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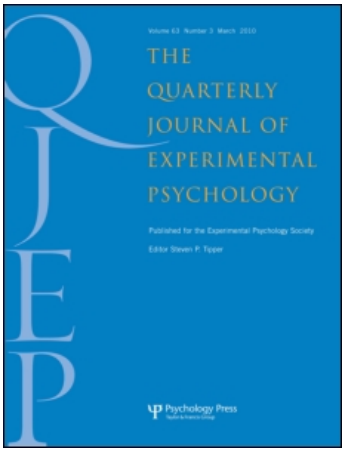

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The modulation of conditional assertions and its effects on reasoning

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The modulation of conditional assertions and its effects on reasoning

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The theory of mental models postulates that conditionals of the sort, *if A then C*, have a "core" meaning referring to three possibilities: *A* and *C*, *not-A* and *C*, and *not-A* and *not-C*. The meaning of a conditional's clauses and general knowledge can modulate this meaning, blocking certain possibilities or adding relations between the clauses. Four experiments investigated such interpretations in factual and deontic domains. In Experiment 1, the participants constructed instances of what was possible and what was impossible according to various conditionals. The results corroborated the general predictions of the model theory and also the occurrence of modulation. The resulting interpretations governed the conclusions that participants accepted in Experiment 2, which also yielded the predicted effects of a time limit on responding. In Experiment 3, the participants drew the predicted conclusions for themselves. In Experiment 4, modulation led to predicted temporal relations between *A* and *C*. We relate these results to current theories of conditionals.

Keywords: Reasoning; Conditionals; Mental models; Modulation; Formal rules of inference.

Reasoning from assertions based on "if" is ubiquitous in daily life. We all make such inferences as:

> If we don't want to miss the plane then we must leave in five minutes.
> We don't want to miss the plane.
> And so we must leave in five minutes.

Inferences based on conditional assertions have also been much studied in the psychological laboratory, but experimenters have tended to use abstract or artificial materials, such as:

> If there is a "B" then there is a "2".
> There is a "B".
> And so there is a "2".

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The reason for avoiding realistic materials is to protect the underlying mental processes from the effects of content and knowledge (see, e.g., Evans & Over, 2004; Johnson-Laird & Byrne, 1991; Rips, 1994; Wason & Johnson-Laird, 1972). Indeed, everyday conditionals do have a variety of meanings. They have been a theoretical nightmare for two millennia, and so there are more books about "if" than about any other two-lettered word.

The theory of mental models—the "model theory" for short—applies to conditionals, and it explains the diversity of their meanings in terms of interactions among a set of simple components (Johnson-Laird & Byrne, 2002). It gives an account of their core meaning and of a mechanism of *modulation* that can transform this meaning into an indefinite number of different sorts of interpretation. Certain sorts of modulation should have a powerful impact on the inferences that individuals draw, and the present paper reports a series of studies that investigated this hypothesis. The paper begins with an outline of the model theory and of other alternative accounts of conditionals. It then reports four experiments that test the modulation hypothesis. Finally, it draws some general conclusions about theories of conditionals.

The model theory of conditionals

Validity is easily defined in logic: "A valid inference is one whose conclusion is true in every case in which all its premises are true" (Jeffrey, 1981, p. 1). Psychological theories based on formal rules of inference aim to capture validity by way of logical form (e.g., Rips, 1994). That goal is simple to achieve in logic, because logic deals with the implications of sentences in a formal language, and so logical form is transparent and unambiguous. However, the goal is difficult to achieve in everyday life, because validity concerns propositions expressed by sentences, not sentences themselves. And the proposition expressed by sentences, such as, "If you do that then I'll do this," clearly depends on its context (Jeffrey, 1981, p. 14). Hence, logical form depends on both the *grammatical* form of a sentence and the context of its use. No algorithm exists for recovering the logical form of all the propositions expressible in a natural language. And some logicians confronted with natural language have found logical form unilluminating (e.g., Barwise, 1989).

The model theory makes the radical assumption that reasoning depends, not on logical form, but on mental models, which are psychological analogues of the models that represent content in logic. According to the theory, individuals use the meaning of words, the grammatical structure of sentences, and their knowledge, to construct models of the possibilities to which propositions refer, and a conclusion is valid if it holds in all these models (e.g., Johnson-Laird, 2006). Hence, validity can be assessed for individual inferences. The theory applies to conditionals (Johnson-Laird & Byrne, 2002; Johnson-Laird, Byrne, & Girotto, 2008), and it postulates that their complexity arises from interactions among several simple components:

1. Basic conditionals are those that are as independent as possible from knowledge and have no semantic or referential relations between their clauses other than their co-occurrence in the same conditional. The *core* meaning of a basic conditional, such as:

   If there is a triangle then there is a circle.

refers to three possibilities:

Δ	o
not-Δ	o
not-Δ	not-o

The conditional can accordingly be paraphrased as:

There isn't a triangle, or, if there is, then there's a circle.

The three possibilities of the core meaning correspond to those of "material implication", a connective in logic (Jeffrey, 1981, p. 61). Children gradually develop the ability to list these possibilities (Barrouillet, Grosset, & Lecas, 2000; Barrouillet & Lecas, 1998, 1999). Young children tend to list just the first possibility above; older children list the first and the third possibilities; and still older children list all three possibilities. A better predictor of the number of possibilities that children list is not their age, but the processing capacity of their working memory.

2. The principle of *truth* stipulates that individuals focus on what is true at the expense of what is false, especially for subordinate clauses (Johnson-Laird, 2006; Johnson-Laird & Savary, 1999). Hence, when individuals reason from a basic conditional, they normally construct a single *mental model* that represents the first possibility above, in which the conditional's antecedent (the *if*-clause) and its consequent (the *then*-clause) are both true, and an implicit mental model—a place holder with no explicit content (as shown by the ellipsis below)—that represents the other possibilities in which the antecedent is false:

   Δ o
   ...

3. In daily life, the meaning of the clauses in conditionals and coreferential relations between them can modulate the core meaning in a process of *semantic* modulation. Likewise, knowledge about the context and the topic of the conditional can modulate the core meaning in a process of *pragmatic* modulation. The effects of the two sorts of modulation are similar. One effect is to block the construction of models of possibilities. For instance, the conditional, "if they played a game then they didn't play soccer", does not refer to three possibilities, because the meaning of "soccer" prevents reference to the possibility in which they didn't play a game yet they did play soccer. It follows from the truth of the conditional alone that they didn't play soccer. Another effect of modulation is to add information about a relation between the events referred to in the antecedent and consequent. The conditional, "if she put a book on the shelf then it fell off", elicits the temporal relation that the antecedent event occurred *before* the consequent event, and the spatial relation that the book ended up below the shelf (cf. Byrne & Johnson-Laird, 1989; and Schaeken, Johnson-Laird, & d'Ydewalle, 1996). There are indefinitely many interpretations of conditionals because there are indefinitely many temporal, spatial, or other relations that modulation may yield.

4. The interpretation of conditionals depends on their grammatical form, tense, mood, aspect, and modal auxiliaries. Certain conditionals are deontic in that they concern what is permissible or obligatory, or, as we shall say, what is deontically possible or necessary. One clue to them is the use of certain modal auxiliary verbs, such as *ought* in this sentence: "If you promised then you ought to go", but context matters too (Stenning & Van Lambalgen, 2008, p. 50). The model theory postulates that such assertions are represented in terms of factual possibilities for their antecedents and deontic possibilities for their consequents:

You promised.	You go.
You didn't promise.	You go.
You didn't promise.	You don't go.

