The Development of Conditional Reasoning: A Mental Model Account

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Conditional (if-then) reasoning is one of the key components of logical reasoning. Studies examining the way that children and adults make conditional inferences have shown that while there are some clear developmental patterns, there is also a great deal of variation in performance due to factors such as problem content. Such variation is difficult to model without an explicit process model. In the following we propose a variant of mental model theory (Johnson-Laird, 1983) that can explain much of the empirical data. This model suggests that the development of conditional reasoning can be explained, at least partly, by such factors as the capacity of working memory, the range of knowledge available to a reasoner and his/her ability to access this knowledge on-line. © 2001 Elsevier Science (USA)

Deductive reasoning involves making inferences on the basis of some given premises. Making logical inferences is one of the key components of advanced thinking in humans. In fact, it could be argued that the ability to make inferences whose truth value depends entirely on the supposed truth of given, and possibly arbitrary, premises is one of the clearest examples of a cognitive capacity that differentiates human from nonhuman species. The distinctiveness of the processes involved in logical reasoning is sufficiently striking to have prompted some researchers to suppose that inference rules may have been biologically built into the human cognitive architecture (Braine, 1978; Cohen, 1981; MacNamara, 1986). However, while human
reasoners often show the ability to make logical deductions in the classic sense, studies on reasoning also clearly show that inferential performance can also be highly variable and subject to a variety of influences. One of the major challenges of any theory of reasoning is to account for both the capacity to make inferences that are logically valid and at the same time to explain variation in reasoning performance due to both developmental and situational variables. While many forms of reasoning exist, one in particular, conditional reasoning, has been studied enough both in adults and developmentally to provide a set of empirical results substantial enough to provide a serious test for any theory of reasoning.

Conditional reasoning is a critical component of logical thinking and has been the subject of many empirical and theoretical studies. Conditional reasoning in its most basic sense involves making inferences with a given major premise of the form “p implies q” and one of four possible minor premises. Modus ponens (MP) is the logical principle that involves reasoning with the premises “p implies q, p is true” and leads to the logically correct conclusion “q is true.” Modus tollens (MT) involves reasoning with the premises “p implies q, q is false” and leads to the logically correct conclusion “p is false.” These two are valid logical forms, since they both lead to a single, logically correct conclusion. Affirmation of the consequent (AC) involves reasoning with the premises “p implies q, q is true.” Denial of the antecedent (DA) involves reasoning with the premises “p implies q, p is false.” In both cases the implied conclusions, “p is true” for AC and “q is false” for DA are not logically correct. Neither of these forms leads to a single, logically correct conclusion and the correct response would be to deny the implied (biconditional) conclusion in both cases.

Piaget (Inhelder & Piaget, 1958) considered conditional reasoning to be a manifestation of formal thinking and thus to require a level of cognitive competence that should be inaccessible to younger children. Many developmental studies of conditional reasoning have as a consequence of the Piagetian position attempted to examine the question of whether young children can reason “logically” with “if-then” premises. Results of these studies have been mixed, with some indicating clear developmental patterns that appear to be consistent with a Piagetian hypothesis (Byrnes & Overton, 1986; Markovits & Vachon, 1989, 1990; O’Brien & Overton, 1980, 1982; Overton, Ward, Black, Noveck, & O’Brien, 1987; Ward & Overton, 1990; Wildman & Fletcher, 1977), but with others appearing to show the existence of quite precocious reasoning abilities (Dias & Harris, 1988, 1990; Hawkins, Pea, Glick, & Scribner, 1984; Kuhn, 1977; Rumain, Connell, & Braine, 1983). At the same time, studies with adult reasoners have shown that even fairly straightforward inferential reasoning is subject to a variety of content and context-based factors that systematically affect the kinds of inferences that adults make to “if-then” premises (Cheng & Holyoak, 1985; Cummins, Lubart, Alksnis, & Rist, 1991; Cummins, 1995; Fillenbaum, 1975; Johnson-
Now-classic Piagetian theory cannot successfully account for many of these results. Of course, it could be reasonably argued that Piaget’s theory is not a psychological one, but an epistemological one in that it attempts to model theoretical competence and is not designed to analyze variation of the kind that has been so often found in reasoning performance. Nonetheless, it is clear that understanding how people make conditional inferences in a way that captures the large amount of variability that has been observed requires an explicit process model. In the following, we propose such a process model adapted from mental model theory.

One theory that has had a great deal of success in accounting for variability in adult reasoning is mental model theory as put forward by Johnson-Laird and his collaborators (Girotto, Mazzocco, & Tasso, 1997; Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991; Johnson-Laird, Byrne, & Schaecken, 1992; Johnson-Laird, Byrne, & Tabossi, 1989). According to this theory, reasoners who are asked to produce deductive inferences on the basis of a given “if-then” premise will start by constructing an initial representation of the major premise that resembles the following:

\[ \begin{array}{c}
\text{p} \\
\text{...} \\
\text{q}
\end{array} \]

The first line refers to a state of affairs in which the antecedent \( p \) and the consequent \( q \) are true. Reasoners will draw inferences on the basis of this initial model when possible, otherwise they will “flesh out” their representation. The other possibilities, in which the antecedent is false, would not be represented explicitly but implicitly (the three dots in the diagram). According to the theory, this implicit model includes a mental footnote indicating that the other possibilities refer to state of affairs in which the antecedent \( p \) is false (Johnson-Laird et al., 1999). Mental footnotes are usually soon forgotten, but if they are retained, the reasoner can flesh out the implicit model to make explicit the other possibilities, resulting in either a biconditional or a conditional interpretation of the “if-then” relation. With a biconditional interpretation, the following models will be produced, where \( \neg \) is used to symbolize the negation of a state:

\[ \begin{array}{c}
\text{p} \\
\neg p
\end{array} \quad \begin{array}{c}
\text{q} \\
\neg q
\end{array} \]

With a conditional interpretation, reasoners will produce the following models:
Inferences are made by examining all relevant models that are constructed by the reasoner, with the proviso that a conclusion will be accepted if it is instantiated in at least one model and not contradicted by at least one model. If there is no relevant model available then no conclusion will be drawn. Now, in its present form, one major factor in explaining variation in conditional reasoning has been the number of models that the reasoner must manipulate. It is assumed that constraints on working memory make it costly to work with more models, and so reasoners will tend to make inferences using a minimum number of models when this is possible.

The current formulation of mental model theory relies explicitly on a truth-table-like analysis of reasoning. In fact, the models used to fully represent premises correspond to all the combinations of the basic components of the major premise that are given the value "true" in the truth-table that characterizes this premise. In addition, the representations and procedures used in the theory correspond to what might well be considered to be quite high levels of symbolic processing, for example, the procedure hypothesized for generating complete sets of alternative models and the symbolic term used to indicate negation. Implicit to the theory is the hypothesis that all reasoners have access to the same basic procedures and symbolic representations irrespective of their level of expertise and that imperfect reasoning is due to basically peripheral factors such as limitations in working memory capacity. While this might be true for at least some educated adult reasoners (and much of the research on mental models has examined such reasoners), such a hypothesis implies claims that are not always consistent with available evidence on how children reason and in at least some cases appear inconsistent with data on adult reasoners. If one assumes, as we do, that there must be some level of developmental continuity in the cognitive procedures underlying reasoning, then the question of how a mental model theory can explain children's reasoning becomes critical, not only in understanding children's reasoning but also by providing baselines for procedures that can be reasonably supposed to exist in adults.

