., conjunction in the true condition and disjunction in the false condition) than those compatible with multiple possibilities. Furthermore, participants exhibited rather systematic patterns of errors. In the true condition, the most typical pattern of response was representation of each connective as if it were conjunction. This "minimalist" one-possibility representation had also sizeable presence in the false condition, where participants often represented logical connectives as a conjunction of negated atomic statements (e.g., *not-A & not-B*). This latter result is consistent with Barres' (1998) finding that people represent falsity by first constructing true possibilities and then negating them. In particular, for some connectives the proportion of correct responses in the

TABLE 3
Percentage of representation responses in the FALSE condition by logical form in Experiment 1

Representations constructed by participants	*Forms presented to participants*			
	AND	*IFF*	*IF*	*OR*
Not-AND	**16.70**	0.06	0.05	0.05
Not-IFF	0.07	**10.66**	0.03	0.08
Not-IF	0.06	5.34	**37.28**	0.04
Not-OR (conjunction-of-negations)	54.36*	36.49	34.67	**69.17***
Other (incorrect)	29.81	47.45	27.27	30.66

Note: Correct responses are in the diagonal cells (in bold). *Dominant response within the respective column, χ^2s (4) > 90, nonoverlapping confidence intervals, *p*s < .01

false condition seem to be related inversely to the proportion of errors in the true condition: Conjunctions generated the smallest number of errors in the true condition and the largest number of errors in the false condition, whereas disjunction generated the largest proportion of errors in the true condition, and the smallest number of errors in the false condition. Note that disjunction in the false condition is similar to conjunction in the true condition in that it is compatible with a single possibility—namely, *not-A & not-B*. These results are consistent with predictions for both the true and false conditions.

Experiment 1 generated suggestive evidence that participants construct the minimalist conjunctive representation of logical connectives. If this is true, then patterns of errors similar to those observed in Experiment 1 should be observed in other representation-dependent tasks, in particular in recognition and recall. Hence, we conducted two additional experiments examining participants' recall (Experiment 2) and recognition (Experiment 3) of logical connectives.

EXPERIMENT 2

The goal of Experiment 2 was to elaborate findings of Experiment 1 by examining recall of various logical connectives. Another goal was to examine reasons for erroneous representation observed in Experiment 1. In particular, it is possible that the one-possibility representation merely reflects poor knowledge of the meaning of logical connectives, and in the absence of such knowledge, participants select conjunction as the most typical connective. We argue, however, that minimalization, or the construction of a one-possibility representation, does not stem solely from a lack of knowledge of the meaning of logical connectives, but it rather stems from a failure to represent relations among the alternative possibilities denoted by logical connectives. If this is correct, then external tools denoting relations among possibilities should improve representation. For example, while indeterminacy of the relative positions of B and C may not be apparent from the verbal description "A is to the right of B, whereas C is to the left of A", it is apparent when the description is represented graphically:

B–C ———— A
C–B ———— A
C ______ A
B
B ______ A
C

Columns here serve as tools externally denoting the relation of mutual exclusivity among the possibilities. External tools denoting relations have been shown to improve the process of inference and problem solving (Bauer & Johnson-Laird, 1993; Larkin & Simon, 1987; Tabachneck & Simon, 1992; Zhang, 1997; Zhang & Norman, 1994).

If participants' errors stem from misunderstanding of logical connectives or from the typicality of conjunction, however, then aid enabling external representations of possibilities corresponding to logical connectives should not improve representation and recall of propositions containing these connectives. Hence the goal of this experiment was to eliminate these explanations by finding a remedy for the tendency to represent disjunctions, conditionals, and bi-conditionals as conjunction in the true condition, and the tendency to represent conjunctions, conditionals, and bi-conditionals as conjunction of negations in the false condition. If our considerations are correct, and the reported errors stem from the "minimalist" representation of logical connectives, then providing participants with external tools to represent these connectives should allow for more complete representations and thus decrease the proportion of errors.

Method

Participants

The sample consisted of 49 Ohio State University post-baccalaureate students majoring in education (mean age = 23.92 years; 13 men and 36 women). There were 26 participants in the no external aid condition and 23 participants in the external aid condition. All participants received extra course credit for participation.

Materials and design

Materials consisted of propositions identical to those used in Experiment 1. Unlike in Experiment 1, however, each proposition was presented along with 10 cutout cards. For all logical forms, cutout cards stated the atomic propositions in the sentences, negations of atomic propositions, and unrelated filler statements. For each statement, there were two cards stating each of the two atomic propositions in the sentence, two cards stating the negation of each of the two atomic propositions, and two unrelated filler items. Presence of multiple cards stating the same atomic proposition was necessary to allow participants to veridically represent the logical forms. For example, to correctly represent a conjunction (*A and B*), they had to select just one pair of cards *(A* and *B*). At the same time, to correctly represent a disjunction (*A or B*), they had to select three pairs of cards (*A* and *not-B*; *not-A* and *B*; and *A* and *B*), with each pair corresponding to a true possibility. On each trial cards were arranged on the table in a random order.

The experiment had a 2 (external aid) by 2 (truth condition) by 4 (logical connective) mixed design, with external aids (external aids vs. no external aids) and truth condition (true vs. false) as between-subject factors, and with logical form (conjunction, disjunction, conditional, and bi-conditional) as a within-subject factor.

Procedure

Participants were tested individually in a quiet room. The experiment consisted of four phases: warm-up, selection, distraction, and cued recall. During the warm-up phase, participants read instructions and completed two practice trials, one of which asked them to select all and only those cards indicating that the sentence was true, and another of which asked them to select all and only those cards indicating that the sentence was false.

There was a minor variation in instruction in the external aids condition: Participants were explicitly told that they could put selected cards on one or separate sheets of paper. After that, two examples (one conjunction and one disjunction) were given showing that co-occurring possibilities could be put on the same sheet of paper, whereas not co-occurring possibilities could be put on separate sheets of paper. No further assistance was given to participants as how to use the sheets of paper.

During the selection phase, participants were presented with one sentence at a time. To ensure their proper encoding of the sentence, participants were asked to repeat it. If their encoding was incorrect the sentence was reread, and participants repeated it again. This procedure continued until the sentence was repeated correctly (in most cases the sentences were repeated correctly from the first trial, and no participants required more than two trials). After that, the experimenter laid down 11 cards in front of the participant. Of these, 1 card had the whole sentence printed on it, whereas 10 cards had atomic propositions, negations of these propositions, and filler items printed on them. Then, depending on the Truth condition, participants were asked to select either all and only those cards that would render the sentence true, or those that would render the sentence was false. For each sentence, all selected cards were placed together into an envelope (with a separate envelope for each sentence) to be presented for future cued recall.