   The case in which you promised and didn't go is factually possible because people do break promises, but it is not deontically possible—that is, it is not permissible for you not to go. Once again, individuals are unlikely to represent all three possibilities above. However, in the domain of prudential obligations, such as, "If the nurse cleans up the blood then she should wear rubber gloves" (Manktelow & Over, 1990), they are likely to represent the salient deontic possibility that the nurse cleaned up blood and wore gloves and the deontic impossibility that she cleaned up blood and did not wear gloves (Byrne, 2005; Quelhas & Byrne, 2003). In other words, individuals are more aware of deontic impossibilities than of factual impossibilities (Bucciarelli & Johnson-Laird, 2005).

5. Another effect of auxiliary verbs is to yield conditional sentences that are subjunctive in mood, e.g.: "If there had been any deserters then they would have been shot". This conditional can express a proposition that leaves open whether or not there were any deserters. However, it can also express a *counterfactual* claim according to which there weren't any deserters, but had there been any, they would have been shot (see Byrne, 2005, for a theory of counterfactuals and corroboratory evidence).
6. In logic, material implication is closest to the core meaning of a conditional, but material

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implication has a "truth-functional" meaning. That is, whether it is true or false depends solely on whether its constituent clauses are true or false: It is false in the case that its antecedent is true, and its consequent is false; and it is true in any other case. Such an interpretation cannot work for all conditionals, because of the effects of modulation. For example, a conditional such as: "If she fell off her bike then she broke her leg", is not necessarily true merely because both of its clauses are true: The two events may have occurred in the wrong temporal order. Indeed, the interpretive process takes into account the meaning and reference of clauses even in those cases in which it results in a core interpretation corresponding to material implication. A corollary is that "conditionals are not truth functional" (Johnson-Laird & Byrne, 2002, p. 673; pace Evans & Over, 2004, p. 21; Evans, Over, & Handley, 2005).

7. A *small-scope* principle applies to any sentential operator, including negation, and phrases such as "it is true that": These operators tend to be interpreted, sometimes wrongly, as applying only to main clauses (Johnson-Laird et al., 2008). We emphasize that "scope" here refers to the grammatical form of sentences, not to the logical form of propositions. According to the small-scope principle, the following question:

   In what cases is it true that if there is a triangle then there is a circle?

will often be taken to mean:

   If there is a triangle then in what cases is it true that there is a circle?

Hence, in Quine's (1974, p. 19) words: "An affirmation of the form 'if p then q' is commonly felt less as an affirmation of a conditional than as a conditional affirmation of the consequent. . . . If the antecedent turns out to be false, our conditional affirmation is as if it had never been made." Quine accordingly distinguishes between the affirmation of a conditional and how individuals often interpret conditionals.

Alternative theories of conditionals

The most important alternative theories are those based on formal rules of inference, on necessary and sufficient conditions, on suppositions, and on probabilities. We outline each of them in turn.

Formal rule theories postulate rules of inference for reasoning from conditional premises (e.g., Braine & O'Brien, 1991). The rule of conditional proof, for example, allows a reasoner to assume a proposition, *A*, for the sake of argument, and should that assumption together with other premises lead to a conclusion, *C*, then the reasoner can draw a conditional conclusion, *if A then C*. Similarly, a conditional premise, *if A then C*, together with a categorical premise, *A*, allows a reasoner to conclude, *C*, which is an inference of the sort known as modus ponens. Formal theorists recognize that conditionals can be interpreted in different ways (see, e.g., Braine & O'Brien, 1991), but they have not proposed any comprehensive theory of how such interpretations arise. Rips (1994), for example, finesses this problem, taking for granted that the input to his "PSYCOP" theory is the logical form of premises. In contrast, Stenning and Van Lambalgen (2008) argue that conditionals have various logical forms, including one that captures a ternary relation of the form: *If A and nothing abnormal is the case then C* (see also, e.g., Reiter, 1980). Experimenters have indeed observed the effects of abnormal conditions on conditional inferences. A disabling condition for the proposition, "if you pull the trigger then the pistol fires", is that there are no bullets in the pistol. When such a disabler is salient, then individuals are less likely to make modus ponens (see, e.g., Bonnefon & Hilton, 2002; Byrne, 1989a, 1989b; De Neys, Schaeken, & d'Ydewalle, 2002). An alternative antecedent for the proposition, "if you catch fish then you have a fish supper" is that you buy fish from a shop. When such an alternative is salient, then individuals are less likely to infer fallaciously that if you didn't catch fish then you didn't have a fish supper (see, e.g., Byrne, 1989a, 1989b; Cummins, 1995; Cummins, Lubart, Alksnis, & Rist, 1991; De Neys, Schaeken, & d'Ydewalle,

Table 1. *The possibilities compatible with five sorts of interpretation of conditionals of the grammatical form,* if A then C

The five sorts of interpretation of conditionals	*The possibilities consistent with each sort of conditional*			
Tautological	**A C**	**A not-C**	not-A C	not-A not-C
Core	**A C**		not-A C	not-A not-C
Enabling	**A C**	**A not-C**		not-A not-C
Biconditional	**A C**			not-A not-C
Relevance	**A C**		not-A C	

Note: The cases in bold correspond to the explicit mental models of the propositions, which are constructed according to the principle of truth.

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2005; Janveau-Brennan & Markovits, 1999; Markovits & Vachon, 1990).

Another way to try to make sense of these results is in terms of necessary and sufficient conditions (Thompson, 1994, 2000). A disabling condition establishes that an antecedent is no longer sufficient for the consequent, and an alternative to an antecedent establishes that an antecedent is no longer necessary for the consequent. This view is similar to certain aspects of the model theory, and we are sympathetic to it. However, the concepts of necessity and sufficiency are probably too technical to be psychological givens, and they yield only four possible interpretations of a conditional (see Table 1):

1. A is necessary and sufficient for C: the biconditional interpretation.
2. A is not necessary but sufficient for C: the core interpretation.
3. A is necessary but not sufficient for C: the enabling interpretation.
4. A is neither necessary nor sufficient for C: the tautological interpretation.

As Table 1 shows, these interpretations can be analysed in terms of models of possibilities. If *A* is sufficient for *C*, then, in any possibility in which *A* holds, *C* also holds. Likewise, if *A* is necessary for *C*, then, in any possibility in which *C* holds, *A* also holds—that is, *C* is sufficient for *A*. Indeed, Markovits and his colleagues have developed a model-based account of the phenomena (e.g., Markovits & Barrouillet, 2002; Markovits & Quinn, 2002; Quinn & Markovits, 1998). Modulation suggests that the blocking of possibilities can yield 10 sorts of interpretation (see Johnson-Laird & Byrne, 2002), and so, for example, the *relevance* interpretation of "if they played a game then didn't play soccer", cannot be analysed in terms of necessity and sufficiency (see Table 1).

The "suppositional" theory of Evans and Over (e.g., 2004) is based in part on the model theory, but it emphasizes an idea of the logician Ramsey (1929/1990). He took the *meaning* of a conditional to be material implication, but he wrote (1929/1990, p. 155):

> If two people are arguing "If p will q?" and both are in doubt as to p, they are adding p hypothetically to their stock of knowledge and arguing on that basis about q; so that in a sense "If p, q" and "If p, not q" are contradictories. We can say they are fixing their degrees of belief in q given p. If p turns out to be false, these degrees of belief are rendered void.

The Ramsey test offers no immediate explanation of how individuals are able to envisage the possibilities consistent with a basic conditional, especially those possibilities in which the antecedent is false (e.g., Barrouillet et al., 2000). However, following Stalnaker (1968), Evans and Over (2004) suggest that the test could define the *meaning* of conditionals. They also write: "Our view of 'if' is that of a linguistic device the purpose of which is to trigger a process of hypothetical thinking and reasoning" (Evans & Over, 2004, p. 153). As they recognize, there are two corollaries of their view. First, a conditional of the form *if A then C* should have a defective truth table—that is, it should be judged as true when both *A* and *C* are true, false when *A* is true, and *C* is false, but have no truth value when

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A is false. Naïve individuals often make such judgements when they are asked to evaluate conditionals (e.g., Johnson-Laird & Tagart, 1969). Second, when individuals are asked for the denial of a conditional, they should respond: *if A then not-C*. Some evidence is consistent with this view (Fillenbaum, 1978; Handley, Evans, & Thompson, 2006). The small-scope principle, described earlier, predicts this response, though it is an incorrect negation of the core meaning of *if A then C*. However, other evidence shows that individuals quite often make the correct denial of such conditionals: *A and not-C* (Khemlani, Orenes, & Johnson-Laird, 2009).