**A DEVELOPMENTAL REFORMULATION OF MENTAL MODEL THEORY**

Our starting point for proposing a mental model theory that can account for developmental patterns of conditional reasoning is the idea that while advanced reasoners may develop strategies specific to logical reasoning, most children and not-so-advanced reasoners will use processes that are general and rely on existing cognitive architectures (see also Polk and Newell, 1995, for a similar idea). The second key point is the idea that children (and
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(Adults) have an understanding of ‘‘if-then’’ propositions that is inherently relational and that brings to bear a fairly rich linguistic and pragmatic experience (Scholnick, 1990). We propose that this experience leads to the construction of a semantic structure for ‘‘if-then’’ statements that provides preferential links to specific types of information (Markovits, 2000).

Specifically, the form of the ‘‘If p then q’’ relation defines a semantic space which is determined by the reasoner’s understanding both of the nature of the terms used in the conditional and the relationship between them. First, this implies an understanding of the directionality of the conditional (see Evans, 1993; Barrouillet, Grosset, & Lecas, 2000). This directionality in turn implies that the p term is generally understood as one possible object/event among many, while the q term produces a dichotomization of potential objects/events into q and not-q. For example, a reasoner who is given a premise such as ‘‘If it rains, then the street will be wet’’ will consider ‘‘it rains’’ as one event among many possible ones (‘‘the sun shines,’’ ‘‘it is cloudy,’’ ‘‘a cleaner has passed,’’ etc.). However, the consequent term allows for two basic possibilities, ‘‘the street is wet’’ or ‘‘the street is not wet.’’ This basic decomposition of possible objects/events that are associated with the original premise is carried out further by the activation of three classes of objects or events. The first concerns cases in which the objects or events concerned are complementary to those specified in the original conditional is, i.e., cases where objects or events that are different from p are related to not-q (we will refer to this as the ‘‘complementary’’ class). In the example we are using, this class would be composed of related events such as ‘‘If it is sunny, then the street will not be wet’’ or ‘‘If it is only cloudy, then the street will not be wet.’’ The second class concerns possible objects/events that share the same relation to q as p does, that is, cases of not-p implies q (we will refer to this as the ‘‘alternatives’’ class). For example, ‘‘If the street cleaner passes, then the street will be wet’’ is one such example. Finally, the third class concerns what Cummins (1995) has called ‘‘disabling conditions,’’ that is, conditions which allow the relationship between p and q to be violated (we will refer to this as the ‘‘disabling’’ class). For example, ‘‘If it rains, but the street is covered, then the street will not be wet’’ is one such example.

Finally, in line with a recent proposal by Halford, Bain, Maybery, and Andrews (1998), we assume that understanding of conditional relationships involve processing possible relations within the three basic classes in an integrated relational schema.

Our model then is based on the following basic suppositions.

1. Information Is Automatically Activated in Memory

We assume that if a child or young adolescent (and in many cases an adult) is given a simple ‘‘if-then’’ statement, then they will start by constructing a simple representation of the major premise that is assumed to contain a
representation of the relation between antecedent and consequent. Active consideration of this premise will result in concurrent activation of the associated knowledge structure. Thus, as soon as a minor premise is added to the major premise and an inference required, the three classes mentioned above will be automatically activated, with the minor premise being used as a supplementary retrieval cue. The strength with which any given elements within any one of these classes will be activated depends on several factors, including available knowledge and the efficiency of a given person's retrieval processes. In line with many models of memory access (Anderson, 1993; Anderson & Lebiere, 1998; Cantor & Engle, 1993; Cowan, 2001), we then assume that only elements that are activated sufficiently strongly enter working memory and will be available for further processing. More specifically, we assume that elements that are most strongly activated will be retrieved from memory and incorporated into the reasoner’s representation of the problem space, unless the reasoner is capable of inhibiting retrieval. The resulting set of models will then be used to make an inference.

Note that in these cases the elements retrieved from memory would not be isolated tokens (like \(-p\) or \(-q\) in the standard theory) but chunks of information (Anderson, 1993) or co-occurrences of elements (Logan et al., 1996). This means that the retrieval process searches for elements or events linked in a definite way. For example, the premises ‘If he is a postman, then he has a blue cap’ and ‘He is not a postman’ would probably direct the retrieval process toward knowledge about hats of professional uniforms rather than toward different kinds of people, on the one hand, and different kinds of hats, on the other hand. This is because we assume that mental models for conditionals represent not only specific elements, but also how they are related.

2. Tokens Refer to Specific Events or Classes of Events, Models Are Relational

The model of activation of information has some direct consequences concerning the nature of the tokens used to construct children’s models. Specifically, if there is one element in a given class that is more strongly activated than any others, then the model will refer directly to this element. If, however, more than one such element is strongly activated, then the resulting token will contain a reference to classes of objects or events. In any case, we assume that these tokens would be organized within a representational structure, a relational schema.

We specifically assume that mental models for conditionals are akin to the relational schemas described by Halford et al. (1998). According to these authors, relational schemas are cognitive representations that include elements and relations between elements and represent the structure of a situation in the environment. Relational schemas have some basic properties which differ from mental models in the standard theory. The first property
is symbolization, which means that there must be a symbol for the specific relation between antecedent and consequent. The second property is binding, which means that the relation-symbol and arguments must be bound in a structure so that each argument is in the correct slot. Thus, arguments that have the same role in the relation must be aligned consistently. According to the authors, this makes explicit representation of roles unnecessary. We assume that binding makes also specific representation of negation unnecessary, although in some cases a class of elements may be described as different from the antecedent or consequent terms.

Halford’s relational schemas are thus similar to the representational structure described by Barrouillet and Lecas (1998), who assumed that an ‘‘if p then q’’ statement would establish a directional relation between a variable $P^1$ (the value of which is specified by the proposition $p$) and a variable $Q$ (the value of which is specified by the proposition $q$). A statement of the type ‘‘If the ball rolls to the left, then the green lamp is lit’’ informs the subject that the color of the lamp which lights up (variable $Q$) depends on the path taken by the ball (variable $P$) and specifies the value assumed by $Q$ (i.e., green) for one of the value of $P$ (i.e., left). The binding property assumes that the possible different values of $P$, on the one hand, and the values of $Q$, on the other hand, are aligned so that (a) it can be read out from the representation that it is the direction taken by the ball which determines the color of the lamp which lights up and not the reverse and (b) different values within a variable are alternatives, rendering explicit tags for negation unnecessary.

A last property of relational schemas which is of concern for conditional mental models is omnidirectional access, which means that, given all but one of the components of a relational instance, we can retrieve the remaining component. This property could account for backward inferences from consequent to antecedent (i.e., AC and MT).

3. Limitations on Reasoning Are Due Both to Number of Models and On-Line Memory Access

In line with the original theory, we suppose that the greater the number of models that a reasoner must manipulate, the greater the chances of error in correctly reading off possible conclusions. This is because mental models are assumed to be held in working memory with limited capacity. In addition, our analysis assumes that the activation and retrieval process used for fleshing out is done on-line during reasoning and has a cognitive cost. As suggested by many authors (Anderson, 1993; Cowan, 2001; Logan, 1988), retrieval from LTM would be triggered by the elements actually present in the focus of attention which activate the chunks of knowledge these elements could take.
are linked with. However, the total amount of attention available would be limited and would differ from one subject to another and across developmental levels (Cowan, 1997, 2001). Moreover, the rate of activation a given chunk of knowledge receives would be all the lower the higher the number of chunks to be activated. As a consequence, retrieval is a limited process which depends both on the rate of available attentional capacities and on the number of chunks of knowledge to be retrieved.