The selection phase was followed by the distraction phase, during which the participants solved simple numerical problems. The purpose of this phase was to clear their working memory. Participants were given 7 min to solve these problems. Even if some problems were not solved within this time frame, the experiment moved to the cued-recall phase.

Prior to the cued, recall phase, the envelopes with selected cards were shuffled, so that the order of recall did not correspond to the order in which the sentences were presented during the selection phase. In addition, the participants were told that due to a lack of time, some of the envelopes were removed (which indeed was *not* the case). This minor deception was used to eliminate a frequency anchor with respect to logical forms (i.e., participants may have noticed that each form appeared on the list with equal frequencies, and thus the recalled list should have the same property). It seemed that the frequency anchor might have prompted guessing, while elimination of the anchor should have reduced the amount of random noise. During the cued recall phase, the researcher opened one envelope at a time, presenting participants with the cards that the participant had earlier selected for a sentence, and asked them to recall the entire original sentence. In the external aids condition, they were presented with cutout cards along with sheets of paper that these cards were placed on. Recall that the cards stated only atomic statements and filler items, but they did not state connectives. Participants recalled one sentence at a time.

If participants recalled an entire sentence, including the connective, the answer was scored as correct. If participants recalled a sentence correctly, but substituted one connective with another, the answer was scored as a substitution error. All other responses were scored as incorrect.

Results and discussion

In this section, we present participants' representation and recall of propositions across external aid, truth, and logical form conditions. As in Experiment 1, we compared participants' selection of cards truth table representations depicted in Table 1. A participant's answer was coded as correct in a given condition if the participant selected all and only the card arrangements marked by plus signs in Table 1.

Aggregated effects of externalization on correctness of representation and recall are presented in the top and bottom panels of Figure 2 respectively. A two (truth condition) by two (externalization condition) between-subjects ANOVA indicated that there were significant main effects of the truth condition (true > false), $F(1, 45) = 13.16$, $p < .005$ and of externalization condition (external aids > no external aids), $F(1, 45) = 4.63$, $p < .05$. There was also a significant truth by externalization interaction (only for the true and not the false condition did externalization result in the increase of correct representations), $F(1, 45) = 31.92$, $p < .0001$. As depicted in the top panel of Figure 2, externalization had positive effects on representation in the true condition (mean $\text{correct}_{\text{external aids}} = 6.8 >$ mean $\text{correct}_{\text{no external aids}} = 3.2$) and negative effects in the false condition (mean $\text{correct}_{\text{external aids}} = 2.4 <$ mean $\text{correct}_{\text{no external aids}} = 4.6$), both ts > 3.6, ps < .003. Significant effects of externalization on representation in the true

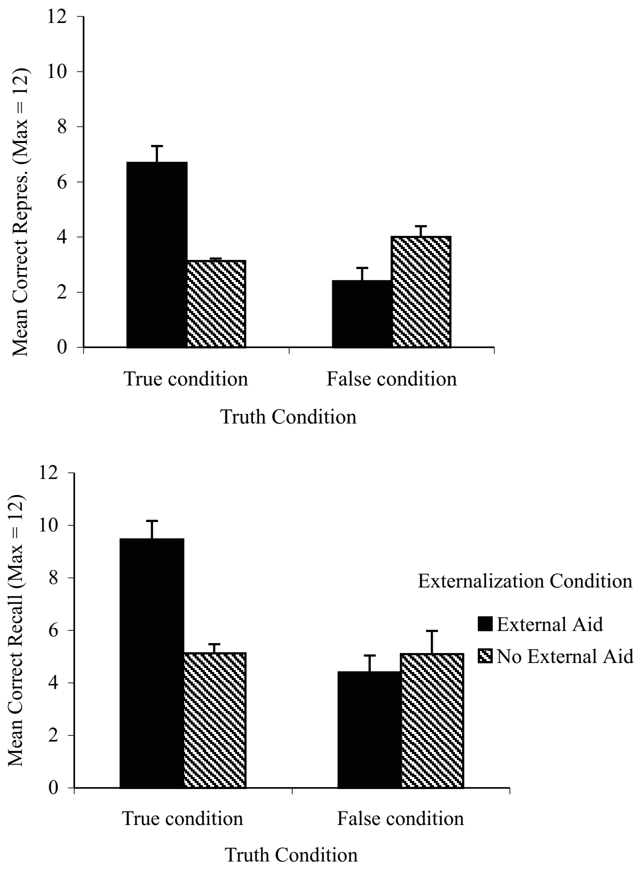

Figure 2. Effects of externalization on the correctness of representation and recall aggregated across logical forms, Experiment 2.

condition suggests that errors observed in Experiment 1 did not stem solely from participants' poor knowledge of meanings of logical connectives.

Effects of externalization on representation in the false condition were largely negative. These effects appear to be driven by attempts to construct multiple-possibility representations of disjunction in the false condition, which in fact is compatible with a single possibility. This issue will receive a more detailed examination below. In what follows, we present a detailed examination of participants' representation and recall across the conditions.

Representation. Numbers of correct representation by truth condition, externalization, and logical form are presented in Figure 3. These data were subjected to two-factor mixed ANOVAs with the externalization condition as a between-subject factor and the logical form as a within-subject variable. In the true condition (the top panel of Figure 3) there was a significant main effect of Externalization, $F(1, 27) = 32.2, p < .0001$, logical form, $F(3, 81) = 108.12$, $p < .0001$, and externalization by logical form interaction, $F(3, 81) = 18.4, p < .0001$. A more detailed analysis indicates that the conjunction generated near perfect performance at both

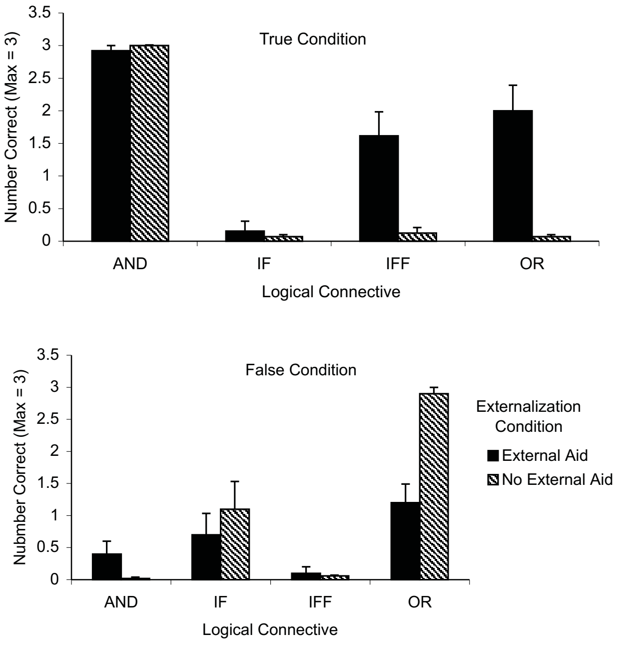

Figure 3. Effects of externalization on the correctness of representation by logical form and truth condition, Experiment 2.

levels of the externalization condition, whereas the conditional elicited near floor performance. At the same time, in the externalization condition, there was a marked increase in correct performance for the bi-conditional, $t(27) = 4.3, p < .0001$ and for the disjunction, $t(27) = 5.1, p < 0001$.