The suppositional theory shares many components with the model theory, which postulates that individuals do make suppositions, though often of propositions other than the antecedents of conditionals (Van der Henst, Yang, & Johnson-Laird, 2002). The two theories diverge principally in their accounts of conditionals. And if it is correct both that conditionals have a defective truth table and that their correct negations negate only their consequents then the model theory's account is wrong. However, another consequence of the model theory's small-scope principle is that individuals should treat the verification of conditionals as a task in which they take the antecedent for granted and assess the truth of the consequent alone. The result is a defective truth table in which *if A then C* has no truth value in any case in which *A* is false (see Evans & Over, 2004; Johnson-Laird & Tagart, 1969). Of course, they are not really evaluating the truth of the conditional, but rather the truth of its consequent given the truth of its antecedent. These issues, however, are highly controversial and not immediately relevant to our present studies (see, e.g., Byrne & Johnson-Laird, 2009; Over, Evans, & Elqayam, 2010, for contrasting views).

Various accounts of human reasoning have postulated a crucial role for probabilistic considerations. Some theorists have proposed that a probabilistic relation between premises and conclusions should replace the notion of validity (Oaksford & Chater, 2001). Other theorists have maintained the notion of validity, but postulated a probabilistic semantics for conditionals: "In everyday contexts it seems to be more plausible to interpret conditionals not by material implications, but by much weaker conditional probabilities" (Pfeifer & Kleiter, 2005). Likewise, many theorists have proposed that the probability of a conditional is the corresponding conditional probability of its consequent given its antecedent (e.g., Evans, Handley, Neilens, & Over, 2007; Evans, Handley, & Over, 2003; Hadjichristidis et al., 2001; Over, Hadjichristidis, Evans, Handley, & Sloman, 2007; Oberauer & Wilhelm, 2003). Oberauer and his colleagues have argued that the model theory needs to be revised in order to explain their participants' judgements of the probabilities of conditionals, which usually corroborated the conditional probability hypothesis (Oberauer, Geiger, Fischer, & Weidenfeld, 2007). However, according to the model theory, these judgements reflect the small-scope principle—that is, individuals take a question of the form:

What is the probability of if A then C?

to mean:

If A, then what is the probability of C?

Experimental participants spontaneously make this change when they think aloud (Girotto & Johnson-Laird, 2004). Serious arguments exist against the conditional probability hypothesis (see, e.g., Byrne & Johnson-Laird, 2009; Schroyens, Schaeken, & Dieussaert, 2008). The issue is controversial, but not relevant to our present experiments, which do not concern probabilities, and so we pursue it no further here.

We have outlined five accounts of conditionals: the model theory, formal rule theories, the theory of necessary and sufficient conditions, the suppositional theory, and probabilistic theories. So, how do they fare in accounting for reasoning and the four standard inferences based on conditionals? Two of these inferences are affirmative:

Modus ponens (MP): If A then C; A; therefore, C.
Affirmation of the consequent (AC):
If A then C; C; therefore, A.

and two of them are negative inferences:

Modus tollens (MT): If A then C; not-C; therefore, not-A.
Denial of the antecedent (DA): If A then C; not-A; therefore, not-C.

In the case of the core meaning of conditionals, only modus ponens and modus tollens are valid. Oberauer (2006) has compared parameterized models of three of the theories with his data for these four inferences. The best accounts were given by two versions of the model theory, one modified by the introduction of a directional effect from antecedent to consequent and the other a "dual-process" version of the model theory due to Verschueren, Schaeken, and d'Ydewalle (2005) and based in part on Johnson-Laird (1983, chap. 6), who defends a dual-process theory. They gave a better account of the data than either the suppositional theory (Evans & Over, 2004) or the probabilistic theory (Oaksford, Chater, & Larkin, 2000).

The present studies concern modulation, and their logic is as follows: First, no existing theory of conditionals provides a recipe for predicting the actual interpretation of particular conditionals. Such a prediction would depend on a comprehensive theory of semantics and pragmatics, which is beyond any immediately foreseeable theory. However, the model theory does predict a set of *possible* interpretations, including those that go beyond necessary and sufficient conditions and beyond other theories of conditionals. Second, we used our intuitions to select conditionals that should yield different predicted interpretations, but we carried out Experiment 1 in order to determine the actual interpretations of these conditionals: The participants had to construct the different possibilities, consistent and inconsistent with the conditionals. No direct path exists to the interpretations of assertions, but this task is simple, reveals a key aspect of interpretations, and yields a clear consensus (Barrouillet et al., 2000). The experiment was accordingly designed to determine operationally the main interpretations of a set of conditionals. Third, these interpretations should predict different patterns of acceptance and rejection of the four standard conditional inferences, and Experiments 2 and 3 were designed to test this prediction. Finally, a further experiment examined whether modulation introduced temporal relations into the interpretation of conditionals, because no previous study had examined this possibility, and because it would be a corrective to the misconception that the model theory proposes a truth-functional analysis of conditionals.

EXPERIMENT 1

Our first experiment examined whether the content of conditionals modulated their interpretation. We presented participants with conditionals of the grammatical form, *If A then C*, and their task was to construct the cases that were possible and the cases that were impossible according to each conditional. They constructed these cases using cards corresponding to the individual propositions *A*, *C*, *not-A*, and *not-C*. We created conditionals that intuitively should yield different sorts of interpretation (according to Johnson-Laird & Byrne, 2002). These interpretations, if they occurred, yield contrasting predictions about which valid inferences individuals should draw. There were two sets of conditionals, one set concerned factual matters, and one set concerned deontic matters. Table 1 lists the possibilities corresponding to the five interpretations we sought to elicit in our entire set of experiments.

Whatever interpretations the participants make, the model theory yields four general predictions about their performance. First, they should construct a greater proportion of possible cases than impossible cases, because mental models represent only possibilities. Second, this difference should be greater for factual conditionals than for deontic conditionals, because in the everyday world of permissions and obligations what is forbidden is more salient than what is factually impossible (see Bucciarelli & Johnson-Laird, 2005; Byrne, 2005, p. 78; Quelhas & Byrne, 2003). Third, participants should construct the *A and C* case first for all interpretations, because this case corresponds to the one explicit mental model of all conditionals in which both clauses are true. Fourth, if modulation has an effect, it

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should become apparent in the cases that the participants constructed second (see Table 1).

Method

Design

The participants were assigned at random either to a group that received factual conditionals or to a group that received deontic conditionals. Within each group, the participants constructed cases for each of 16 conditionals with different contents (four instances of each of these putative interpretations: core, biconditional, enabling, and tautological). The order of the conditionals was randomly assigned to each participant.

Participants

A total of 60 first-year psychology students (48 woman, 12 men) from Instituto Superior de Psicologia Aplicada (ISPA) in Lisbon participated in the experiment for course credit (factual group: $n = 30$; deontic group: $n = 30$).

