Dual-process theories of reasoning: The test of development

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Abstract

Dual-process theories have become increasingly influential in the psychology of reasoning. Though the distinction they introduced between intuitive and reflective thinking should have strong developmental implications, the developmental approach has rarely been used to refine or test these theories. In this article, I review several contemporary dual-process accounts of conditional reasoning that theorize the distinction between the two systems of reasoning as a contrast between heuristic and analytic processes, probabilistic and mental model reasoning, or emphasize the role of metacognitive processes in reflective reasoning. These theories are evaluated in the light of the main developmental findings. It is argued that a proper account of developmental phenomena requires the integration of the main strengths of these three approaches. I propose such an integrative theory of conditional understanding and argue that the modern dual-process framework could benefit from earlier contributions that made the same distinction between intuition and reflective thinking, such as Piaget’s theory.

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Introduction

In the past decades, dual-process theories of thinking and reasoning have become increasingly influential (Evans, 2010; Evans & Frankish, 2009). This upsurge is most probably related to the need to explain the apparent paradox created by the discovery of a series of cognitive biases violating elementary rules of logic in educated university students when solving reasoning and decision making tasks (Evans, 1989; Reyna, 2004; Tversky & Kahneman, 1974, 1983; Wason, 1966), while the scientific and technological advances of our societies would suggest that human beings are intrinsically rational. A possible solution to this problem was to imagine the coexistence of two kinds of thought, intuitive and deliberative (Evans, 2007). Though some of the dual-process theories assume that these two kinds

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of thought rely on different cognitive processes (Evans, 1984, 1989; Klaczynski, 2000; Sloman, 1996), other theories go further and suggest that this duality is rooted in the existence in human brain of two distinct cognitive systems with different evolutionary histories and different functioning (Evans, 2010; Evans & Over, 1996; Stanovich, 1999). Stanovich (1999) coined the terms System 1 and System 2 which are now in common use. The former is usually described as unconscious and automatic, associative, massively parallel, and thus rapid. Because it would not require central resources of working memory, its functioning would not be affected by individual differences in general intelligence. By contrast, System 2 would be inherently conscious and controlled. Because it involves working memory, it is usually assumed as slow, sequential, and strongly related to individual differences in working memory capacity and fluid intelligence. While System 1 would be evolutionary old and share many of its features with other animals, System 2 would be recent and probably unique to humans (Evans, 2010).

Such a contrast between the two systems should have strong implications at the developmental level. Indeed, it can be expected that the processes of the evolutionary old, unconscious, and automatic System 1 should not strongly evolve with age, or at least that they should reach their maturity level in the early ages, whereas the controlled and working memory-dependent System 2 should become functional later in development and strongly evolve with age over an extended developmental period. Thus, it could have been expected that the developmental approach would have been used to test and refine these theories but, surprisingly, apart from rare exceptions (Brainerd & Reyna, 2001; Klaczynski, 2000), the dual-process theories have disregarded developmental questions, exclusively focusing on adult reasoning. However, as Piaget cogently said in his film with Claude Goretta The epistemology of Jean Piaget: “to comprehend a psychological phenomenon, one must understand its development”. The purpose of this article is to apply Piaget’s strategy to the dual-process approach, using what is known about child and adolescent development of reasoning as a testing ground for some of the main dual-process theories. I will concentrate on conditional reasoning, the development of which is well known and has been documented in a variety of tasks.

Thus, I first outline the main findings that have been observed in studying the development of reasoning on familiar and artificial conditional relations. Then, I confront with the developmental data some of the prominent dual-process theories of conditional reasoning. For this purpose, I distinguish three different approaches within this general theoretical framework. The first is the heuristic–analytic theory that has been developed by Evans over the last two decades (1989, 2006, 2007). The second concerns theories which assume that System 1 is probabilistic in nature, while System 2 could be assimilated to the manipulation of mental models. This is the case of Verschueren and Schaeken’s (2010; Verschueren, Schaeken, & d’Ydewalle, 2005) theory, but also of recent proposals by Oaksford and Chater (2010) and Geiger and Oberauer (2010). Finally, I address theories that emphasize the role of metacognitive processes in triggering System 2, such as Thompson (2009, 2010) and Stanovich (2009). In the light of these theories, I propose some suggestions for an integrative dual-process theory of conditional reasoning based on the mental model approach. In a concluding section, I discuss the interest of the modern dual-process approach compared with more ancient but akin conceptions that distinguished between intuitive and reflective thinking, as in Piaget’s theory.