In the false condition (the bottom panel of Figure 3), the main effect of externalization, $F(1, 18) = 6.7, p < .02$, the main effect of logical form, $F(3, 54) = 27.9, p < .0001$, and externalization by logical form interaction, $F(3, 54) = 7.2, p < .05$, were significant. The interaction indicated that externalization did not result in changes in performance for the conditional and the bi-conditional (both ts < 1), it resulted in a small increase for conjunction, $t(18) = 1.8, p < .1$, and it resulted in significantly decreased performance for disjunction, $t(18) = 5.5$, $p < .0001$. Reasons for such become transparent when one analyses the effects of externalization on the number of represented possibilities (see Table 4 for details).

As shown in Table 4, in the true condition, for all logical forms except conjunction, externalization led to the increase of represented possibilities. At the same time, in the false condition, externalization resulted in the increased number of represented possibilities for disjunction only. Such an increase in the number of considered possibilities led to improved representation in the true condition, but it also decreased performance for representing the disjunction in the false condition. This decrease is related to a simple reason—there is only one false possibility for the disjunction (i.e., $\neg A$ & $\neg B$).

A more detailed distribution of patterns of representation by truth condition, externalization condition, and logical form is presented in Tables 5 and 6. As shown in Table 5, in the true condition, in the absence of external aids, conjunctions were most likely to be represented

TABLE 4
Mean numbers of represented possibilities[a] by Logical form, Truth condition, and Externalization condition, Experiment 2

	Truth and externalization conditions					
	True			*False*		
Logical form	*No EA*	*EA*	*EA versus No EA*	*No EA*	*EA*	*EA versus No EA*
Conjunction (AND)	1.05	1	*ns*	1	1.3	*ns*
Bi-conditional (IFF)	1.03	1.5	$t(27) = 4.6, p < .001$	1	1.1	*ns*
Conditional (IF)	1	1.4	$t(27) = 3.8, p < .001$	1	1.2	*ns*
Disjunction (OR)	1.04	2.5	$t(27) = 7.1, p < .001$	1	1.8	$t(18) = 3.8, p < .001$

* EA = External Aid.
[a]Max = 30.

TABLE 5
Percentage of representation responses in the TRUE condition by logical form in Experiment 2

	Forms presented to participants							
	No external aids				*External aids*			
Forms represented by participants	*AND*	*IFF*	*IF*	*OR*	*AND*	*IFF*	*IF*	*OR*
AND (conversion-to-conjunction)	**100.00***	95.83*	100.00*	95.83*	**97.44***	41.03	53.85	23.08
IFF	0.00	**4.17**	0.00	0.00	0.00	**56.41**	23.08	0.00
IF	0.00	0.00	**0.00**	0.00	0.00	0.00	**10.26**	0.00
OR	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00	**66.67***
Other	0.00	0.00	0.00	4.17	2.56	2.56	12.82	10.26

Note: Correct responses are in the diagonal cells (in bold). *Dominant response within the respective column, χ^2s(4) > 30, nonoverlapping confidence intervals, *p*s < .01.

TABLE 6
Percentage of representation responses in the FALSE condition by logical form in Experiment 2

	Forms presented to participants							
	No external aids				*External aids*			
Forms represented by participants	*AND*	*IFF*	*IF*	*OR*	*AND*	*IFF*	*IF*	*OR*
Not-AND	**0.00**	0.00	0.00	0.00	**6.67**	0.00	3.34	0.00
Not-IFF	0.00	**0.00**	0.00	0.00	0.00	**3.33**	0.00	3.33
Not-IF	0.00	0.00	**36.67**	0.00	0.00	0.00	**23.33**	3.33
Not-OR (conjunction-of-negations)	93.33*	56.67	56.67	**96.66***	76.67*	73.34*	60.00	**40.00**
Other (incorrect)	6.66	43.33	6.64	0.00	16.64	23.33	13.33	53.34

Note: Correct responses are in the diagonal cells (in bold). *Dominant response within the respective column, χ^2s(4) > 30, nonoverlapping confidence intervals, *p*s < .01.

correctly, whereas other logical connectives were most likely to be represented as conjunctions. However, when external aids were introduced, proportions of conjunctive representations of conditionals, bi-conditionals, and disjunctions dropped markedly, all χ^2s(1, 87) > 9, $p < .005$. The sharp decrease in erroneous conjunctive representations was accompanied by a modest increase in correct representations for conditionals (19%) and a large increase for bi-conditionals and disjunctions (52% and 67% respectively), all χ^2s(1, 79) > 7.5, $p < .01$. When external aids were used, disjunctions were most likely to be represented correctly, bi-conditionals were slightly more likely to be represented correctly than to be represented as conjunctions, and conditionals were most likely (albeit not significantly) to be represented as conjunctions.

In the false condition, however (see Table 6), both with and without external aids, the most dominant representation was conjunction of negations, which happened to be the correct representation for disjunctions and an erroneous representation for other logical connectives. This was a dominant representation of disjunctions, conjunctions, conditionals, and bi-conditionals, although there was a sizeable minority of participants who represented false conditionals correctly with and without external aids (23% and 36%, respectively). The only deviation from this pattern was a relatively low proportion of correct representation of disjunctions when external aids were used. As shown in Table 4, this deviation may stem from participants' tendency to use multiple possibilities to represent false disjunction in the external aids condition.

In short, in the true condition, external aids led to a marked decrease in the proportion of erroneous conjunctive representations and to a sizeable increase in the proportion of correct representations for bi-conditionals and disjunctions. The effects of external aids in the false condition were more mixed: While the proportion of erroneous conjunction of negation representations dropped, the proportion of correct representations did not increase.

Recall. Effects of externalization on recall rates by logical form and truth conditions are presented in Figure 4. These data are quite similar to those on representation. The effects of externalization were pronounced in the true condition, and they were absent in the false condition. Numbers of correctly recalled items depicted in Figure 4 were subjected to two (externalization condition) by four (logical form) repeated measures ANOVA. In the true condition (the top panel of Figure 4) there was a significant main effect of externalization, $F(1, 27) = 33.4$, $p < .0001$, logical form, $F(3, 81) = 21.3$, $p < .0001$, and externalization by logical form interaction, $F(3, 81) = 9.04$, $p < .0001$. In particular, there was a 70% increase for the disjunction $t(27) = 7$, $p < .0001$, a 42% increase for the conditional $t(27) = 3.9$, $p < .0001$, and a 29% increase for the bi-conditional, $t(27) = 2.7$, $p < .02$.