In our model, the elements which trigger retrieval would be the antecedent and consequent values, the information conveyed by the minor premise, but also the kind of relation between antecedent and consequent. We also suppose, in line with a proposal by Sperber and Wilson (1986), that the retrieval process should ensure the retrieval of knowledge from LTM in a way that maximizes the relevance of the conditional statement, i.e., which allows subjects to formulate new hypotheses. Sperber, Cara, and Girotto (1995) have shown that subjects tend to reach the maximum relevance at the lowest possible cognitive cost. As a consequence, we assume that all other things being equal, the first kind of knowledge to be retrieved would be of the form [not p—not q] (referred to earlier as complementary) because it conveys the most additional information (i.e., maximizes relevance). Indeed, retrieval of [not p—not q] instances ensures a representation of the conditional which links different outcomes (i.e., q and not q) to different values of the variable P, leading to a representation referred as ‘‘complete’’ by Barrouillet and Lecas (1998). The second level of activated knowledge would be either of the form [not p—q] (alternatives) or of [p—not q] (disabling) both of which simply modify the existing relation introduced between p and q by the conditional statement. In summary, the complementary, alternative, and disabling hypothesis to be added to the first p—q model should differ in their probability of retrieval, with the complementary class being most easily retrieved.

A final factor that must be considered is the need for inhibiting information in some cases. Retrieval from memory could activate knowledge irrelevant for the logical task in hand. If this knowledge is not inhibited, it will be incorporated into the set of models used for reasoning. This suggests that inhibition may be in some respects as important as activation for reasoning. In fact, some theoretical models which conceive working memory as the activated part of LTM suggest that inhibitory processes are central for cognition (Conway & Engle, 1994) and that they are resource demanding (Engle, Conway, Tuholski, & Shisler, 1995). Indeed, Bjorklund and Harnishfeger (1990) have suggested that these inhibitory processes become increasingly efficient with age.

4. Some Specific Developmental Assumptions

The model that we have presented up to this point assumes that the basic processes used in conditional reasoning are similar irrespective of developmental considerations. In order to account for conditional reasoning per-
formance in children and young adolescents, we must make some specific assumptions about possible limitations in processing capacity that are age-related. Halford (Andrews & Halford, 1998; Halford, Wilson, & Phillips, 1998) has presented evidence that younger children appear to be limited to processing two simultaneous relational schemata. We have assumed that the models that are used for reasoning resemble such schemata and it seems reasonable to suppose that younger children will at the least have difficulty in manipulating more than two models in the context of a given inference. In fact, a recent analysis of 6- and 7-year-old children’s justifications of conditional inferences has been found to be consistent with use of only two models (Markovits, 2000). However, by 8 or 9 years of age, children appear to be able to store three models simultaneously in working memory, although with some difficulty. A second assumption is that young children’s memory retrieval processes are less efficient than older children and adolescents (Kail, 1992). Retrieval should be more costly for younger children and thus access to available information will be less likely. We also assume that young children simply have less knowledge than older ones and that this will also restrict possible access to relevant information.

We also make one further assumption concerning the ability of reasoners to disregard information that may be activated in memory but is inappropriate to the logical task. This specifically concerns the ability to disregard (inhibit) information about disabling conditions or alternative premises that are empirically true in the case of counterfactuals in response to standard instructions to suppose that the major premise is true. We specifically assume that the ability to inhibit retrieval of disabling information is relatively difficult (Vadeboncoeur & Markovits, 1999) and, in line with Bjorklund and Harnishfeger (1990), becomes increasingly efficient with age.

We can use these assumptions to present a model of conditional reasoning with familiar or neutral premises within a familiar or unspecified context. We attempt to show how this model can account for many observed phenomena. Following this, we discuss how this basic model can be extended to include abstract reasoning.

**A MODEL OF REASONING WITH FAMILIAR PREMISES**

We start by describing the reasoning of children when making an inference on the basis of some given “If p then q” premise which is meaningful to the child. Minimally, this implies that the consequent term and the relation between antecedent and consequent must be familiar. We first suppose that when receiving the major premise, the child will construct a relational representation of this premise:

\[ p \quad \rightarrow \quad q \]

where the symbol (\(\rightarrow\)) indicates the form of the relation between p and q.
Conditional Reasoning with Familiar Premises in Very Young Children (5 to 7 Years Old)

We assume that children between 5 and 7 years of age will find processing of more than two models very difficult. This implies that the child will generally be able to represent the major premise and only one other class of information. The impact of this limit will differ depending on how much information is strongly activated by a given “if-then” premise. There are two kinds of cases that must be considered in this context, premises which do not activate much associated information and premises which do activate such information.

Case 1: Reasoning with premises for which there is little knowledge easily activated. Given the relatively small knowledge base and the relatively weak retrieval processes of young children, many kinds of conditional premises will produce low levels of activation of associated information. In these cases, we can suppose that very young children will have almost no disabling cases readily available, nor will there be many alternatives readily available. Thus, the most readily accessible cases will be those in the complementary class, i.e., possible cases of [not-p and not-q]. When given the MP inference, they will receive “p is true” as the minor premise, which will then be used as a retrieval cue. Since neither this cue nor the major premise will activate any other information at a level strong enough to ensure retrieval, the initial model will remain as is and the conclusion “q is true” will follow directly. When given the AC inference, they will receive “q is true” as minor premise, which will tend to leave only the original model and will lead to the conclusion “p is true.” For the two inferences which involve negation, MT (“q is false”) and DA (“p is false”), the minor premise will strongly activate the complementary class. Assuming that at least one element of the form [a --- not-q] is strongly activated (where a is an object/event that is different from p), then the reasoner will produce the following models:

\[
\begin{align*}
p & \rightarrow q \\
a & \rightarrow \neg q
\end{align*}
\]

Using these models, the child will infer that if “p is false” then “q is false” and if “q is false” then “p is false.” Thus for these kinds of premises, young children will give responses that formally correspond to the logical biconditional. Note that for the negative forms two models will be used, while for the positive forms only one is produced.

Case 2: Reasoning with premises for which alternatives can be easily activated. For some limited kinds of premises (e.g., “If an animal is a dog, then it has legs”), young children appear to be able to easily activate possible alternatives (Bucci, 1978; Markovits et al., 1996, 1998). In this case, they will have both the complementary [not-p and not-q] and alternatives [not-p and q] classes accessible. For MP, the minor premise indicates neither of
these classes, and the original model will be used, leading to the inference ‘q is true.’’ Possible variation will occur with the AC and DA forms, which we analyze in detail.

For AC, the minor premise ‘‘q is true’’ will tend to activate the alternatives class. Once again, supposing that there is a single element (b --- q, where b is different from p) that is sufficiently strongly activated, this will be incorporated into the resulting set of models as follows:

\[
\begin{align*}
p & \quad \rightarrow \quad q \\
b & \quad \rightarrow \quad q
\end{align*}
\]

This will lead to an uncertain conclusion, since either p or b may be true in this case.

The situation for the two negative forms is somewhat more complex. For MT, the minor premise is ‘‘q is false.’’ This will tend to strongly activate the complementary class and will produce the following set of models:

\[
\begin{align*}
p & \quad \rightarrow \quad q \\
a & \quad \rightarrow \quad \neg q
\end{align*}
\]

In this case, the conclusion that ‘‘p is false’’ follows directly.

For DA, the minor premise is ‘‘p is false.’’ This premise will activate both the complementary and the alternatives class. If the alternatives class is activated more strongly, then the following models will be produced:

\[
\begin{align*}
p & \quad \rightarrow \quad q \\
b & \quad \rightarrow \quad q
\end{align*}
\]

These models lead to the conclusion that ‘‘q is true.’’ However, if, as is almost always the case with children at this age, they are asked to evaluate the possible conclusion ‘‘q is false,’’ they will then deny this. If the complementary class is activated more strongly, then the following models will be produced:

\[
\begin{align*}
p & \quad \rightarrow \quad q \\
a & \quad \rightarrow \quad \neg q
\end{align*}
\]

which will lead to the conclusion that ‘‘q is false.’’