Materials

The materials were 16 factual and 16 deontic conditionals. For both sets, we constructed four instances of each of the four sorts of interpretation identified in Johnson-Laird and Byrne (2002). The full set of materials for this experiment is in Appendix A. Here are four factual examples (translated, as are all the materials in this paper, from Portuguese):

> Core interpretation: *If the dish is kidney beans then its basis is beans.*
> Biconditional interpretation: *If the animal is a lion then the female is a lioness.*
> Enabling interpretation: *If the dish is made of meat then it can be Portuguese stew.*
> Tautological interpretation: *If the dessert is made of apple then it can be pie.*

The deontic contents were similar—for example, an example of the core interpretation is:

> *If a person gets his driving licence then he or she must be at least 18 years old.*

The participants constructed the instances from four sorts of cards representing an affirmation of the antecedent of the conditional, a negation of its antecedent, an affirmation of its consequent, and a negation of its consequent.

Procedure

The participants were tested individually in a quiet room. The key instructions were as follows: "In this experiment, we are interested in how people imagine different situations based on conditional sentences. I will show you sentences that you will read out aloud. Next I will give you sets of four cards, and your task will be to construct all the situations that come to mind after reading the initial sentence. Construct the situations in the same order as you imagine them." The instructions explained that the task was to use the cards provided for each conditional to construct cases, both those that were possible and those that were impossible, factually or deontically, depending on the group. The participants were told that they were free to construct the cases in whatever order they came to mind, but they had to indicate the status of each case as possible or impossible. As an example, the experimenter showed the participants a disjunctive assertion and constructed an example of a situation that was possible given the assertion, and another that was impossible, either factually or deontically, again depending on the group.

Results and discussion

The results corroborated the model theory's four general predictions. First, of the cases constructed by the factual group, 97% were possibilities, and only 3% were impossibilities. Likewise, of those constructed by the deontic group, 82% were possibilities, and 18% were impossibilities. The overall proportions according to the four interpretations in Table 1 should have been 75% to 25%. Hence, the participants omitted a greater proportion of impossibilities than possibilities: All 30 participants in the factual group had this bias (binomial test, $p = .5^{30}$); and 28 out of the 30 participants in the deontic group had this bias (binomial test, $p < .0001$). Individuals focus more on what is possible than on what is impossible.

Second, as the percentages above show, this bias to focus on what is possible was greater for

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Table 2. *The percentages of each of the four possibilities that the two groups in Experiment 1 constructed second—that is, typically after they had constructed* A and C

	The four possibilities that the participants constructed			
The four sorts of conditional	*A and C*	*A and not-C*	*not-A and C*	*not-A and not-C*
Tautological	12 13	67 50	7 24	14 13
Core	9 9	5 8	38 30	43 40
Enabling	9 15	66 39	2 3	23 39
Biconditional	12 15	5 2	2 1	78 49

Note: The left-hand column in the cells presents the percentages for the factual group, and the right-hand column presents the percentages for the deontic group. The balance of percentages in a row are impossible cases that the participants constructed second.

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factual conditionals than for deontic conditionals, and the difference between the two groups was reliable (Mann–Whitney test, $z = 5.417$, $p < .00001$). Hence, individuals are more concerned about what is impermissible according to deontic conditionals than about what is impossible according to factual conditionals.

Third, the participants had an overwhelming bias to construct first the case corresponding to the explicit mental model in which both the antecedent and the consequent of a conditional were true. This bias occurred for all four putative sorts of conditional in both the factual and deontic groups, and the percentages ranged from 72% to 90%, and in each case more participants showed this bias than would be expected by chance (binomial tests, $p < .0001$, for all cases).

Fourth, the effects of modulation were apparent in the cases that the participants constructed second. Table 2 presents these percentages. As it shows, the participants' second cases tended to be *not-A and not-C* as possible for the core and biconditional interpretations, but *A and not-C* as possible for the enabling and tautological interpretations. All 30 of the participants in the factual group had this bias (binomial test, $p = .5^{30}$), and 28 out of the 30 participants in the deontic group had this bias, 1 participant went against it, and 1 was a tie (binomial test, $p < .0001$). These results show that the conditionals did yield distinct interpretations that should affect reasoning.

EXPERIMENT 2

The interpretations corroborated in Experiment 1 should elicit different patterns of inference. For example, modus ponens follows from the core and biconditional interpretations, but not from the enabling interpretation, whereas denial of the antecedent has the opposite pattern of validity. Table 3 summarizes the valid conclusions for the different interpretations of conditionals. The first aim of the present experiment was to test whether the predicted patterns of inference did occur. The second aim was to test a prediction about time pressure. Previous studies have examined its effects on various sorts of reasoning. It led to an increased matching bias in Wason's selection task—that is, the selection of those cards in the one explicit mental model of the conditional (Roberts & Newton, 2001)—to more errors in syllogistic reasoning (Evans & Curtis-Holmes, 2005) and conditional reasoning (Schroyens, Schaeken, & Handley, 2003), and to less sensitivity to potential counterexamples in inferences from causal conditionals (Verschueren et al., 2005). If individuals have only a limited time to evaluate a conditional inference, they should focus on the mental models of the conditional (see the items in bold in Table 1). The consequence should be that they should tend to make the valid affirmative inferences, which depend only on mental models, but fail to make the valid negative inferences,

Table 3. *The patterns of valid inferences for five sorts of interpretation of a conditional of the grammatical form,* if A then C

	The four sorts of inference depending on the categorical premise			
The five sorts of interpretation of conditionals	*Modus ponens:* A	*Affirmation of the consequent:* C	*Modus tollens:* not-C	*Denial of the antecedent:* not-A
Tautological				
Core	$\therefore C$		$\therefore$ *not-A*	
Enabling		$\therefore A$		$\therefore$ *not-C*
Biconditional	$\therefore C$	$\therefore A$	$\therefore$ *not-A*	$\therefore$ *not-C*
Relevance	$\therefore C$			

which depend on possibilities that are not explicitly represented in the mental models of the conditionals.

Method

Design

The participants were randomly assigned to one of four groups, depending on whether they evaluated inferences from factual or from deontic conditionals, and on whether they had an unlimited or limited time to carry out each evaluation. Each participant carried out 64 inferences based on four instances of each of four sorts of conditional premise (tautological, core, enabling, and biconditional) in the four standard conditional inferences: modus ponens, affirmation of the consequent, modus tollens, and denial of the antecedent.

Materials and procedure

The participants were tested in small groups, using computers running the E-prime program. They were told to imagine that they were graduate students from the National Security Academy that teaches secret service agents and that they were taking part in a test of reasoning. They were instructed to read the conditional premises, which were presented on the first screen, to press the space bar in order to read the second premise (the categorical assertion) and the putative conclusion, and then to evaluate whether the conclusion was "correct", "incorrect", or "may or may not be correct", by pressing the appropriate colour-coded key.

In the limited time groups, the computer program curtailed the presentation of the problems. The time limit was equal to the mean latency to evaluate modus ponens in a pretest minus one standard deviation (2,368 ms for the factual group, and 2,626 ms for the deontic group). The participants in the unlimited time groups had no time limit in which to make their evaluations.

Participants

A total of 68 first-year psychology students (58 woman, 10 men) from ISPA in Lisbon participated in the experiment for course credit. They were randomly assigned to one of the four groups (factual unlimited time, $n = 18$; factual limited time, $n = 19$; deontic unlimited time, $n = 15$; deontic limited time, $n = 16$).

Results and discussion

Table 4 shows the percentages of inferences endorsed in the two groups evaluating factual inferences, and Table 5 shows the percentages for the two groups evaluating deontic inferences. Both tables show that the participants tended to endorse valid inferences for the particular interpretation of the conditionals and not to endorse the invalid inferences for these interpretations. This pattern was reliable in all four groups. The numbers of participants who made more predicted than unpredicted responses according to modulation were as follows:

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Table 4. *The percentages of inferences endorsed as valid for factual inferences in Experiment 2*

	The four sorts of inference							
The four sorts of conditional	*Modus ponens*		*Affirmation of the consequent*		*Modus tollens*		*Denial of the antecedent*	
Tautological		25 37		38 37		4 13		11 17
Core	**Valid**	99 86		38 61	**Valid**	75 30		35 33
Enabling		20 42	**Valid**	85 60		17 21	**Valid**	69 33
Biconditional	**Valid**	96 86	**Valid**	94 76	**Valid**	78 43	**Valid**	86 50

Note: The first percentage in each cell is for the unlimited time group, and the second percentage in each cell is for the limited time group.