In the false condition (the bottom panel of Figure 4), the effect of logical form was significant, $F(3, 54) = 12.7$, $p < .0001$, with the following likelihood of correct recall: AND > OR = IF = IFF, for all the differences, pair-sample ts (19) > 4, all Bonferroni adjusted ps < .005. At the same time, neither the main effect of externalization $F(1, 18) = 0.4$, $p = .5$, nor the externalization by logical form interaction, $F(3, 54) = 0.3$, $p = .3$, were significant. Paired-sample t-tests indicated that externalization did not affect recall rates for any of the logical forms, all ts < 1.5.

A more detailed distribution of patterns of recall by truth condition, externalization condition, and logical form recall is presented in Tables 7 and 8. As shown in Table 7, in the

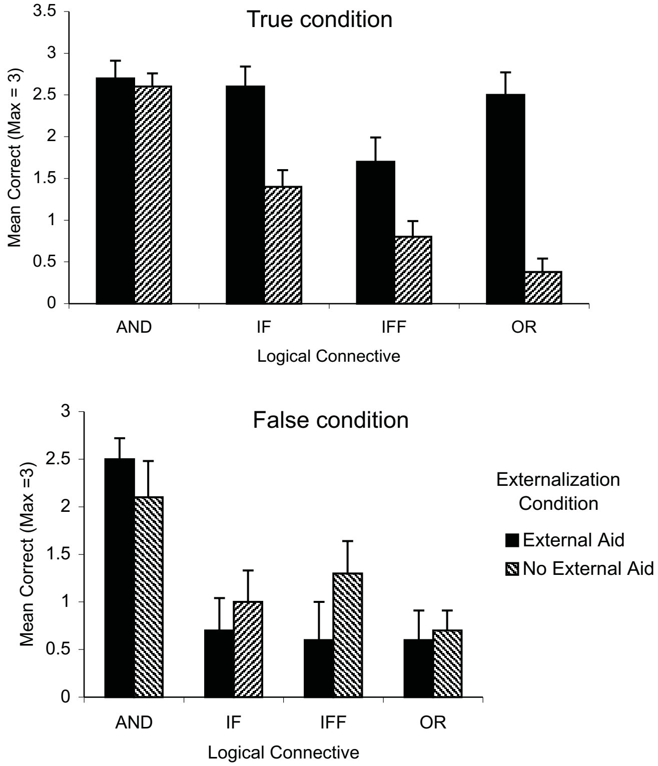

Figure 4. Effects externalization on recall by logical form and truth condition, Experiment 2.

TABLE 7
Percentage of recall responses in the TRUE condition by logical form in Experiment 2

	Forms presented to participants							
	No external aids				*External aids*			
Forms represented by participants	*AND*	*IFF*	*IF*	*OR*	*AND*	*IFF*	*IF*	*OR*
AND (conversion-to-conjunction)	**85.41***	41.67	43.75	66.67*	**90.00***	12.82	12.69	7.69
IFF	4.17	**27.08**	4.17	2.09	0.04	**56.41***	0.02	2.56
IF	4.17	25.00	**45.80**	8.30	7.64	28.51	**87.17***	5.13
OR	2.00	4.10	0.03	**12.50**	0.05	2.49	0.04	**82.05***
Other	0.08	0.07	1.00	0.03	2.52	0.07	0.07	3.85

Note: Correct responses are in the diagonal cells (in bold). *Dominant response within the respective column, χ^2s(4) > 30, nonoverlapping confidence intervals, *p*s < .01.

TABLE 8
Percentage of recall responses in the FALSE condition by logical form in Experiment 2

	Forms presented to participants							
	No external aids				*External aids*			
Forms represented by participants	*AND*	*IFF*	*IF*	*OR*	*AND*	*IFF*	*IF*	*OR*
AND (conversion-to-conjunction)	**70.00***	20.00	40.00	60.00*	**83.33***	40.00	60.00*	30.00
IFF	0.04	**43.33**	0.03	0.07	0.05	**20.00**	0.04	0.03
IF	6.58	6.67	**33.30**	6.60	6.62	6.67	**23.29**	0.06
OR	0.06	3.33	6.67	**23.33**	3.33	3.33	0.02	**19.97**
Other	17.66	20.00	20.00	6.67	6.67	30.00	16.65	49.94

Note: Correct responses are in the diagonal cells (in bold). *Dominant response within the respective column, χ^2s(4) > 30, nonoverlapping confidence intervals, *p*s < .01.

True condition, in the absence of external aids conjunctions were most likely to be recalled correctly, whereas disjunctions were more likely to be recalled as conjunctions. At the same time, conditionals and bi-conditionals were equally likely to be recalled correctly and to be recalled as conjunctions. When external aids were introduced, all logical forms were likely to be recalled correctly. In the false condition, however (see Table 8), both with and without external aids, only conjunctions were likely to be recall correctly. In terms of errors, in the external aids condition, conditionals were most likely to be recalled as conjunctions, whereas in the no-external aids condition, disjunctions were most likely to be recalled as conjunctions.

One important effect of external aids on recall is a marked decrease in the number of "conversions-to-conjunctions" in the true condition in all logical forms except conjunctions (recall that in the conjunction a representation of a proposition via a possibility *A* & *B* happens to be a correct answer). In particular, there was a 31% decrease for the conditional, a 29% decrease for the bi-conditional, and a 59% decrease for the disjunction, all χ^2s(1, 87) > 8.74, $p < .005$. The effects of external aids in the false condition were mixed, with neither difference reaching significance.

Representation versus recall. There are two seemingly contradictory findings pertaining to conditionals in the TRUE condition: While external aids failed to increase accuracy of representation (Figure 3), they resulted in an increased accuracy of recall (Figure 4). These results seem to stem from specific effects of external aids. Recall that external aids allowed participants to encode more than one possibility by placing cards on different sheets of paper. As a result, in the external aids condition participants used different codes for representing conjunctions and conditionals. In particular, as shown in Table 4, the average number of represented possibilities without and with external aids did not increase for conjunctions ($M_{\text{no external aids}} = 1.05$ and $M_{\text{external aids}} = 1$), whereas this number increased for conditionals ($M_{\text{no external aids}} = 1$, and $M_{\text{external aids}} = 1.4$, p < .001). At the same time, as shown in Table 5, external aids resulted in a small increase of correct representation of conditionals. Thus, as a result of using external aids, a participant could construct a two- or three-possibility representation, which could be erroneous (e.g., *P & Q*, *not-P & not-Q*, and *P & not-Q* is an erroneous three-possibility representation of the conditional), and yet help participants to represent different connectives differently, and thus help them recall all connectives (including conditionals) more accurately.