The detailed analysis that we have made of the four logical forms allows some general predictions about reasoning in young children. While the specifics of these predictions vary, it should be noted that they are all basically determined by the relative accessibility of information and the resulting models that are constructed by the reasoner.

First, it is assumed that for most kinds of premises, young children are not able to activate information other than the complementary class during on-line reasoning. It should be specifically noted here that we are not assuming that children do not have access to information about alternatives (although this is less certain for disabling information). In fact available evi-
dence shows clearly that when asked specifically to generate alternatives, they can do so (Markovits et al., 1998). We are assuming that the necessity to actively process information related to the explicit task and the lack of specific instructions for retrieval reduces the amount of cognitive effort available for information activation and retrieval. In these cases, most children will produce conclusions for the four logical forms that correspond to the logical biconditional, something that is well documented (e.g., Wildman & Fletcher, 1977). However, for premises for which cases in the alternatives class are very easily activated, the model would predict that the MP and MT inferences should be maintained, but there would be an increasing number of uncertainty responses to AC and DA, the extent of which should vary according to the strength of activation.

This general analysis can be made more precise by differentiating two major types of conditionals, class-based and causal. Class-based conditionals refer to “if-then” (or, alternatively, “All A are B”) relations for which antecedent and consequent terms refer to classes and/or properties of classes and the basic relation is that of class membership (e.g., “If an animal is a cow, then it has four legs”). Causal conditionals refer to “if-then” relations for which antecedent and consequent terms refer to events and/or outcomes and the basic relation is that of causality. Most forms of class-based relations appear to be stored directly in semantic memory, with the exception of so-called “ad hoc” categories which are constructed on the basis of some given definition (e.g., “things to be taken on a trip”; Barsalou, 1983). This implies that access to information referring to alternatives should be relatively direct and also that there should be relatively few available cases of disabling conditions. Causal conditionals require more complex processing. Specifically, generating information on both alternatives and disabling conditions requires constructing classes of events that correspond to naïve causal theories (Cummins, 1995; Cummins et al., 1991). For example, for the causal conditional “If a rock is thrown at a window, the window will break,” constructing possible alternative antecedents requires constructing the class of things that can break windows, which in turn requires specifying such characteristics as “hard things” that reflect theories about how things can be broken.

If we suppose that young children can access only readily available information during reasoning, then the preceding analysis leads to some fairly clear predictions. Specifically, this would imply that young children should be able to produce relatively high levels of uncertainty responses to AC and DA for class-based premises for which alternatives are strongly associated with the consequent term. In fact, Markovits et al. (1996) have found that 7- and 8-year-old children do give quite high levels of uncertainty responses (around 50%) to AC and DA with premises such as “If an animal is a dog, then it has legs.” In addition, younger children should produce fewer uncertainty responses to AC and DA for class-based conditionals having relatively few available alternatives (e.g., “If something is a cactus, then it has
thorns”), which is also the case (Markovits, 2000). Finally, causal conditionals should be the most difficult for younger reasoners, since generation of relevant information is made difficult by the necessity of an intervening step and thus should produce a high level of biconditional responses irrespective of the individual characteristics of the premises (Janveau-Brennan & Markovits, 1999; Lecas & Barrouillet, 1999).

Three other, more specific, phenomena can also be inferred from the previous analysis. The first concerns the relative difference between MP and MT. In both cases mentioned above, young reasoners should accept both the MP and MT inferences. However, the MP inference is made on the basis of a single model, while the MT inference is made on the basis of two models. Assuming that manipulating two models puts an additional cognitive load on the young reasoner, this would imply that MT would result in more processing errors and that MP would generally have a higher level of correct responding, which generally appears to be the case for young children.

The second concerns responses to AC and DA when children do not accept the biconditional response. The above analysis assumes that when children deny the biconditional inference to AC (“q is true”) they do so on the basis of the following two models:

\[
\begin{align*}
p \rightarrow q \\
b \rightarrow q
\end{align*}
\]

These models would lead to the conclusion that “p can be either true or not true.” In this case, one would expect a relatively high proportion of justifications to involve explicit uncertainty. In the case of DA (“P is false”), denying the biconditional inference is done on the basis of the following two models:

\[
\begin{align*}
p \rightarrow q \\
b \rightarrow q
\end{align*}
\]

These models would lead to the conclusion that “q is true,” which would contradict the biconditional inference, but not lead to an explicit response of uncertainty. Thus it would be predicted that for young children, a greater proportion of inferences denying the biconditional would be accompanied by explicit uncertainty justifications for AC than for DA, a result which has been found by Markovits et al. (1996, study 1).

A final prediction can be made concerning the influence of the formulation of the minor premise in the case of the DA inference. Specifically, it would be predicted that the way that the DA premise is framed will have a major effect on the probability of activating possible alternatives. In the case of causal premises, the normal formulation is “p is not true,” which implicitly dichotomizes possible cases into p and not-p. For example, the corresponding minor premises for “If a rock is thrown at a window, the window will break” is “a rock is not thrown at a window.” This formulation suggests that if p
is not true, then nothing is true and would tend to restrict activation of alternatives. However, such a formulation is not possible for class-based premises; instead, the formulation ‘If something is not p’ must be used. Such a formulation explicitly suggests the existence of possible alternatives. It would thus be predicted that the relative proportion of uncertainty responses to DA compared to AC would be much higher for class-based premises than for causal premises, something has been demonstrated in several experiments (Janveau-Brennan & Markovits, 1999; Markovits et al., 1996, 1998).

**Conditional Reasoning with Familiar Premises in Older Children and Adolescents**

In the case of older children and adolescents, we assume that they are more easily capable of retaining three models in working memory. We also assume that their memory retrieval processes are increasingly more efficient, although access to information remains a key variable that determines the kinds of inferences that are made. We continue to assume that the complementary class remains the most readily available; however, as a consequence of increasing capacity, we suppose that relatively more classes of information will possibly be activated. We start by examining how these basic assumptions will affect responding on each of the four logical forms.

Reasoners making the MP inference will start with the initial model and will use ‘‘p is true’’ as a retrieval cue. We suppose two principal strategies for fleshing out this model, depending on whether disabling cases are readily activated in memory. If this is not the case, then the initial model will be used and the MP inference will be made. If, however, a disabling case is activated at a sufficiently high level, then retrieval of this information must be inhibited by the reasoner or it will be incorporated into the model of the premises. Assuming a failure to inhibit, then the following models will be used:

\[
\begin{align*}
p & \quad \text{---} \quad q \\
p.d & \quad \text{---} \quad \text{not-q}
\end{align*}
\]

where p.d refers to p in combination with some condition that prevents q from being true. In this case, the reasoner will conclude that if ‘‘p is true’’ then q is not necessarily true.

This model also allows for one further form of fleshing out. It may be that some reasoners will rely on the consequent of the major premise as a principal retrieval cue. In this case, they would activate alternative cases if these were easily accessible and produce the following models:

\[
\begin{align*}
p & \quad \text{---} \quad q \\
b & \quad \text{---} \quad q
\end{align*}
\]

In most cases, this would lead to the conclusion that ‘‘q is true.” However, it would also be predicted that the presence of an extra model plus the load
imposed by retrieval of information related to alternatives might lead to an uncertain conclusion in some cases, particularly in children and younger adolescents. It would thus be predicted that there would be a weak relation between accessibility to alternatives and a refusal to accept the MP inference. In fact, there is some evidence that this is the case for children (Rumain, Connell, & Braine, 1983) and for adolescents (Markovits & Vachon, 1990).