Table 5. *The percentages of inferences endorsed as valid for deontic inferences in Experiment 2*

	The four sorts of inference							
The four sorts of conditional	*Modus ponens*		*Affirmation of the consequent*		*Modus tollens*		*Denial of the antecedent*	
Tautological		18 30		22 19		12 6		20 27
Core	**Valid**	90 84		18 25	**Valid**	85 63		12 31
Enabling		15 34	**Valid**	98 66		12 27	**Valid**	83 63
Biconditional	**Valid**	87 80	**Valid**	82 64	**Valid**	53 55	**Valid**	90 78

Note: The first percentage in each cell is for the unlimited time group, and the second percentage in each cell is from the limited time group.

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Unlimited time factual group: 17 out of 18 with one tie (binomial test, $p < .5^{17}$).
Unlimited time deontic group: 15 out of 15 (binomial test, $p = .5^{15}$).
Limited time factual group: 16 out of 19 with three ties (binomial test, $p < .5^{16}$).
Limited time deontic group: 15 out of 16 and 1 contrary to predictions (binomial test, $p < .001$).

The second salient result in the two tables is the effect of time pressure. The participants in the time pressure groups tended to endorse fewer valid inferences than those in the unlimited time groups (63% vs. 84%; Mann–Whitney, $z = 4.521$ $p < .0001$). Similarly, those in the time pressure groups tended to endorse more invalid inferences than those in the unlimited groups (29% vs. 20%; Mann–Whitney, $z = 2.429$, $p < .015$).

The third and most important effect, as the theory predicted, was the differential effect of time pressure on inferences. For the factual groups (see Table 4), the decline in correct affirmative inferences (modus ponens or affirmation of the consequent) from unlimited to limited time was only 18%, whereas the decline in correct negative inferences (modus tollens or denial of the antecedent) was 37%, and this interaction was reliable (Mann–Whitney test, $z = 2.78$, $p < .005$). In contrast, for the deontic groups (see Table 5), the theory predicts less of an effect because of the availability of prohibited cases, and the interaction was not significant (a 16% decline for affirmative inferences and only a 14% decline for negative inferences, Mann–Whitney test, $z = 0.11$, $p < .9$).

In sum, the results bore out the pattern of inferences predicted from the modulated interpretations of the conditionals in Experiment 1. One potential criticism of the experiment is that the enabling and tautological conditionals contained a modal auxiliary verb in their consequents, but the conclusions did not—for example:

If the dish is made of codfish then it can be codfish "Braz" style.

The dish is not made of codfish.
Therefore, it isn't codfish "Braz" style.

However, the fact that most participants evaluated the inference as correct corroborates the model theory, which postulates that individuals use the meaning of premises. However, it presents a difficulty to existing psychological theories based on formal rules of inference, which contain no rules to explain such inferences. Another potential criticism is that the participants evaluated conclusions given to them, and so they may not have reasoned at all, but merely guessed their responses or used their general knowledge to guide them. The problem with this explanation is that it fails to explain the main interaction that occurred in the experiment. Nevertheless, in order to obviate this criticism, our next experiment called for the participants to draw conclusions for themselves.

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EXPERIMENT 3

In order to strengthen the case that modulation affects reasoning, the participants in this experiment drew their own conclusions. In the previous experiment, they rightly tended not to accept any inferences from tautological conditionals, and so we replaced these conditionals with those that the theory predicts should have a relevance interpretation (see Table 1), and which accordingly should yield modus ponens inferences alone (see Table 3). We pretested the conditionals used in the present experiment in a task in which a separate sample of participants listed what was possible and what was impossible for each conditional (as in Experiment 1). In general, the conditionals elicited the predicted interpretations, with one exception: The conditional predicted to elicit an enabling interpretation did so on a minority of trials; otherwise, on 53% of trials, it elicited the biconditional interpretation.

Method

Design

Participants wrote down their own conclusions on 80 trials based on 20 different conditionals that occurred on separate trials with categorical premises for the four sorts of inference: modus ponens, affirmation of the consequent, modus tollens, and denial of the antecedent. The 20 conditionals consisted of four different instances of conditionals with five different interpretations according to the modulation hypothesis: a core interpretation, a biconditional interpretation, an enabling interpretation, and two sorts of relevance interpretation—one with an affirmative consequent and one with a negative consequent. The 80 trials were presented in a different random order to each participant.

Participants

A total of 28 students in the last year of high school (20 women, 8 men) from a public school in Lisbon participated in the experiment. Their mean age was 17.5 years ($SD = 0.638$).

Materials and procedure

The experiment was based on 20 conditionals consisting of four instances of each of the five sorts of predicted interpretation. Appendix B presents the full set of materials, and here are examples:

Core: *If the driver steps on the brake, then the car slows down.*
Biconditional: *If the key is the right one, then it opens the door.*
Enabling: *If the fishermen go out to the sea, then they catch swordfish.*
Relevance with affirmative consequent: *If Ricardo wants to go to Rossio, then there is a metro stop.*
Relevance with negative consequent: *If João goes traveling, then he doesn't go by aeroplane.*

As these examples illustrate, none of the conditionals contained modal auxiliaries.

The participants carried out the experiment in a single group in the classroom. Each of them received a booklet containing 82 pages: 1 for each inference plus 2 for instructions and examples. Their task was to write down a conclusion, if any, that followed correctly from each of the 80 sets of premises. If the participants thought that nothing followed from the premises, they wrote, "nothing follows".

Results and discussion

The participants' responses were classified into two main categories: categorical conclusions, and

Table 6. *The percentages of categorical conclusions that the participants drew in Experiment 3*

	The four sorts of inference			
The four sorts of conditional	*Modus ponens*	*Affirmation of the consequent*	*Modus tollens*	*Denial of the antecedent*
Core	**98**	30	**96**	32
Enabling	76	**96**	72	**96**
Biconditional	**96**	**96**	**89**	**93**
Relevance	**90**	19	12	3

Note: Predicted conclusions shown in bold.

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other responses, principally "nothing follows". Categorical conclusions, depending on the particular sort of conditional were either as predicted or contrary to prediction, and Table 6 presents the percentages of categorical conclusions of both sorts for the four conditional inferences based on the different sorts of predicted interpretation. There was no reliable difference in the responses to the two sorts of relevance interpretation, and so we have pooled the percentages for them.

Overall, the participants drew the predicted valid conclusions, depending on the interpretation of the conditionals, on 83% of the 40 relevant trials, and responded correctly "nothing follows" on 72% of the 40 relevant trials. All 28 participants made more predicted responses than unpredicted responses (Binomial test, $p = .5^{28}$). These results bore out the pattern of inferences predicted from the modulated interpretations of the conditionals. As Table 6 shows, the one major discrepancy in the results was that the conditionals predicted to have the enabling interpretation tended to elicit all four sorts of inference, as though they had instead the biconditional interpretation. The pretest of these conditionals had indeed elicited this interpretation on more than half the trials, probably because they did not contain a modal auxiliary expressing the mere possibility of their consequents.

EXPERIMENT 4

The previous experiments have shown that modulation can block possibilities, giving rise to different interpretations of conditionals that in turn affect the inferences that individuals tend to make. However, the model theory also predicts that modulation can add information to models (Johnson-Laird & Byrne, 2002, p. 651). For instance, appropriate contents should introduce a temporal relation between antecedent and consequent events—for example:

If Lisa received some money, then she paid Frederico.