In short, in Experiment 2 it was found that (1) in the true condition, conjunctions were more likely to be correctly represented and recalled than other logical forms, whereas in the false condition disjunctions were more likely to be represented correctly; (2) external aids positively affected recognition and recall in the true condition, but not in the false condition; and (3) in the no external aids condition, conditionals, and bi-conditionals were as likely to be recalled correctly as they were to be recalled as conjunctions, whereas disjunctions were most likely to be recalled as conjunctions. In addition, it was found that for the true condition, external aids resulted in better recall of all logical forms, except conjunctions (these elicited near ceiling recall with and without external aids) and a decrease of erroneous "conversion-to-conjunction" recall responses. As opposed to the true condition, in the false condition external aids failed to improve recall.

The positive effects of externalization for disjunctions and conditionals in the true condition suggest that errors reported in Experiment 1 stemmed from one-possibility "minimalist" representations and not from a lack of understanding of meanings of logical connectives. Some misunderstanding of the logical connective, however, may have contributed to erroneous representations of conditionals. It also seems that in the false condition, errors stem from a confusion of falsification and negation, in addition to incomplete representations.

EXPERIMENT 3

This experiment used an old/new recognition paradigm consisting of study, distraction, and recognition phases. This paradigm affords the creation of a set of recognition foils such that patterns of hits and false alarms reveal which aspects of study items are represented and which are left out. In the study phase, participants were presented with a set of compound propositions connected by logical connectives. In the recognition phase, in addition to "old" items, several combinations of "new" items were presented as foils. Some of these items contained the same nouns as the study items but used a different logical connective, whereas other items used the same logical connective as study items but used nouns that differed from those used in study items. If results of Experiments 1 and 2 reflect participants' tendency to construct the minimalist representations with conjunctions as default representations, then conjunctions should be represented veridically, whereas other logical forms should be represented as conjunctions. Hence, conjunctions should be recognized more accurately than other logical forms. Experiment 3 tested this prediction by comparing acceptance rates by logical form and test item.

Method

Participants

A total of 84 undergraduates from Ohio State University completed the experiment for course credit. Of these 4 participants were eliminated from the analyses because they had not responded on more than a half of the trials. In addition, 7 participants were eliminated because of a low overall accuracy: Each of these participants wrongly accepted more than 50% of control items that were used to check for random responding (as described below). The final sample thus included 73 participants (mean age = 21.6 years; 51 women and 21 men).

Materials

The study list included 36 compound propositions, hereafter referred to as *original propositions*, with 12 each in the forms of conjunction, disjunction, and conditional. These propositions were similar to those used in Experiments 1 and 2. Propositions were constructed in the same manner as in Experiments 1–2, with atomic statements being randomly paired into compound sentences. To reduce the overall time of the experiment, only conjunctions, disjunctions, and conditionals were included in the design.

The recognition test included 144 compound propositions (hereafter *test propositions*). The list of test propositions included the original 36 items (targets) along with 108 foils; three foils were based on each target. Two of these foils, the different-form foils, presented the content of the original target in the other two logical forms (e.g., a conjunction target would have disjunction and conditional different-form foils). A third foil, the different-noun foil, altered one noun in one atomic proposition from the original target. For these foils, a noun was changed into another one that was semantically sensible for that atomic proposition's verb. These foils were used to control for the overall accuracy—it has previously been found that participants readily detect such semantic changes, correctly rejecting more than 80% of different-noun foils (see Begg & Wickelgren, 1974; Dosher, 1983, for converging findings). Therefore, targets and different-form foils are of primary interest because hypotheses concern participants' abilities to discriminate the targets of each propositional form from these foils.

An example of each type of foil, using an original conjunction, is shown below.

Original (target): *This person takes medicine and he likes the zoo.*
Different-form-disjunction foil: *This person takes medicine or he likes the zoo.*
Different-form-conditional foil: *If this person takes medicine then he likes the zoo.*
Different-noun foil: *This person takes medicine and he likes the opera.*

All propositions were presented on a computer screen in 18-point type. Presentation of items and the recording of participants' responses were controlled by a PC running the program Superlab, Version 1.05 (Cedrus Corporation, 1997). It was established in a calibration experiment that participants did not have a baseline bias for each of the logical forms: When new conjunctions, disjunctions, and conditionals were included in the calibration experiment, participants equally frequently and very accurately rejected each of these forms.

Design and procedure

The experiment had a two-factor (original form and test form) within-subject design. Both factors had three levels: conjunction, disjunction, and conditional. Each participant was tested individually. Instructions, displayed on-screen, informed the participant that they would see a series of descriptions (each one sentence long) of people, one at a time. The instructions advised the participant to study the descriptions carefully because memory for the descriptions would be tested after they had all been presented. The instructions also advised the participant not to be concerned if some of the descriptions seemed odd or unusual, but simply to study them carefully. During presentation of these instructions, the experimenter went over them with the participant and answered any questions. The experiment comprised of the study, distraction, and recognition phases.

During the study phase, participants were presented with the original list of 36 sentences. Each sentence was presented by itself, centred, on-screen, appearing for 8 s. The sentence then disappeared, and the process was repeated for the next sentence. The order of presentation was randomized.

After the last sentence was presented and had disappeared, the distraction phase began. This phase continued for approximately 5 min, during which participants were presented with arithmetic word problems. Then the recognition phase started with another set of instructions appearing on-screen. These instructions informed the participant that she would see another series of sentences, one at a time. Some of these sentences would be from the initial list, whereas others would be new ones that had not appeared on the list. For each sentence, the participant was to press the "Z" key if she believed it was an old sentence—that is, from the initial list. If she believed the sentence was a new one that had not appeared on the initial list, she was to press the "M" key. The instructions stated explicitly that the participant should only respond with "old" to sentences that she believed matched the original sentences verbatim. If a test sentence showed any change at all from the original, it was to be considered "new". The participant was then instructed to place one finger each on the "Z" and "M" keys for the duration of the experiment, and several reminders to hit "Z" for old and "M" for new appeared on-screen throughout the instructions. The order of presentation of test sentences was randomized for each participant.

Results and discussion

In this section we will focus on the overall accuracy and the ability to discriminate across logical forms. As discussed above, the measures of overall accuracy were mean rejection rates of different-noun foils. These rates for conjunctions, disjunctions, and conditionals respectively were 87.19%, 94.06%, and 92.22%. Thus, participants took the task seriously, and their accuracy for all forms was significantly above chance, all $ts(73) > 20.23$, $ps < .0001$.