For MT reasoners would be given ‘‘If p then q and q is false.’’ For younger children, this would tend to strongly activate only the complementary class, which would lead to the following models:

\[
\begin{align*}
p & \quad \rightarrow \quad q \\
a & \quad \rightarrow \quad \neg q
\end{align*}
\]

this would lead to the conclusion that ‘‘p is false,’’ which is the logically correct conclusion. However, with age improved retrieval would lead to activation of additional information, where the major premise would be used as a retrieval cue. In the case that alternatives are more readily accessible than disabling conditions, then the primary form of fleshing out would involve the following three models:

\[
\begin{align*}
p & \quad \rightarrow \quad q \\
a & \quad \rightarrow \quad \neg q \\
b & \quad \rightarrow \quad q
\end{align*}
\]

In this case, the overall cognitive load is much higher, since both amount of information retrieved and number of models is greater. Thus, although the conclusion that follows from these models is that ‘‘p is false,’’ it would be supposed that younger reasoners in particular would tend to falsely conclude that there is no conclusion for MT, simply because of difficulties in processing such a relatively large quantity of information. As older reasoners would be assumed to have generally more capacity, they would tend to make the logically correct conclusion more often in this case. Thus, we would assume that age-related responses to MT would form a U-shaped developmental function, which appears to be the case (O’Brien & Overton, 1980, 1982). This analysis would also suppose that performance on MT would decrease when alternatives are made more readily available to reasoners, which is also the case (Rumain et al., 1983; Markovits, 1985).

One final element must also be considered. In some cases, information on disabling conditions might also be readily available. If disabling conditions are more strongly activated than are alternatives, then the following models will be produced:

\[
\begin{align*}
p & \quad \rightarrow \quad q \\
a & \quad \rightarrow \quad \neg q \\
p.d & \quad \rightarrow \quad \neg q
\end{align*}
\]
In this case, the conclusion is that $p$ may or may not be true, since the third model allows for $p$ to be true with an associated disabling condition.

The analyses of the MT and MP inferences allows for one relative prediction. For MP, the minor premise ("$p$ is true") tends to activate only disabling conditions ($p.d \rightarrow \neg q$), while for MT the minor premise ("$q$ is false") can activate either complementary ($a \rightarrow \neg q$) or disabling information. Thus, all other things being equal, the influence of disabling conditions should be stronger for MP than for MT. Available data is somewhat mixed in this respect. Cummins (Cummins et al., 1991; Cummins, 1995) has found that MT inferences are very responsive to disabling conditions. However, these studies used a modal form of evaluation, where subjects were asked to rate the degree of necessity of a possible inference. Johnson-Laird, Legrenzi, Girotto, Legrenzi, and Caverni (1999) have proposed a model for modal inferences that uses somewhat different procedures than those used for deductive inferences requiring necessity. Studies that have examined production of necessary inferences have found that MT appears to be less affected by possible disabling conditions than MP (Vadeboncoeur & Markovits, 1999; Janveau-Brennan & Markovits, 1999), both with adults and children.

For the AC inference, the minor premise ("$q$ is true") will tend to strongly activate possible alternatives, if these are available. Reasoners will thus use either the initial model and make the biconditional inference to AC or will produce the two models that include a possible alternative:

\[ p \rightarrow q \]
\[ b \rightarrow q \]

In this case, they will respond with uncertainty to the AC inference. Note that this analysis supposes that the AC inference will not be affected to any extent by the presence of possible disabling conditions.

For the DA inference, the minor premise ("$p$ is false") will tend to activate the complementary class and the alternatives class. If only the complementary class is strongly activated, then the two models corresponding to the biconditional inference will be produced:

\[ p \rightarrow q \]
\[ a \rightarrow \neg q \]

which will lead to the inference that "$p$ is false." If the alternatives class is also activated, then three models will be produced:

\[ p \rightarrow q \]
\[ a \rightarrow \neg q \]
\[ b \rightarrow q \]

This will lead to the conclusion that $q$ may or may not be true. However, given the necessity of manipulating three models and the additional retrieval load, it would be expected that DA would be more difficult than AC for premises having equal access to possible alternatives (except in cases where
the formulation of the minor premise for DA leads to increased access to alternatives as described previously). This prediction is consistent with results obtained with children and adolescents (Markovits & Vachon, 1989; Roberge & Masson, 1978), although results with adult reasoners are less clear (see Evans, 1993, for a summary).

The analysis that has been presented of reasoning with familiar content for each of the four logical forms allows the making of predictions concerning the effects of some general factors on reasoning.

1. Effects of access to alternatives. Generally, this model predicts that production of uncertainty responses to AC and DA should be strongly influenced by the relative accessibility of possible alternatives. This leads to two general predictions. First, premises which allow for many possible alternatives should produce more uncertainty responses to AC and DA than premises which allow for fewer possible alternatives. This particular relation has been well documented in both adults (Cummins et al., 1991; Cummins, 1995; Thompson, 1994) and children (Bucci, 1978; Markovits & Vachon, 1990; Janveau-Brennan & Markovits, 1999). Second, there should be a strong influence, not only of number of available alternatives but the associative structure of major available alternatives. Specifically, we would predict that premises for which the major alternative is strongly associated to the consequent of the major premise (e.g., “If something is a car, then it has a motor”) should result in more uncertainty responses to AC and DA than premises for which this association is less strong (“If something is a refrigerator, then it has a motor”), something that has been verified for both children (Markovits et al., 1998) and adults (Quinn & Markovits, 1998).

These general predictions must, however, be modulated by considering the interaction between premise type and processing speed. We have stated earlier that a clear distinction must be made between class-based premises and causal conditionals. Class-based premises contain specific markers to the relevant classes of information, and it would be supposed that as reasoners become more efficient in retrieving information from memory, content-related differences in premises would have increasingly small effects on reasoning. This does appear to be the case, since both numbers of available alternatives (Markovits, 2000) and the associative structure of alternatives (Markovits et al., 1998) affect production of uncertainty responses for class-based premises among younger children, but not among older ones. Causal premises require use of an intermediate step involving naïve causal theories (Cummins, 1995) to generate relevant classes of information. Thus, it would be expected that content-related differences would be more robust even among older reasoners for causal premises. In fact, both numbers of alternatives (Cummins, 1995) and associative structure (Quinn & Markovits, 1998) affect adults’ reasoning with causal premises.

2. Effects of access to disabling conditions. The analysis of responses to MP and to a lesser extent to MT allow for incorporation of possible disabling conditions (Cummins, 1995) into the models of a given reasoning problem.
This would lead reasoners to tend to deny the MP inference for premises for which there are relatively many possible disabling conditions, which is consistent with results obtained with adult reasoners (Cummins et al., 1991; Cummins, 1995; Thompson, 1994; Vadeboncoeur & Markovits, 1999). However, there is also a developmental prediction that can be made in this respect. First, most class-based premises that are not counterfactual in nature do not allow for many possible disabling conditions. Thus it would be predicted that MP would tend to be accepted for class-based premises, irrespective of age, which is indeed the case (Kodroff & Roberge, 1975; Wildman & Fletcher, 1977). The tendency to deny MP would generally be much stronger for causal premises. However, according to our analysis of information types, disabling cases provide less information than complements and are correspondingly more difficult to retrieve. Thus, it follows that younger children would tend to accept MP irrespective of the existence of possible disabling conditions, since they would be less able to retrieve such information even if available. Older children, on the other hand, would be more able to activate such information and thus should deny the MP inference more often with causal premises, which has also been confirmed (Janveau-Brennan & Markovits, 1999; Markovits et al., 1998). However, older children are also developing the ability to inhibit information that has been activated. Thus, as the ability to inhibit information increases, we would expect that older adolescents and adults would tend to accept MP in the logical task despite the existence of possible disabling conditions. We would thus predict that the proportion of subjects accepting the MP inference for causal premises for which there are possible disabling conditions should follow a U-shaped curve, with younger children and older adolescents and adults showing high levels of accepting MP in the logical task, a prediction that remains to be examined.