Conditional reasoning and its development

Conditional reasoning is the reasoning permitted by propositions containing the connector If. Though If can be used in several different syntactic structures like “If ... then ...”, “... only if ...”, “If and only if ... then ...”, “... if ...”, I will in this article concentrate on the form “If ... then” as in “If an animal is a dog, then it has legs”, which has been the most studied. A variety of tasks has been used to assess how individuals understand and reason from this type of sentence. Participants can be asked to list the cases that are permissible, or those that are impermissible, when a conditional is true. In the

1 Recent versions of dual-process models (Evans, 2008, 2009, Stanovich, 2011) have moved away from the System 1/System 2 terminology to adopt a Type 1/Type 2 processing distinction. This is due to the fact that the terms System 1 and System 2 suggested singular systems that could be neurally distinguished, whereas it is now assumed that both systems include a variety of processes (see Stanovich, West, & Toplak, 2011, and Evans, 2011b). Nonetheless, I will here keep the commonly used terminology of Systems 1 and 2 without any underlying assumption of singularity at the cognitive or neural levels.
other way round, they can be asked, as in the truth table task, to evaluate the truth value of a conditional from a series of cases. They can also be asked to either produce or evaluate inferences from a conditional premise of the form \( \text{If } p \text{ then } q \) and a minor premise than can either affirm or deny the proposition \( p \), known as the antecedent, or the proposition \( q \), known as the consequent. In a very famous task designed by Wason (1966) and known as the Wason’s selection task, people are asked to select the information related to \( p \) and \( q \) that they need to decide whether a given conditional \( \text{If } p \text{ then } q \) is true or false. More recently, a new task has been introduced by Evans, Handley, and Over (2003) and Oberauer and Wilhelm (2003) in which participants are asked to evaluate the probability of a conditional from a series of cases.

All these tasks have also been used to assess the development of conditional reasoning. Let me begin by the simplest of them, aiming at assessing the way children and adolescents understand conditionals. Earlier and more recent works have shown that young children often interpret \( \text{If } \) in a conjunctive way (Barrouillet, 1997; Barrouillet & Lecas, 1998, 2002; Paris, 1973; Taplin, Staudenmayer, & Taddonio, 1974). When asked to list the cases that are possible when an \( \text{If } p \text{ then } q \) conditional is true, they only produce the \( pq \) case, and when asked to identify the impermissible cases, they list all the other possibilities (i.e., \( \neg p \text{ q, } p \neg q \), and \( \neg p \neg q \)). For example, presented with a conditional like “if the piece is a square, then it is red”, they consider only the red squares as permissible and all the other possibilities as contradicting the conditional sentences. Later in development, young adolescents move to a biconditional understanding in which \( pq \) and \( \neg p \neg q \) cases are now considered as permissible (they add in our example the pieces that are not square and not red to the red squares), whereas the \( \neg p \text{ q and } p \neg q \) cases (pieces that are not square but red and squares that are not red respectively) are still judged impermissible. Finally, older adolescents and adults usually adopt a conditional reading: \( p \neg q \) is the only case that is impermissible, all the others being judged as compatible with the conditional.

The theoretical framework provided by the mental model theory (Johnson-Laird & Byrne, 1991, 2002) seems to be the most appropriate to account for this developmental trend. The conjunctive reading adopted by young children would result from the construction of a very simple representation of the co-occurrence of the antecedent and the consequent that would have the following form:

\[
p \quad q
\]

Such a representation would correspond to the initial model of the conditional postulated by Johnson-Laird and Byrne (1991, 2002), except that this initial model also involves an implicit representation of the possibilities in which the antecedent does not occur\(^2\) that would not be part of young children’s representation. This single-model representation would be enriched by young adolescents with an additional model representing the negation of both propositions (\( \neg p \neg q \)), while older adolescents and adults should be able to construct the three-model representation corresponding to the complete conditional representation postulated by the mental model theory. Such a complete representation is depicted in the following diagram in which each line represents a mental model, that is a possibility that can occur when the conditional is true.

\[
p \quad q
\]

\[
\neg p \quad \neg q
\]

\[
\neg p \quad q
\]

A corresponding developmental trend was observed by Barrouillet, Grosset, and Lecas (2000) in conditional inference production. When given an \( \text{If } p \text{ then } q \) conditional premise involving an artificial relation between \( p \) and \( q \) (e.g., If the musician is Polish, then he plays the bassoon), young children concluded \( q \text{ is true from p is true} \) (an inference known as Modus Ponens, MP) and \( p \text{ is true from q is true} \) (an inference known as Affirmation of the Consequent, AC, and considered as a fallacy in formal logic). By contrast, they judged that nothing follows from minor premises of the form \( p \text{ is false or q is false} \). This pattern corresponds to the inferences that can be drawn from a representation restricted to