Mean acceptance rates for the critical test descriptions by original form and test form are presented in Figure 5. A 3 (original form) × 3 (test form) ANOVA on the numbers of acceptances, with repeated measures on both factors, found a significant effect of test form, $F(2, 144) = 14.94$, $MSE = 0.04$, $p < .0001$. The Original Form × Test Form interaction was also significant, $F(4, 288) = 15.12$, $MSE = 0.03$, $p < .0001$. The effect of original form was not significant, $F(2, 144) = 2.31$, $p > .1$.

In the case of the test form effect, paired comparisons pointed to the following order among the logical forms: test items that were conjunctions were significantly more likely to be accepted than test items that were disjunctions or conditionals, for all differences $ts(72) > 3.2$,

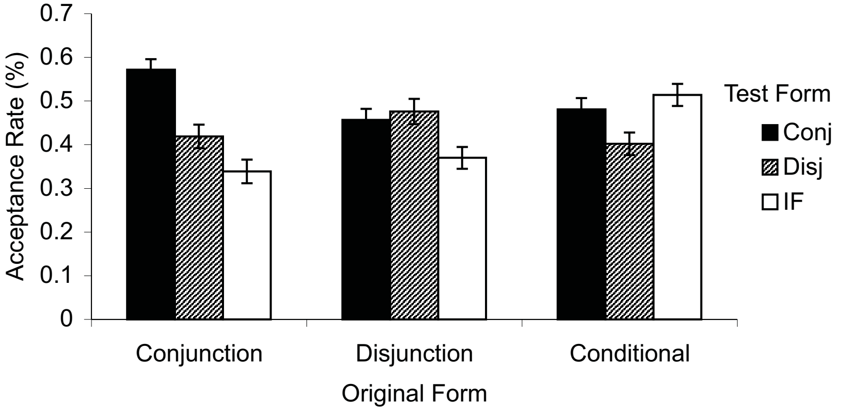

Figure 5. Mean acceptance rates by original form and test form, Experiment 3.

all Bonferroni-adjusted ps < .01. At the same time, there were no differences between acceptance of test items that were disjunctions and conditionals, $t(72) < 1$.

The interaction was examined through paired-comparisons of acceptance rates for the test forms within each original form. These analyses pointed to the following orders of acceptance within each original logical form. For original conjunctions, test items that were conjunctions were significantly more likely to be accepted than test items that were disjunctions or conditionals, whereas test items that were disjunctions were more likely to be accepted than test items that were conditionals (conj > disj > cond), for all differences ts(72) > 2.6, all Bonferroni-adjusted ps < .05. For original disjunctions, test items that were conjunctions or disjunctions were significantly more likely to be accepted than test items that were conditionals, whereas there were no differences between test items that were disjunctions and conjunctions (conj = disj > cond), for all differences ts(72) > 3.1, all Bonferroni-adjusted ps < .01. Finally, for original conditionals, test items that were conjunctions or conditionals were significantly more likely to be accepted than test items that were disjunctions, whereas there were no differences between test items that were conditionals and conjunctions (conj = cond > disj), for all differences ts(72) > 2.6, all Bonferroni-adjusted ps < .05.

The observed interaction is consistent with predictions of the "conjunction bias" hypothesis. The interaction points to an important dissociation: There was a relatively high discrimination of conjunctions from other forms and very low discrimination of other forms from conjunctions. Participants readily discriminated original conjunctions from disjunctive and conditional foils (they were much more likely to accept as "old" those exact descriptions than they were to accept disjunction and conditional foils). At the same time, participants poorly discriminated original disjunctions and conditionals from conjunctive foils (they were equally likely to accept the originals and their conjunction foils). Also, as indicated by the test form effect, participants were more likely to accept conjunction test descriptions than disjunction or conditional test descriptions.

Results of this experiment corroborate findings of Experiments 1 and 2, further supporting the hypotheses: In a simpler old/new recognition task with instructions to simply remember the presented statements participants still exhibited (1) higher accuracy for conjunctions and (2) "conjunction bias" in their recognition of nonconjunctive logical connectives.

GENERAL DISCUSSION

The major findings of the three reported experiments are as follows. Experiment 1 suggests that in the true condition, sentences with conjunctions (AND) are likely to be represented correctly, whereas sentences with disjunctions (OR), conditionals (IF . . . THEN), and biconditionals (IF AND ONLY IF . . . THEN) are likely to be erroneously represented as conjunctions. In the false condition, for some connectives the proportion of correct responses is related inversely to the proportion of errors in the true condition: conjunctions generated the smallest proportion of errors in the true condition and the largest proportion of errors in the false condition, whereas disjunctions generated the largest proportion of errors in the true condition, and the smallest proportion of errors in the false condition. Experiment 2 corroborated findings of Experiment 1, suggesting that in the true condition only conjunctions were represented correctly, whereas in the false condition only disjunctions elicited predominantly correct representations.

In both Experiments 1 and 2, disjunctions, conditionals, and bi-conditionals were most likely to be represented as conjunctions in the true condition. In the false condition, however, there was a tendency to represent all logical connectives as a conjunction of negations of constituent atomic statements. The tendency, however, was stronger in Experiment 2 than it was in Experiment 1, and it was stronger for conjunctions and disjunctions than it was for conditionals and bi-conditionals.

Recall data corroborated these findings for the true condition, where conjunctions were most likely to be recalled correctly, disjunctions were most likely to be recalled as conjunctions, and conditionals and bi-conditionals were as likely to be recalled correctly as they were to be recalled as conjunctions. Data on how connectives are recalled present strong converging evidence as to how these connectives are represented (cf. Favrel & Barrouillet, 2000, for similar arguments).

Finally, effects of externalization (Experiment 2) suggest that most of the reported errors are not limited to poor understanding of meanings of logical connectives, but these errors rather reflect the ways in which people intuitively represent logical connectives. When external aids were introduced, the number of represented possibilities increased, thus leading to an increase in correct responses for disjunctions and bi-conditionals in the true condition (both disjunctions and bi-conditionals have more than one true possibility) and to a decrease in correct responses for disjunctions in the false condition (disjunction has only one false possibility).

Results of Experiment 3 corroborate findings of Experiments 1 and 2 using an old/new recognition paradigm. It was found that conjunctions were most likely to be recognized correctly, whereas disjunctions and conditionals were as likely to be recognized correctly as they were to be recognized as conjunctions. Of course, it could be argued that the "conjunction bias" found in recall (Experiment 2) and in recognition (Experiment 3) stems from higher base rates of conjunctions in human discourse; however, the authors were unable to locate research tabulating the incidences of usage of various logical forms in everyday discourse. Furthermore, results of the calibration experiment, conducted prior to conducting Experiment 3 in conjunction with results of Experiment 3, undermine this possibility, suggesting instead that the "conjunction bias" stems from the preference for the "minimalist" one-possibility representation rather than from higher typicality of conjunction. The "minimalist" tendency may be indicative of people's preference for determinacy over indeterminacy: While the former is a product of a single possibility, the latter is a product of multiple possibilities.