Individuals know that payment can be made only if a payer has money, and so modulation should yield an interpretation of the conditional in which if Lisa received some money then she did so before she paid Frederico. The experiment aimed to test whether individuals made such temporal inferences, which have not hitherto been reported for conditionals. It used pairs of conditionals and questions about the temporal order of the events to which they referred—for example:

If Lisa received the money, then she paid Frederico.
If she paid Frederico, then he bought a new laptop.
Lisa received the money.
Did Lisa receive the money before Frederico bought a new laptop?

The experiment contrasted such *forwards* temporal inferences with those in which the conditionals conveyed a *backwards* temporal order in which the antecedent event occurred after the consequent event—for example:

If Tania gave Mauro a scooter, then he did well on the exams.
If he did well on the exams, then he studied a lot.
Tania gave Mauro a scooter.
Did Tania gave Mauro a scooter after he studied a lot?

In this case, the participants should infer that Mauro's studying occurred before his performance on the exams, which in turn preceded Tania's gift of the scooter. Such inferences show that modulation is not just an effect of the order of clauses in a conditional, but depends on knowledge about the temporal sequence of events in the world. This knowledge is embodied in mental models of the pairs of premises, and so reasoners can infer the temporal sequence implied by the two conditionals. Such a phenomenon would show that conditionals cannot be interpreted in a truth functional way.

In an initial study, we counterbalanced the grammatical format of the conditional sentences. On half the trials the conditionals were in the standard format illustrated in the examples above, and on half the trials the conditionals were presented with their main clauses first—for example: "Laura infected Renato, if she got the virus". As predicted, the counterbalancing had no reliable effect on performance: The predicted temporal inferences occurred on 85% of trials using the standard format and on 82% of trials using the format with the main clause first. However, one difficulty with this method of counterbalancing the order of mention is that some sentences in Portuguese become slightly artificial. Hence, we used a different method in the present experiment.

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Method

Design

The participants acted as their own controls and responded to temporally forwards and backwards problems, each based on a pair of conditionals. In the forwards problems, the antecedent of each conditional referred to the first event of the two, and the consequent referred to the second event of the two. In the backwards problems, the antecedent of each conditional referred to the second event of the two, and the consequent referred to the first event of the two. To prevent the participants from paying attention only to the antecedent of the first conditional and the consequent of the second conditional, half of both the forwards and backwards problems were presented in this "figure":

If A then B.
If B then C.
A.

and half of them were presented in this figure:

If B then C.
If A then B.
A.

Four sorts of question were paired with the premises on different trials

Did A happen before C?
Did A happen after C?
Did C happen before A?
Did C happen after A?

Every participant encountered four instances of each sort of question (two for the forwards problems and two for the backwards problems), and the questions were matched to the premises so that half of the predicted responses were "yes", and half of the predicted responses were "no". Each participant carried out an equal number of forwards and backwards problems in both orders of premises with the four sorts of question.

Participants

A total of 64 first-year psychology students (49 woman, 15 men) from ISPA in Lisbon participated in the experiment for course credit.

Materials

We devised 16 pairs of related conditionals in the grammatical form: *If A then B. If B then C.* Each pair referred to two individuals (one female and one male), and the meaning of their clauses and general knowledge implied a temporal order over three events referred to in the pairs of conditionals (see Appendix C for the full materials). For 8 of the pairs, the temporal order was forwards: *A*, *B*, and then *C*, and for 8 of the pairs the order was backwards: *C*, *B*, and then *A*.

Procedure

The participants were tested individually using a computer running the E-Prime program. When the participants were ready for a trial, they

pressed the space bar, which presented first the conditional premises, then the categorical premise, and finally the question. The participants answered the question by pressing one of two colour-coded keys (green–yes; red–no), and the program recorded their responses and their latencies.

Results and discussion

Table 7 shows the percentages of predicted responses to the forwards and backwards problems. The participants tended overwhelmingly to make the predicted responses: A total of 59 participants made more predicted than unpredicted responses with forwards problems, 3 participants had the opposite bias, and 2 were ties (binomial test, $p < .0001$); 60 participants made more predicted than unpredicted responses with backwards problems, 2 participants had the opposite bias, and 2 were ties (binomial test, $p < .0001$). There was no reliable difference in the overall percentages of predicted responses between forwards and backwards problems (Wilcoxon test, $z = 0.148$, $p < .9$, two-tailed). However, the participants made about 8% more predicted "no" responses then predicted "yes" responses, and the difference was reliable (Wilcoxon test, $z = 2.764$, $p < .005$, two-tailed). No obvious reason exists for this difference, though it may be an instance of "negative conclusion bias" (Evans, 1982). Table 8 shows the mean latencies for the predicted responses in milliseconds to the forwards and backwards problems. The participants were reliably faster with the forwards inferences (6690 ms) than with the backwards inferences (7847 ms; Wilcoxon test, $z = 3.297$, $p < .001$, two-tailed). This result bears out the slightly more natural interpretation in which the event referred to in the antecedent occurs before the event referred to in the consequent. The latencies of the predicted "yes" responses (7229 ms) and "no" responses (7367 ms) did not differ reliably (Wilcoxon test, $z = .508$, $p > .616$, two-tailed), but the participants had a marginal tendency to respond faster to problems in the figure: *If A then B, If B then C* (6827 ms) than in the figure: *If B then C, If A then B* (7614 ms; Wilcoxon test, $z = 1.806$; $p < .071$, two-tailed). Overall, the pattern of inferences shows that modulation leads to temporal interpretations, which in turn yield distinct and predictable patterns of inference.

Table 7. *The percentages of predicted responses for the temporally forwards and backwards problems in Experiment 4*

	Problems	
The four sorts of question	*Temporally forwards*	*Temporally backwards*
A before C	69 (yes)	84 (no)
A after C	81 (no)	77 (yes)
C before A	88 (no)	76 (yes)
C after A	80 (yes)	81 (no)

Note: Predicted responses shown in parentheses.

Table 8. *The mean latencies of the predicted responses for the temporally forwards and backwards problems in Experiment 4*

	Problems					
	Temporally forwards			*Temporally backwards*		
The four sorts of question	*M*	*SD*		*M*	*SD*	
A before C	7336	6038	(yes)	7560	6551	(no)
A after C	6254	3678	(no)	6383	3760	(yes)
C before A	5801	4273	(no)	8146	7223	(yes)
C after A	6934	5003	(yes)	9021	8591	(no)

Note: Predicted responses shown in parentheses.

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GENERAL DISCUSSION

Consider these two conditionals of the grammatical form, *if A then C*:

If the dish is kidney beans then its basis is beans.
If the dish is meat then it can be Portuguese stew.

At first sight, they seem similar, and few readers are likely to notice the subtle difference in their interpretations of them. Yet, the results of our experiments corroborated a theory in which the meanings of their constituent clauses, and general knowledge, modulate their interpretation (Johnson-Laird & Byrne, 2002). Individuals in Experiment 1 constructed different possibilities for these two sorts of conditional. For the first sort, they tended to construct the possibilities for a core interpretation of a conditional (see Table 1):

A C (e.g., the dish is kidney beans, and its basis is beans)
not-A C (e.g., the dish isn't kidney beans, and its basis is beans)
not-A not-C (e.g., the dish isn't kidney beans, and its basis isn't beans)

However, for the second sort of conditional, they tended to construct the possibilities for an enabling interpretation:

A C (e.g., the dish is meat, and it is Portuguese stew)
A not-C (e.g., the dish is meat, and it isn't Portuguese stew)
not-A not-C (e.g., the dish isn't meat, and it isn't Portuguese stew)

Hence, what is impossible for the core interpretation, *A and not-C*, is possible for the enabling interpretation, and what is impossible for the enabling interpretation, *not-A and C*, is possible for the core interpretation. Experiment 1 similarly corroborated analogous differences in the possibilities that individuals constructed for the tautological and biconditional interpretations (see Table 2). The experiment also bore out the model theory's general predictions, including the bias to construct what is possible rather than what is impossible, which was greater for factual than for deontic conditionals. Similarly, it showed that the participants tended to construct first the possibility corresponding to the one explicit mental model in which both clauses are true.