3. Level of abstraction of tokens. We have assumed that tokens used by younger children will refer to specific instances. However, in presenting our model we also allowed for at least one difference in the level of abstraction of tokens. Specifically, it is supposed that if a reasoner strongly activates a single instance of a given class of information, then this will be used to construct the corresponding model. For example, suppose that a child receives the major premise “If something is a car, then it will have a motor” and is asked the AC inference (“something has a motor”). If only one specific alternative is strongly activated, e.g., “a bus has a motor,” then this case will be used in the set of models constructed by the subject. In this case, if the child denies the AC inference, the justification will tend to use the specific case included in the model (e.g., “If something has a motor then it is not necessarily a car, it might be a bus”). If more than one instance is strongly activated, then the token will refer to a class of possible antecedents. In this case, the corresponding justification will either refer to the class (“it might be another mode of transport”) or be undetermined (“it might be
something else’). On the assumption that younger children’s retrieval processes are less efficient, we would expect that younger children would more often activate single instances than older children for the same premises. Thus, we would predict that older children would use justifications referring to specific instances less often than younger ones. This was in fact observed by Markovits et al. (1998), who found that 38% of justifications used by 11-year-olds were specific while the corresponding percentage was 75% for 8-year-olds.

4. Relation between memory retrieval and reasoning with familiar premises. This model supposes that one of the key factors that determine the response that will be produced to a given premise is the efficiency of the reasoner’s memory retrieval processes. For example, if a reasoner is able to maintain the premises in memory and at the same time retrieve possible alternatives from memory, then they will tend to produce uncertainty responses to AC and DA. If retrieval under these circumstances is more difficult, then the reasoner will tend to make the biconditional inferences to AC and DA. Thus, we would predict that within reasoners of the same developmental level, there should be a relation between the responses made to conditional inference problems and efficiency of retrieval from memory. There have not been many studies looking at such a relation. Janveau-Brennan and Markovits (1999) did find a significant correlation between a simple measure of retrieval (number of alternatives produced in a limited time for premises differing from those used in reasoning) and children’s production of uncertainty responses to AC and DA with causal conditionals. Interestingly, there was also a correlation between the former measure and the tendency to refuse the MP inference. Since the tendency to refuse the MP inference appears to be related to the retrieval of possible disabling conditions, this result suggests that retrieval efficiency (for both alternatives and disabling conditions) may be a general factor in individual differences in conditional reasoning.

REASONING WITH FAMILIAR TERMS IN UNSPECIFIED RELATIONSHIPS

We have assumed that the tokens used in mental models of premises correspond to relational schemas as described by Halford et al. (1998). However, consider the particular case of premises that use familiar terms that are in an arbitrary relation (‘‘If there is a square then there is a circle’’). However, given the familiar nature of the terms in these premises, we can suppose that younger children would tend to treat these premises as if they were familiar ones. In this case, however, none of the three possible classes of information can be directly activated, since they must be retrieved from memory according to some relational context, which is not available with these types of premise. Thus the process of retrieval from LTM cannot provide the subject with ‘‘ready-made’’ models representing co-occurrences already stored in memory.
This will have some direct consequences for the reasoning process. In the case of these premise types, the most readily available sources of information are possible alternative values of p, on the one hand, and possible alternative values of q, on the other hand. We propose that these alternatives must then be coordinated in transient mental models since they do not correspond to existing relational schemas. Specifically, children will attempt to flesh out the initial model by inferring from their existing knowledge the individual nature of the variables P and Q and the values which can be assumed by Q for values of P not specified in the conditional premise. Thus, the nature of the mental models constructed would depend on the structure of the semantic spaces in which the values p and q are individually embedded (e.g., the variable ‘‘sex’’ can only have two values, male and female, whereas the variable ‘‘color’’ can have many values). We also suppose that the need to construct and maintain mental models representing such arbitrary co-occurrences (which are not supported by preexisting relational structures) will impose an additive cognitive load which will tend to reduce the number of models children can easily construct. This analysis allows the making of some specific predictions.

A first consequence of the additional cognitive load required for the construction of models that do not have an existing relational underpinning would be to reduce the number of models that can easily be constructed. In younger children, who appear to be constrained to using two models when presented with familiar relational premises, a reduction in number of models would result in a tendency to use the initial model for reasoning, which, as we have mentioned previously, would lead to making the MP and AC inferences and refusing the DA and MT inferences. Older children who have greater cognitive capacities should be able to add a second model to their representation. For the same reasons as we presented earlier, the most informative hypotheses are of the form not p—not q, resulting in a biconditional interpretation which would lead to making all the conditional inferences (i.e., MP, AC, DA, and MT). Finally, older adolescents and adults should be able to construct three models by adding a not p–q model to the previous ones, resulting in a conditional interpretation which lead to making MP and MT and refusing the AC and DA inferences.

Thus our model predicts that younger children should tend to produce MP and AC only; older children should produce all the four inferences, whereas older adolescents and adults should produce MP and MT more often than AC and DA. In fact, this is exactly what Barrouillet and Lecas (1998; Barrouillet, Grosset, & Lecas, 2000) observed in children, adolescents, and adults who had to produce conclusions from conditional syllogisms with arbitrary relations. Moreover, several studies have shown that the interpretation of conditional statements with arbitrary relations evolves from a one-model interpretation to a two- and then a three-model interpretation (Barrouillet, 1997; Barrouillet & Lecas, 1998, 1999; Lecas & Barrouillet, 1999).
A second prediction concerns possible information about disabling cases. Our analysis of conditional statements with arbitrary relations suggests that the models corresponding to the complementary and alternatives classes of information must be constructed by the reasoner by considering possible alternative values of p and q. This analysis also suggests that models corresponding to disabling conditions would not be easily constructed by reasoners. First, although considering possible cases of not-p and of not-q allows constructing models corresponding to both complementary [not-p and not-q] and alternatives [not-p and q] classes in a fairly natural way, they do not in themselves provide possible disabling conditions, which requires constructing a third class of information that is independent of not-p and not-q. In this case, the closest a reasoner could come to a disabling model would involve constructing a [p and not q] model which would contradict the sole information explicitly conveyed by the conditional statement. As a consequence, the rate of MP endorsement should not follow the U-shaped developmental curve hypothesized for familiar premises, but should remain relatively high. Indeed Barrouillet and Lecas (1998) found that the rate of endorsement of MP increases with age with a ceiling effect observed from the beginning of adolescence.

Another prediction concerns the link between the number of models a subject is able to construct and his or her processing capacities. Because the complementary and alternatives models cannot be retrieved from memory, efficiency of retrieval will not affect reasoning. Thus in the case of premises with unspecified relations, the major constraint on reasoning should be the number of models a subject can construct, which should in turn be related to his or her working memory capacity. This prediction has been tested by Barrouillet and Lecas (1999), who had children ages 9 to 15 years perform a counting span task (Case, Kurland, & Goldberg, 1982) and a reasoning task in which they had to produce as many instances compatible with a conditional sentence as possible. As predicted, they found a very high correlation between the counting span, which is considered as a measure of working memory capacity, and the number of models the children could construct, even when the effect of age was partialled out ($r = .65$).