\(^2\) Such an implicit representation can be compared with a mental footnote keeping in mind that there are other possibilities in which \( p \) is false, but that have not yet been represented.
suggests that the underlying representation takes into account both biconditional by Evans and Over (2004), matches the biconditional level described above because it assigns the truth-value as indeterminate for the conditional true for the con
tional reading described above. In our studies, as children did, adolescents mainly deemed the old children exhibit the same conjunctive response pattern already observed when evaluating possi-
ence known as Modus Tollens, MT) and \( q \) is false from \( p \) is false (an inference known as Denial of Antecedent, DA, also considered as a fallacy in formal logic). This is what could be expected from a biconditional understanding underpinned by the construction of a two-model representation (i.e., \( pq \) and \( \neg p \neg q \)). Finally, Barrouillet et al. observed that a majority of adults produced MP and MT but resisted the AC and DA fallacies, concluding that nothing follows with certainty from the affirmation of \( q \) and the negation of \( p \). This pattern corresponds to the conclusions supported by the three-model representation described above, in which the third model \( \neg p q \) prevents adult reasoners from concluding \( p \) from \( q \) (because it is also possible that \( p \) is false), and from concluding \( q \) is false from \( p \) is false (because it is also possible that \( q \) is true).

It is worth noting that this developmental trend is observed when children reason from artificial conditional relations for which they have no previous knowledge available. When reasoning from familiar relations, even young children aged 5–7 years are able to find cases of the form \( \neg p q \) from what Markovits and Barrouillet (2002) called the complementary class. So, they can for example easily conclude from the relation “If I push the button, the light will be on” that if the light is off, the button has not been pushed (i.e., an MT inference). Several studies has even demonstrated that, for some limited kinds of premises like “if an animal is a dog, then it has legs”, young children are able to evoke alternatives of the form \( \neg p q \) (e.g., cows have legs too) that prevent them from endorsing AC and DA inferences and to conclude that an animal that has legs is necessarily a dog (AC) or that an animal that is not a dog has no legs (DA; Bucci, 1978; Markovits, Fleury, Quinn, & Venet, 1998; Markovits et al., 1996). It has also been demonstrated that the availability of alternatives has a strong effect on correct uncertainty responses to AC and DA for causal conditionals. This effect of availability of alternatives, which has been documented in adults (Cummins, Lubart, Alksnis, & Rist, 1991), has been observed in adolescents (Barrouillet, Markovits, & Quinn, 2001) and even in children. Janveau-Brennan and Markovits (1999) reported that as soon as 10 years of age, children give correct uncertainty responses to AC and DA when reasoning from causal relations with many possible alternatives (e.g., “If someone drops a pot, then there will be a noise”). Thus, even in young children, the availability and evokability of semantic and episodic knowledge in long-term memory plays a major role in inference production. This creates a sharp contrast between reasoning from artificial and familiar conditional relations in which the conjunctive level is not observed. However, with both familiar and artificial relations, it seems that the final level at which MP and MT are produced while AC and DA are given uncertainty responses (i.e., the conditional level) is preceded by a developmental level at which all the four inferences are endorsed, reflecting a biconditional reading of \( I \).

By now, we have addressed developmental data from tasks in which participants are asked to consider the conditional statement as true. Other tasks of interest are those in which the truth-value of the conditional is under inquiry. This is the case of the truth-table task in which participants have to evaluate the truth-value of a conditional from the four possible logical cases \( pq \), \( \neg p q \), \( p \neg q \), and \( \neg p \neg q \). Adult studies using this task have revealed a striking phenomenon: a vast majority of adults exhibit what has been called a defective truth-table (Wason & Johnson-Laird, 1972). They deem the conditional true for the \( pq \) case, false for the \( \neg q \) case, but consider that the conditional is neither true nor false when the antecedent is false (i.e., for the \( \neg p q \) and \( \neg p \neg q \) cases). The developmental approach sheds light on this phenomenon by revealing that the defective table is a developmental achievement (Barrouillet, Gauffroy, & Lecas, 2008). When presented with a truth table task, 8-year-
old children exhibit the same conjunctive response pattern already observed when evaluating possi-
ble responses to AC and DA when reasoning from causal relations with many possible alternatives (e.g., “If someone drops a pot, then there will be a noise”). Thus, even in young children, the availability and evokability of semantic and episodic knowledge in long-term memory plays a major role in inference production. This creates a sharp contrast between reasoning from artificial and familiar conditional relations in which the conjunctive level is not observed. However, with both familiar and artificial relations, it seems that the final level at which MP and MT are produced while AC and DA are given uncertainty responses (i.e., the conditional level) is preceded by a developmental level at which all the four inferences are endorsed, reflecting a biconditional reading of \( If \).