The four sorts of conditional established in the first experiment should yield different patterns of valid inferences (see Table 3). Experiment 2 corroborated these patterns in the conclusions that the participants accepted as correct (see Tables 4 and 5). For example, they tended to accept the following modus ponens inference based on a core interpretation:

If the dish is kidney beans then its basis is beans.
The dish is kidney beans.
Therefore, its basis is beans.

However, they tended to reject modus ponens for an enabling interpretation:

If the dish is made of meat then it can be Portuguese stew.
The dish is made of meat.
Therefore, it is Portuguese stew.

The conclusion in this case does not contain the modal auxiliary, "can", in the consequent of the conditional, but this factor is not crucial. The participants accepted the denial of the antecedent in which the same sort of discrepancy occurs:

If the dish is made of meat then it can be Portuguese stew.
The dish is not made of meat.
Therefore, it is not Portuguese stew.

However, they tended to reject this inference for a core interpretation:

If the dish is kidney beans then its basis is beans.
The dish is not kidney beans.
Therefore, its basis is not beans.

Similarly predictable effects occurred with the other two conditional inferences (modus tollens and denial of the antecedent, see Table 4).

The results of Experiment 2 corroborated analogous differences for inferences from the biconditional and tautological interpretations. A biconditional interpretation for, say, "if the animal is a chicken then the female is a hen", refers to two possibilities (*A and C*, and *not-A and not-C*), and so, as these possibilities predict, the participants tended to accept all four sorts of conditional inference (see Table 4). A tautological interpretation for a conditional, such as, "if the dessert is made of chocolate then it can be a pudding", refers to all four possibilities, and so, as these possibilities predict, the participants

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tended not to accept any of the four sorts of conditional inference (see Table 4). Experiment 2 also showed a remarkably similar pattern for the four sorts of conditionals with deontic contents, concerning matters of permissibility (see Table 5).

To envisage two or three possibilities takes time, and so what happens when individuals are short of time? According to the theory, by default they should tend to reject a putative conclusion. However, they should have time to accept valid affirmative inferences of modus ponens and affirmation of the consequent, which depend on possibilities represented in mental models, whereas they should be less inclined to accept valid negative inferences of modus tollens and denial of the antecedent, which depend on possibilities that are not represented in mental models. One way in which these inferences can be drawn is to flesh out mental models into fully explicit models of all the possibilities to which the conditionals refer (Johnson-Laird & Byrne, 1991). A caveat is that individuals tend to represent what is forbidden in the case of deontic assertions, and so the difference between affirmative and negative inferences should be less pronounced for deontic conditionals. Experiment 2 corroborated all these effects of time pressure. Experiment 3 added a further corroboration of the theory. The participants had to formulate conclusions for themselves rather than merely to evaluate given conclusions. The patterns of their inferences corresponded to the predicted interpretations for four sorts of conditional, including those with the relevance interpretation from which they tended to make only the modus ponens inference (see Table 6).

Modulation can add information to the models of conditionals, and Experiment 4 showed that individuals make predictable inferences about the temporal order of events referred to in pairs of conditionals. Given a conditional, such as:

If Carla printed the report, then the toner ran out.

modulation yields the interpretation that the printing occurred before, and indeed brought about, the event of the toner running out. However, given a conditional, such as:

If Jessica visited Lisbon, then Leonel invited her.

modulation yields the interpretation that Jessica's visit occurred after, and indeed was occasioned by, Leonel's invitation. The problems had pairs of such conditionals with an event in common, and the results showed that the participants inferred the predicted forwards or backwards temporal sequences of three events from them.

At first glance, an alternative explanation of the phenomena might be that the participants based their conclusions on the believability of conclusions. This account, however, fails to explain the results of our experiments. Consider these conclusions from our earlier illustrative examples:

Its basis is beans.
It is Portuguese stew.

Nothing in these two assertions signals how they should be evaluated: They seem equally likely, equally believable, equally acceptable. Yet, the participants tended to accept the modus ponens inference yielding the first conclusion, but to reject it for the second conclusion. In general, the predicted effects of modulation on the inferences in Experiments 2 seem inexplicable on the basis of any properties of the conclusions alone. The participants were instead considering whether or not the conclusions followed from the premises. The same argument applies a fortiori to Experiment 3, because in this study the participants drew their own conclusions. Likewise, the use of two conditional premises in Experiment 4 insulated responses from beliefs. For example, they not provide the answer to questions, such as:

Did Rodrigo send the email after he hired another secretary?

The model theory predicts that meaning, reference, and knowledge can all modulate the interpretation of conditionals. We have modelled the process computationally using fully explicit models to represent knowledge in long-term memory (see Johnson-Laird & Byrne, 2002, p. 659). In our earlier description of alternatives to the model theory, we outlined theories based on formal rules of inference (e.g., Rips, 1994), on necessary and sufficient conditions (e.g., Thompson, 2000), on suppositions (e.g., Evans

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& Over, 2004), and on probabilities (e.g., Oaksford & Chater, 2001). They are all consistent with the effects of modulation. However, they have little to say about how individuals carry out the task of constructing cases of what is possible or impossible according to assertions. Indeed, theories often take as given the underlying logical forms of assertions and then apply formal rules of inference to them (e.g., Rips, 1994). Granted the recovery of logical form, formal rules could probably account for the most of the inferences in our experiments, though they may fail to explain those in which a modal auxiliary in the consequent of a conditional yields a categorical conclusion—for example, the denial of the antecedent with an enabling interpretation. Likewise, it is unclear how to specify the logical form of the conditionals in Experiment 4, or the temporal logic required for the inferences from them.

The key issue for many theories is the recovery of logical form. Unlike logic, the syntax of sentences in natural language cannot yield their logical form. It can be determined only from their meanings in context, which depend in part on modulation, and even perhaps from the particulars of the reasoning task (Stenning & Van Lambalgen, 2008). These latter authors argue rightly that the recovery of logical form is itself dependent on reasoning. No algorithm exists for carrying out the process, and no decisive evidence exists that human reasoning depends on logical form. It could be superfluous. The meaning of a conditional refers to a set of possibilities, amongst which temporal and other relations may hold. Once the system has constructed models of these possibilities, the models themselves can be used for reasoning (see, e.g., Goodwin & Johnson-Laird, 2008). An analogous argument can be made about those theories that postulate probabilistic interpretations of conditionals (e.g., Pfeifer & Kleiter, 2005): To assess the conditional probability of the consequent of a conditional given its antecedent, the first step must be to represent the possibilities to which they refer. However, as yet, the circumstances are unknown in which these possibilities must be supplemented with probabilities in order to understand a conditional. Perhaps Aristotle (*Rhetoric*, Book I, 1357a27, Barnes, 1984) had the right answer: only when probabilities are explicitly referred to in the conditional or its context.

Necessary and sufficient conditions can account for four interpretations of conditionals: A is sufficient for C yields the core interpretation, A is necessary for C yields the enabling interpretation, A is both necessary and sufficient for C yields the biconditional interpretation, and A is neither necessary nor sufficient for C yields the tautological interpretation (see Table 1). But other interpretations are feasible, such as the relevance interpretation of our earlier example, "if they played a game then it wasn't soccer". Necessary and sufficient conditions likewise provide no account of the temporal, spatial, and other relations, to which certain conditionals refer.