Another class of predictions concerns the relation between the semantic fields of the p and q terms and the fleshing out process. We have assumed that the number and nature of available alternatives to the categories included in both P and Q will influence the number of models constructed by reasoners. It is possible to distinguish two types of categories according to the characteristics of the semantic fields corresponding to the complement of the category. On the one hand, some categories create dichotomous fields such that their complement contains a single instance. For example, the complement of the category “boy” is the single category “girl.” We refer to these as binary categories (Barrouillet & Lecas, 1998). Other categories have
complements that contain many potential cases; for example, the complement of the category ‘red’ is composed of ‘yellow,’ ‘green,’ and so on.

Generally, it can be assumed that it should be easier to generate the complement of a binary category than that of a category that allows for many possible complements (Barrouillet & Lecas, 1998). Now a comparison of premises comprising antecedent and consequent terms that are binary (e.g., ‘If the pupil is a boy, then he wears a shirt with short sleeves’) to those that have antecedent and consequent terms that both allow for many possible complements (e.g., ‘If the piece is a square, then it is red’) provides some general predictions. Specifically, we can assume that constructing the complement of both antecedent (not-p) and consequent (not-q) terms would be easier with binary premises. Thus, any attempt to retrieve knowledge from memory would activate these definite alternative values and a second model of the form [not p–not q] should easily come to mind. However, as Barrouillet and Lecas (1998) have pointed out, the uniqueness of these alternatives would not only facilitate their retrieval but also impede any subsequent fleshing-out. This is because constructing the two models corresponding to [p–q] and [not-p–not-q] results in an association of each of the two possible values of P with a different value of Q, resulting in an explicit one-to-one correspondence which conveys the highest amount of information and is thus extremely stable. For example, with the premise ‘If the pupil is a boy, then he wears a shirt with short sleeves,’ the following two models would be easily constructed:

<table>
<thead>
<tr>
<th>boy</th>
<th>short sleeves</th>
</tr>
</thead>
<tbody>
<tr>
<td>girl</td>
<td>long sleeves</td>
</tr>
</tbody>
</table>

With these two models, all the four possible cases are used in a natural way that suggests a biconditional interpretation of the premise. The only way for a reasoner to construct a model corresponding to the alternatives class would be to generate [girl short sleeves], which requires explicitly using the same element twice in different models and should thus be quite difficult.

In the case of premises that allow for multiple complements our analysis suggests that constructing a second model corresponding to the complementary class should be more difficult than with binary premises. However, assuming that the model corresponding to the complementary class is indeed constructed, then it should be subsequently easier for the reasoner to construct a model corresponding to the alternatives class. For example, suppose a reasoner is given the premise ‘If the piece is a square, then it is red.’ The complementary class would minimally require generating a specific example of something that is not a square. If this is done, then the following two models would be generated (note that we have previously assumed that the directionality of if-then implies that the consequent term is understood as a dichotomy):
In this case, construction of a model corresponding to the alternatives class could be done by considering one of the other possible cases of not-p. For example, the model [rectangle red] could be constructed in this way. Thus, to the extent that the reasoner will have activated more than one case of not-p in memory, this should reduce the effort required to construct a third model compared to that required by binary premises.

We can use this analysis to make some specific developmental predictions. Very young children can be assumed to have limited working memory capacities and will have difficulty producing more than one model. Now, producing a definite alternative model of the form [not p–not q] should be more difficult with nonbinary terms than with binary terms. As a consequence, young children should tend to use the initial model for reasoning more often (and produce correspondingly fewer biconditional responses) with nonbinary terms than with binary terms.

On the other hand, consider older children who have sufficient working memory capacity to produce many mental models. Our analysis implies that these children should exhibit conditional inference patterns (i.e., uncertainty responses on AC and DA) more often with nonbinary terms than with binary terms the nature of which constrain the fleshing-out process to the establishment of a one-to-one correspondence. In fact, this developmental pattern was found by Barrouillet and Lecas (1998). Biconditional response patterns were predominant in 9-year-old children as in 15-year-old children when conditional with binary terms are used. However, when nonbinary terms are used, the younger children exhibited a higher rate of production for MP and AC, which are supported by the initial model, than for DA and MT which require a second model, whereas older children produced MP and MT more often than AC and DA.

Finally, our model permits a prediction concerning the effect of the kind of negation used in the minor premise for both DA and MT when arbitrary relations linking nonbinary terms are used. Indeed, the negation of the proposition “the piece is red” can be either explicit (i.e., “the piece is not red”) or implicit (i.e., “the piece is green”). The use of implicit negation suggests that the value in the conditional premise (i.e., red) is one among many possible values and that the conditional relation would link complex semantic spaces. On the other hand, an explicit negation focuses on the same value as the affirmative sentence (i.e., “red”) leading to a dichotomization of the semantic space of colors. The value of concern is “red” and the piece is either “red” or “not red.” Thus, explicit negation would lead subjects to treat nonbinary semantic spaces as if they were binary in nature. Following the previous analysis on binary and nonbinary terms, biconditional response patterns (i.e., endorsement of DA and AC) should be more frequent with
explicit than with implicit negation. In fact this effect has been observed in many experiments (Barrouillet & Lecas, 1998; Barrouillet, Grosset, & Lecas, 2000).

Development of Abstract Reasoning

The preceding analyses have looked at reasoning with premises for which the antecedent and consequent terms have specific (concrete) referents. One of the important dimensions of advanced reasoning is the capacity to reason with abstract referents. This kind of reasoning has received very little attention and there are few indications as to how it may develop. The model that we have presented specifically assumes that the terms used in the premises refer to concepts and/or actions that are at least potentially accessible in long term memory. In fact, one of the important questions that must be answered by any mental model account of conditional reasoning is how at least certain reasoners can develop the ability to reason with purely abstract problems.

We can suggest two possible mechanisms that may account for the ability of children and adults to reason with abstract premises. The first involves the use of a form of structure mapping (Gentner, 1983; Halford et al., 1998) in order to create an analogy between abstract premises and concrete forms that are familiar to the reasoner. Gentner (1983) has presented a model of structure mapping that assumes that analogies involve representations of relations between objects and are independent of the specific content of the domains in question. If we assume that a structure mapping procedure is indeed accessible to children, then we can make a useful distinction between forms of abstract premises.

Specifically, consider a premise such as “If p then q.” Such a premise uses abstract referents, but in addition, there is no indication of what kind of relation is involved. The most direct form of analogy that can be formed from such a premise would be “If state A then state B,” which corresponds to an unknown relation between two known referents. Now, the analysis that we have made of this form of premise suggests that older children and adolescents would have a tend to access only information about possible complements and thus produce biconditional responses to all four logical forms in this case. We would then expect that use of a structure mapping procedure would result in a strong tendency to produce biconditional responses to abstract premises of the form mentioned above, something that does indeed appear to be the case at least among adolescents (Markovits & Vachon, 1990).

Now consider a premise such as “If p is done, then q will happen.” Such a premise uses abstract referents, but these are presented in such a way as to suggest that a causal relation exists between the antecedent and consequent terms. In this case, the premise suggests a possible relational context that can be used to make the structure mapping procedure more specific. We
could thus expect that it would be easier in this case for a reasoner to map these premises onto a known causal structure that would allow potential access to information about possible alternatives. We would then predict that it would be easier for reasoners to produce uncertainty responses to AC and DA when given an abstract premise that provides some referential information, something that remains to be examined.