Results of the reported experiments support the proposed hypotheses, indicating that (1) there is a "conjunction bias", and (2) this conjunction bias reflects the participants' tendency to minimize the number of represented possibilities to just one possibility. Results of the recognition experiment are critically important—they indicate that even under instructions to simply remember sentences, participants exhibited patterns of responses similar to those when their task was to select possibilities indicating that the proposition was true.

The reported results are compatible with previous findings with respect to representation of conditionals (e.g., Evans et al., 1996), they are novel with respect to bi-conditionals, and they differ from previous findings with respect to disjunctions. In particular, there is a large body of research indicating that, when presented with disjunctions *P or Q* and asked to select truth table entries that verify the disjunction, participants often selected *P & not-Q* (TF) and *not-P & Q* (FT) cases, while they less often selected *P & Q* (TT) cases (Braine & Rumain, 1981; Evans & Newstead, 1980). We believe that these differences stem from the fact that in our studies disjunctions were presented as *P or Q, or both*, thus prompting an inclusive interpretation, whereas "or both" was not included in the presentation of disjunctions in previous studies. In fact, we have preliminary evidence supporting this explanation: When in a truth table procedure similar to that in Experiment 1, disjunctions were presented as *P or Q, but not both*, the proportion of TF and FT responses increased to approximately 90%, which was comparable to many of the earlier studies.

Results of the false condition suggest that errors in the false condition may stem from the minimized representation and from the confusion of falsification with negation of atomic propositions. In particular, while negation of atomic statement (i.e., *not-A & not-B*) falsifies conjunction and disjunction, it represents true possibilities for the conditional and the bi-conditional. The data for conjunctions, disjunctions, and bi-conditionals point to these sources of error, whereas data are more mixed for conditionals. In particular, participants were equally likely to represent false conditionals correctly and to represent them as a conjunction of negations in Experiment 1 (37% vs. 35%, respectively), whereas they were less likely to represent conditionals correctly than they were to represent conditionals as a conjunction of negations in Experiment 2 (37% vs. 57%, respectively). Given that results with conditionals are mixed, it seems that the issue of whether participants confuse falsification with negation for all connectives requires further research. Note that previous research generated evidence pointing to such confusion (e.g., Barres, 1998) as well as evidence pointing to fairly accurate falsification of conditionals (e.g., Evans et al., 1996).

Of course, the minimalist representation and the conjunction bias found here do not always characterize people's representations of connectives: There are circumstances when the content of a sentence forces a multipossibility representation. For example, when the sentence conjoins mutually exclusive outcomes, thus implying an alternation (e.g., *Bill is in Paris or in London*) or when a deontic content of a sentence implies bi-conditionality (e.g., *If you are over 21, you can drink beer*), people may have to construct multiple-possibility representations. However, while effects of prior knowledge and content on reasoning have been studied extensively (Cheng & Holyoak, 1985; Griggs & Cox, 1983; Markovits, Fleury, Quinn, & Venet, 1998; see also Evans et al., 1993, for an extensive review), effects of prior knowledge on initial representations is a relatively under-researched issue (Newstead et al., 1997, is an example of such a study).

Although the reported findings support the minimalist representation hypothesis, we deem it necessary to consider several alternative explanations. First, the reported findings could stem from task-specific response tendencies. In particular, it could be argued that participants' responses stem from their tendency to reduce effort by looking at elements mentioned in the proposition and ignoring the logical connective. However, while this interpretation can explain results of Experiment 1 and results of the no external aids condition of Experiment 2, this interpretation does not explain results of either the external aids condition of Experiment 2 or results of Experiment 3. In particular, the external aid condition used in Experiment 2 led to a marked increase in the proportion of correct representations of disjunctions and bi-conditionals, although task demands and materials did not change. In addition, if participants in Experiment 3 were simply ignoring the connective, they should be equally likely (1) to confuse original conjunctions with disjunctions and conditionals and (2) to confuse original conditionals and disjunctions with conjunctions.

This however was not the case—the participants were more likely to exhibit (2) than they were to exhibit (1).

Another possibility is that conditionals are rarely interpreted as material implication, in which case propositions with negated antecedent are considered irrelevant rather than true (Johnson-Laird & Tagart, 1969). As a result, the only case confirming the conditional is a conjunction of the true antecedent and the true consequent. This explanation, however, while capable of accounting for representation of conditionals in the true condition, cannot account for representation of conditionals in the false condition. In addition, this interpretation cannot explain recognition data. Recall that the recognition task used in Experiment 3 requested that participants merely remembered the sentences, and it did not mention finding instances making the conditional true.

It is also possible that some of the reported findings are limited to the abstract content used in current tasks. In particular, it is well known that content of natural language often directs the interpretation of conditionals. For example, content may imply a relatedness of the antecedent and the consequent, inviting inferences that facilitate a bi-conditional interpretation of the conditional (e.g., the statement "If you paint my house, I will pay you $100" may invite "If you don't paint my house, I will not pay you $100"). Furthermore, conditionals are less likely to elicit three-possibility representations when content is unfamiliar, and alternatives to the antecedent are not easily available (Cummins, Lubart, Alksnis, & Rist, 1991; Markovits, 1986). However, even in natural language there are frequent instances of conditionals similar to those used in current studies. For example, a simple rule (e.g., "If the temperature falls below X, the lever has to be pressed"), a regulation (e.g., "If your income is below X, then file tax form Y"), or class inclusion statements (e.g., "If an enzyme has property X, then it belongs to class Y") seem to be similar to conditionals used in the present research and thus are likely to elicit similar responses. However, the question of whether current results with conditionals would generalize to more meaningful and familiar conditionals used in natural language remains open, and additional research is needed to answer this question. In short, some of the reported findings taken separately could generate plausible alternative explanations. These include participants' tendency to reduce effort, their interpretation of conditionals, their misunderstanding of instructions, or their lack of understanding of the meaning of logical connectives. However, taken together, the results strongly indicate that, at least with abstract content, participants tend to minimize possibilities denoted by logical connectives, often representing only one possibility: a conjunction of atomic proposition asserted in a compound statement. We believe that this tendency stems from people's preference of determinacy over indeterminacy, leading to their selective focusing on a single possibility.