Evidence that the representation of possibilities preserves temporal order comes from priming studies (e.g. Santamaría & Espino, 2002, and see also Byrne, 2005, p. 163). Similarly, individuals can reason from temporal premises, such as, "John takes a shower before he drinks coffee" (Schaeken et al., 1996). However, in Experiment 4, no temporal relations were stated explicitly: They resulted from modulation, and the participants inferred the predicted temporal relations both for forwards conditionals in which the antecedent events occur before the consequent events and for backwards conditionals in which the antecedent events occur after the consequent events.

Temporal interpretations are a decisive objection to the view that conditionals can be interpreted in a truth functional way, sensitive only to the truth or falsity of the antecedent and consequent clauses. Both clauses could be true, and yet the conditional would be false if the two events occurred in the wrong temporal order. The model theory is therefore not truth functional—despite claims to the contrary—because the theory postulates, first, that the machinery of understanding normally depends on a representation of possibilities rather than of truth values and, second, that modulation can introduce temporal and other sorts of relation.

In conclusion, our results bear out the view that the complexity of conditionals is a result of the interaction among several simple components. One component yields the core and tautological interpretations, and other components use meaning, reference, and knowledge to modulate this interpretation. One effect of modulation, as we have shown, is to block the construction of possibilities and thereby to yield a variety of interpretations both for factual and for deontic conditionals. This modulation in turn has predictable consequences for the inferences that individuals draw from conditionals. The inferences that they deem to be valid depend on the possibilities to which the premises refer. As these possibilities change from one sort of conditional to another so, too, does the pattern of inferences that logically untrained individuals make. Another effect of modulation is to add information, such as a temporal relation, to the models of the antecedent and consequent events. No theory of conditionals that fails to account for these phenomena can be complete.

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APPENDIX A

The materials for Experiment 1 and 2 (from the Portuguese)

FACTUAL SENTENCES

Core interpretation

If the dish is kidney beans then its basis is beans.
If the dish is lasagne then its basis is pasta.
If the dish is cabbage soup then its basis is cabbage.
If the dish is sweet yellow pastry then it is made of yolk.

Biconditional interpretation

If the animal is a chicken then the female is a hen.
If the animal is a lion then the female is a lioness.
If the animal is a dog then the female is a bitch.
If the animal is a duck then the female is a female duck.

Enabling interpretation

If the dish is made of meat then it can be Portuguese stew.
If the dish is made of codfish then it can be codfish "Braz" style.
If the dish is made of spinach then it can be spinach stew.
If the cake is made of eggs then it can be "suspiro".

Tautological interpretation

If the dessert is made of chocolate then it can be a pudding.
If the dessert is made of walnuts then it can be a cake.
If the dessert is made of apple then it can be a pie.
If the dessert is made of carrot then it can be a tart.

DEONTIC SENTENCES

Core interpretation

If a person gets his or her driving licence then he or she must be at least 18 years old.
If a person gets married then he or she must be at least 18 years old.
If a person is a candidate for parliament then he or she must be at least 18 years old.
If a person applies to be a member of the police then he or she must be at least 18 years old.

Biconditional interpretation

If a plumber repairs the pipes then he must be paid.
If a watch-maker repairs the watch then he must be paid.
If a painter paints the house then he must be paid.
If a private physician examines the patient then he must be paid.

Enabling interpretation

If a person is at least 18 years old then he or she can join the Air Force.
If a person is at least 18 years old then he or she can get a licence to fly an aircraft.
If a person is at least 18 years old then he or she can get a licence to carry a weapon.
If a person is at least 18 years old then he or she can join the Navy.

Tautological interpretation

If a person is 48 years old then he or she can get a truck-driving licence.
If a person is 39 years old then he or she can work.
If a person is 53 years old then he or she can build a company.
If a person is 44 years old then he or she can get a motorcycle licence.

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APPENDIX B

The materials for Experiment 3 (from the Portuguese)

Core interpretation

The mechanic says that:
If the driver steps on the brake, then the car slows down.
One person says that:
If Teresa breaks an arm, then she has pain.
The doctor says that:
If the patient has malaria, then he has fever.
The cook says that:
If the sweet is egg-soft, then it is made out of yolks.

Biconditional interpretation

The electrician says that:
If the switch is on, then the light is on.
The doorman says that:
If the key is the right one, then it opens the door.
The cook's assistant says that:
If João switches on the oven, then the oven heats up.
The animal's keeper says that:
If that animal is a lion, then its female is a lioness.

Enabling interpretation

A supporter says that:
If Sporting reaches the final, then they win the Championship.
The fishmonger says that:
If the fishermen go out to the sea, then they catch swordfish.
The patroness says that:
If there is flour in the house, then the female cook makes bread.
An agent of a musician says to his client:
If you have your telephone on, then it is going to ring.

Relevance interpretation with affirmative consequent

A friend says that:
If Ricardo wants to go to Rossio, then there is there a metro stop.
A person says that:
If Tiago wants to visit Jerónimos, then the Monastery is in Belém.
Marta says that:
If Eva wants to watch the series "Morangos com Açucar", then it is on TVI.
A colleague says that:
If Paulo wants to swim, then the Jamor Complex has a swimming pool.

Relevance interpretation with negative consequent

The Grandmother says that:
If Maria goes to the restaurant, then she doesn't go to an Indian restaurant.
The Father says that:
If João goes travelling, then he doesn't go by aeroplane.
A friend says that:
If Ana drinks a juice, than she doesn't drink an orange juice.
A colleague says that:
If Manuel plays a game, then he doesn't play football.

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APPENDIX C

The materials for Experiment 4 (from the Portuguese)

The forwards problems

1. If Laura got the virus, then she infected Renato.
   If she infected Renato, then he went to the hospital.
   Laura got the virus.
2. If Ana received the job, then Paulo congratulated her.
   If Paulo congratulated her, then she bought him a gift.
   Ana received the job.
3. If Lisa received the money, then she paid Frederico.
   If she paid Frederico, then he bought a new laptop.
   Lisa received the money.
4. If Luisa bought the tickets, then she called Daniel.
   If she called Daniel, then he took care of the kids.
   Luisa bought the tickets.
5. If Inês went to the conference, then she heard David's talk.
   If she heard David's talk, then she got inspired.
   Inês went to the conference.
6. If Sandra kissed Edgar, then he got embarrassed.
   If Edgar got embarrassed, then he blushed.
   Sandra kissed Edgar.
7. If Carla printed the report, then the toner ran out.
   If the toner ran out, then Carla asked Cristiano to change it.
   Carla printed the report.
8. If Rodrigo read the email, then he fired Catarina.
   If he fired Catarina, then he hired another secretary.
   Rodrigo read the email.

The backwards problems

9. If Tânia gave Mauro a scooter, then he did well on the exams.
   If he did well on the exams, then he studied a lot.
   Tânia gave Mauro a scooter.
10. If Filipa uploaded the photo, then Oscar emailed it to her.
    If Oscar emailed the photo to her, then he sat down at the computer.
    Filipa uploaded the photo.
11. If Cristina wrote the article, then Marco asked her to write it.
    If Marco asked her to write it, then he met her at the meeting.
    Cristina wrote the article.
12. If Rosa read the book, then Sandro recommended it.
    If Sandro recommended it, then he saw it at FNAC.
    Rosa read the book.
13. If Rute cooked the lasagna, then Tiago gave her the recipe.
    If Tiago gave her the recipe, then he found it in a magazine.
    Rute cooked the lasagna.
14. If Jessica visited Lisbon, then Leonel invited her.
    If Leonel invited her, then he knew her in Porto.
    Jessica visited Lisbon.
15. If Clotilde bought the toy, then Rui asked for it.
    If Rui asked for the toy, then he saw it on TV.
    Clotilde bought the toy.
16. If Joana left, then Ricardo called a cab for her.
    If Ricardo called a cab for her, then he turned his cell phone on.
    Joana left.

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