Structure mapping thus provides one mechanism for reasoners to translate abstract premises by making a specific analogy with known forms of reasoning. As we have seen, the use of such a procedure allows some potentially interesting predictions to be made that rely on the informational structures of particular kinds of concrete premises. However, such a mechanism may not be sufficient to explain a more general form of abstract reasoning that may characterize older and more experienced reasoners. Specifically, Markovits and Vachon (1990) found that while adolescents produced biconditional inferences to abstract premises with no relational information of the form “If p then q,” educated adults were able to produce uncertainty responses to the AC and DA forms. They proposed that adults may be able to use abstract tokens in the mental models of such premises. This is also consistent with the observation made by Barrouillet and Lecas (1998) that, contrary to children and adolescents, adults are not sensitive to the binary/nonbinary nature of the terms involved in conditional premises. There would thus be a developmental progression from tokens that refer to specific elements to those referring to more general classes of elements and finally to abstract tokens that would correspond to those of the classic mental model theory (Markovits, 1993). However, if such abstract models are constructed by older reasoners, then the question arises as to how abstract information corresponding to the different classes of information that we assume to characterize the conditional are constructed. One mechanism that can account for this is Karmiloff-Smith’s (1995) notion of representational redescription. This model suggests that information is stored in increasingly abstract forms. Specifically, very familiar forms of information are internally redescribed in an iterative process that conserves essential aspects of the information while eliminating specific domain referents. Such redescriptions thus provide progressively more abstract representations of classes of information, while remaining linked to the original classes of information. Specifically, we would propose that reasoners gradually form abstract representations of the complementary and alternatives classes, with the former appearing much earlier than the latter. Thus the transition to more abstract tokens would be supported by the construction of these two classes of information, with the alternatives class being latter to develop.

Both the proposed mechanisms suppose that abstract reasoning relies on access to specific knowledge. Both suggest that the default response for abstract premises, at least among older children and adolescents, would be to make the biconditional inference to all four forms, except in conditions
where associated knowledge allows access to some form of possible alternatives. Thus one general prediction that this model would make is that it would be easier to produce uncertainty responses to abstract premises when access to existing knowledge is facilitated. One way of varying access to information is by using context, as we saw above. Venet and Markovits (2001) presented adolescents with abstract premises in realistic and fantasy contexts and found that production of uncertainty responses to AC and DA was indeed facilitated by the realistic contexts, in a way that was indeed consistent with a redescriptive model.

*Development of metacognitive knowledge.* Another dimension that may be related to abstract reasoning and whose development is important to understand is the increasing ability of reasoners to metacognitively reflect on their own reasoning processes. Moshman and Franks (1986) have shown that young children become increasingly able to reflect on their own inferential processes in order to develop an explicit understanding of notions such as inferential validity. Vadeboncoeur and Markovits (1999) have recently suggested that another dimension in metacognitive development could be the increasing ability of reasoners to consciously choose what forms of information are to be incorporated into a fleshed-out model set. Thus, although the fleshing-out process may be automatic in younger children and determined mostly by the associative structure of semantic information concerning a given conditional relation, development might allow for a separation between the process of activating information concerning a given conditional relation and the actual fleshing-out process which could then be (more or less) consciously controlled. Interestingly, such a notion appears to be consistent with Evans and Over’s (1996, 1997) recent distinction between two forms of rationality or with Falmagne’s (1990) distinction between formal and contentful representations.

**DISCUSSION**

The model that we have presented can account for most of the developmental data concerning the way that inferences are made on the basis of “if-then” conditionals. It should also be noted that, in one form or another, it has also been used to make a variety of novel predictions about conditional reasoning (Barrouillet & Lecas, 1998, 1999; Barrouillet, Grosset, & Lecas, 2000; Markovits & Vachon, 1990; Markovits, 1995; Markovits et al., 1996, 1998; Janveau-Brennan & Markovits, 1999; Quinn & Markovits, 1998; Vadeboncoeur & Markovits, 1999; Venet & Markovits, 2001).

The major developmental alternatives to the proposed theory are rule-based theories (e.g., Braine, 1978, 1990; Braine & O’Brien, 1991; Overton, 1990; Overton & Newman, 1982; Rips, 1983, 1994). Generally, such theories propose that specific content-independent inference rules are available, or become available, as part of existing cognitive processes. The reasoning process is assumed to undergo a series of stages during which verbally presented
premises must be encoded into a form that allows the reasoner to choose an appropriate inferential rule. Content-related variability is assumed to occur primarily in the encoding stages due to such processes as pragmatic inferences (Rumain, Connell, & Braine, 1983) and incorporation of external information (Rips, 1994). Such theories can indeed provide detailed accounts of the relative differences that characterize various types of inferences. However, while their description of what rule-guided inferential processes might look like is quite detailed, they do not yet provide any clear description of the encoding stage that allows more than a post hoc explanation of the kinds of content and developmental variation that are so commonly observed in conditional reasoning. Rips (1994) makes this point explicitly by acknowledging that his PSYCOP model cannot account for why reasoners incorporate information not explicitly presented in problem premises (p. 179). In order for this model to account for reasoning performance this information must be independently put into the model.

Nonetheless, it must be acknowledged that rule-based theories can, at least in principle, account for the data that have been observed in conditional reasoning. However, evaluation of their current level of adequacy depends on the nature of the underlying conception of the reasoning process. If reasoning is considered to be a process that is in some sense autonomous and can function independently of other basic cognitive processes, then the lack of precision in the encoding stage does not create a serious problem, since it could be argued that what occurs in this stage is not "reasoning." However, if, as we assume here, reasoning is not considered to be an autonomous cognitive module, then the inability to predict variability, both content and developmentally based, represents a serious failing in any theory attempting to describe conditional reasoning performance.

CONCLUSION

We have presented a mental model account of conditional reasoning that attempts to account for much of the observed developmental and content-related variability in conditional reasoning performance. It must be noted that this model explains a very limited class of reasoning problems, for example, there is no attempt to explain performance on the related selection task. While this presents some evident problems in generalization, there is nonetheless a clear advantage to limiting the model to this class of reasoning at its current stage. The extensive research on conditional reasoning has resulted in a very large base of empirical data, both with children and adults. Attempting to fit any model to this database requires a consequent precision in the mechanisms that are postulated. In turn, the insights that are provided into the processes that may be involved in conditional reasoning can be expected to inform us about the nature of some of the general mechanisms involved in inferential reasoning.

Our analysis of conditional reasoning points out some key factors that
must be considered in understanding how reasoners make conditional inferences. The idea that most reasoners are able to use content-free reasoning procedures in any systematic way appears highly unlikely given the very large sources of variation in inferential performance observed in the various studies we have cited. In a similar way, we consider it unlikely that reasoning problems are easily represented in even a semiastract way, particularly among children. Our analysis indicates that reasoning performance is affected by the nature and accessibility of information about the premises that is maintained in memory, particularly with children, but also for many adults. Such information reflects reasoners’ experience with the relations involved in a given reasoning problem, and understanding how children and adults make inferences must involve an understanding of how this information is accessed on-line during the inferential process.

More specifically, our model presents some general factors that may be used to account for developmental patterns in conditional reasoning. First, the sheer quantity of information available will have a strong effect on the kinds of inferences that are made. Within this factor, we have postulated that development reflects increases in the efficiency of information retrieval processes and in children’s representational capacity. In addition, the ability to inhibit information that is not appropriate to the logical problem must also be considered a vital component of reasoning. Finally, the development of a more abstract “expert” reasoner requires processes that allow generation of more abstract forms of information, and we have proposed some possible processes that could account for this.

REFERENCES


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