These results seem to have important implications for theories of reasoning. For example, according to the syntactic or rule-based approach to reasoning, logically untrained individuals possess procedural inference schemata, stored in the lexical entries for logical connectives, and these schemata apply to arguments of incoming discourse (Braine & O'Brien, 1991; Lea, 1995; Sperber & Wilson, 1995; see also Rips, 1995). Note that rule-based theories consider mostly arguments and not propositions. However, in an attempt to explain errors in reasoning with conditionals, rule-based theories put forward a hypothesis pertaining to representation of conditionals. According to this hypothesis, errors in conditional reasoning often stem from people's representation of conditional as bi-conditionals (Braine & O'Brien, 1991; Rumain, Connell, & Braine, 1983). In particular, a conditional of the form *If P then Q* leads one to infer that *If not-P then not-Q*. Research presented here does not support this hypothesis: Participants rarely selected *If not-P then not-Q* as a true instance of conditionals. The reported results suggest that any theory of reasoning should include a semantic component—a theory of how people represent possibilities. This contention is consistent with previous findings pointing to effects of representation on reasoning. In particular, if adequate representations are prompted by visual aids (Bauer & Johnson-Laird, 1993) or inadequate representations are suppressed by content (Byrne, 1989; Cheng & Holyoak, 1985; Markovits et al., 1998), reasoning improves dramatically.

According to the probabilistic theory of reasoning (Oaksford & Chater, 1998) many of the systematic biases in human reasoning result from participants' applying probabilistic strategies. The probabilistic account has been applied to the Wason selection task (Oaksford & Chater, 1998), to syllogistic reasoning (Chater & Oaksford, 1999), and most recently to conditional reasoning (Oaksford, Chater, & Larkin, 2000). It is suggested that reasoning with conditionals consists of evaluation of the conditional probability of the conclusion given the categorical premise. As a result, the acceptance of the conclusion increases for low-probability premises and for high-probability conclusions. If participants apply probabilistic strategies, their representation of conditionals (*If P then Q*) might be explained by their computations of the conditional probability of $Q \mid P$ (*Q* given *P*). Assuming that participants know that *not-P* is irrelevant for these computations, it could be predicted that they should focus on *P*, *Q*, and *not-Q* cases. Further assuming that they know that *P & not-Q* falsifies the conditional *If P then Q*, the probabilistic model predicts the conjunctive representation of the conditional (and the bi-conditional) as *P & Q*. However, it is unclear how the probabilistic model would handle disjunctions as well as all the connectives in the false condition. In addition, it is unclear how the probabilistic approach would account for findings of the recognition experiment. The difficulty stems from three issues: (1) The recognition experiment did not involve explicit reasoning; (2) when participants are not asked to reason, the probabilistic effect does not hold (Rader & Sloutsky, 2002, Exp. 3); and (3) in the recognition experiment participants tended to construct conjunctive representations of conditionals and disjunctions. Therefore, it seems unlikely that the reported tendencies stem from people's computations of conditional probabilities. While issues (1) and (3) state simple facts stemming from the present research, issue (2) requires an explanation. Recall that the probabilistic effect represents a greater likelihood of the fallacy of affirming the consequent (i.e., inferring that *P* is the case from the premises *If P then Q* and *Q*) when the conditional probability of $P \mid Q$ is high (e.g., *If it is dark outside, then it is night*) than when the conditional probability of $P \mid Q$ is low (*If it is cold outside, then it is night*). The effect has been demonstrated in a series of studies (Cummins et al., 1991; Janveau-Brennan & Markovits, 1999; Markovits et al., 1998; Oaksford et al., 2000; Quinn & Markovits, 1998; see also Cummins, 1995; Thompson, 1994). However, when arguments are embedded in text and participants are asked to read the text, rather than to reason, the probabilistic effect disappears: Participants are equally likely to automatically make an erroneous affirming the consequent inference regardless of the conditional probability (Rader & Sloutsky, 2002, Footnote 1). In short, it does not seem that the reported findings can be reduced to probabilistic effects.

The reported findings are mostly consistent with the mental model theory. First, for the true condition, the theory predicts the conjunctive representation of conditionals and bi-conditionals (Johnson-Laird & Byrne, 1991). Second, the theory predicts that people represent falsity by first constructing true possibilities and then negating them (Barres, 1998). However, according to the mental model theory, disjunction should elicit a two-model representation:

P
    Q

rather than a conjunctive one-model representation. We believe that representation of disjunctions specified by the mental model theory stems from (1) the use disjunctions that prompt the exclusive interpretation by blocking the inclusive interpretation (e.g., Bob is in Paris or in London) and (2) not using "or both" clauses that may block the exclusive interpretation and prompt the inclusive interpretation. Our findings suggest that when the exclusive interpretation of disjunction is blocked, participants tend to construct a single-possibility minimalist representation. If this is the case, it seems that the mental model theory should include different representations for inclusive and exclusive disjunctions.

There are several unresolved issues that should be addressed in future research. Do people limit themselves to the "minimalist" representation or do they initially consider multiple possibilities, but then discard all but one of them? If the former is the case, then determinate problems should have solution times comparable to those of indeterminate problems. However, if the latter is the case, then indeterminate problems should have longer solution times than determinate problems. This should happen because indeterminate problems would require reasoners to represent more possibilities. The issue has been examined, in part, in relational reasoning. For example, Carreiras and Santamaría (1997) presented participants with one-possibility and two-possibility reasoning problems. A one-possibility problem stated that *A is on the right of B*, *C is on the left of B*, *D is in front of C*, *E is in front of A*, and it asked whether or not *D is on the left of E*. A two-possibility problem stated that *A is on the right of B*, *C is on the left of A*, *D is in front of C*, *E is in front of A*, and it also asked whether or not *D is on the left of E*. Results indicated that solution times for one-possibility problems were significantly shorter than those for two-possibility problems. However, the issue remains unresolved with respect to propositional reasoning.

The reported results describe an important component of reasoning—the initial representation of logical connectives—while leaving out other components, such as search for counterexamples. It is known that under some conditions, search for counterexamples may reduce representational errors (e.g., Johnson-Laird & Byrne, 1991). However, at least some reasoning errors may be explained by the tendency to construct the minimalist representation of possibilities. While unresolved issues require further research, the reported results indicate that untrained participants tend to construct the minimalist one-possibility representations of different logical connectives and that this tendency cannot be reduced to their poor knowledge of meaning of logical connectives.

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APPENDIX

Conjunction (AND):
(1) This person drinks orange juice in the morning and watches history channel.
(2) This person rides a bicycle to work and does not like Chinese food.
(3) This person does not enjoy cooking and does not travel abroad.

Disjunction (OR):
(1) This person likes fishing or volunteers in a public school, or both.
(2) This person wears boxers or does not eat boiled eggs, or both.
(3) This person does not go to church or does not play golf on weekends, or both.

Conditional (IF):
(1) If this person works on weekends, then he supports scientific research.
(2) If this person likes horseback riding, then he does not support the Democratic Party.
(3) If this person does not have a college degree, then he does not like hamburgers.

Bi-conditional (IFF):
(1) If and only if this person is honest, he drives a blue minivan.
(2) If and only if this person attends meetings, he does not read mystery novels.
(3) If and only if this person does not eat grilled chicken, he does not wash his car.