Interestingly, the truth table task also reveals a developmental level corresponding to the biconditional reading described above. In our studies, as children did, adolescents mainly deemed the conditional true for the \( pq \) case and false for both the \( \neg q \) and the \( \neg p q \) cases, but they considered its truth-value as indeterminate for the \( \neg p \neg q \) case. This interpretation, that has been called defective biconditional by Evans and Over (2004), matches the biconditional level described above because it suggests that the underlying representation takes into account both \( pq \) and \( \neg p \neg q \) cases while excluding \( \neg p q \) and \( p \neg q \) cases that are consequently assumed to make the conditional false. It is only in
In adulthood that the \( \neg p \) case is no longer considered as making the conditional false but as leaving its truth-value indeterminate. The false response is then restricted to the \( p \land q \) case, resulting in the defective truth table described above in which both \( p \) cases leave the truth-value of the conditional indeterminate (Fig. 1).

In a recent study (Gauffroy & Barrouillet, 2009), we observed that these three levels (i.e., conjunctive, defective biconditional, and defective conditional) are also reflected in the evaluation of the probability of a conditional. In this kind of task, participants are for example presented with a pack of either yellow or red cards that have either a circle or a diamond printed on them (say one yellow circle, four yellow diamonds, 16 red circles, and 16 red diamonds), and they are asked to evaluate the probability that a claim like “If the card is yellow then it has a circle printed on it” is true for a card drawn at random from the pack. Evans et al. (2003) as well as Oberauer and Wilhelm (2003) observed that a majority of adult participants evaluate the probability of the conditional as the conditional probability \( P(\neg q/p) \) that is equal to \( P(p \land q)/[P(p \land q) + P(p \land \neg q)] \). They consider only the \( p \) cases (i.e. the yellow cards) as relevant and evaluate the probability of the conditional as the probability to find a card with a circle among the yellow cards. What our developmental study revealed is that this response is preceded by at least two other developmental levels. The first level, observed in young adolescents, consists in evaluating the probability of the conditional as the probability of the conjunction of \( p \) and \( q \) (i.e., the probability of finding a yellow card with a circle among all the cards of the pack). Of course, this level echoes the conjunctive level that we have already encountered, though at earlier ages, in the other tasks. The second level, predominant in old adolescents, consists in disregarding the cases that are considered as irrelevant at the defective biconditional level (i.e., the \( p \land \neg q \) cases, the black cards with a diamond) and to calculate the probability to find a yellow card with a circle among the remaining cards (i.e., \( P(p \land q)/[P(p \land q) + P(\neg q) + P(p \land \neg q)] \)). As we have seen, the final level reached in adulthood consists in disregarding all the \( p \) cases, as in the truth table task, a strategy resulting in evaluating the conditional probability.

To conclude, developmental studies using a variety of tasks provide us with the coherent picture of a strong development of conditional reasoning from childhood to adulthood following a fixed hierarchy of levels that seems to reflect the increasing complexity of the underlying representations. In all the tasks, the responses that are typical in adulthood are never predominant in childhood and adolescence. Thus, any theory of conditional reasoning must not only account for adult performance, but also for the different developmental levels and their succession. In the following, I assess in this way some of the recent dual-process accounts of conditional reasoning, with the general hypothesis that System
2 should exhibit stronger developmental changes than System 1. In the next section, I will comment on this general hypothesis before presenting the different dual-process theories.

The development of System 1 and System 2

The distinction between System 1 and System 2 is based on a series of contrasts concerning both the nature and the functional properties of the two systems. While System 1 is often assumed to be evolutionary old, shared with animals, unconscious, implicit, contextualized, based on beliefs and linked with emotions, System 2 would be evolutionary recent, unique to humans, conscious, explicit, decontextualized, abstract and thus without direct link with emotion. Consequently, System 1 would be fast, parallel, automatic, and effortless whereas System 2 would be slow, sequential, controlled, and effortful. System 2 would thus strongly depend on fluid intelligence and working memory capacity, whereas System 1 would be independent of these capacities. Because it is well known that cognitive control and working memory capacity strongly evolves with age (Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009; Case, Kurland, & Goldberg, 1982; Diamond, 2006; Gathercole, Pickering, Ambridge, & Wearing, 2004; Zelazo, Müller, Frye, & Marcovitch, 2003), it can be expected that there are important developmental changes concerning System 2 capacity and functioning.

Because System 1 is independent from general intelligence and working memory, it could be expected to be relatively independent of age as the unconscious and implicit processes on which it relies (Vinter & Perruchet, 2000). However, several studies using tasks issued from the “heuristic and biases” literature have reported age-related increase in the efficiency of System 1 (Davidson, 1995; Jacobs & Potenza, 1991; Markovits & Dumas, 1999; Morsanyi & Handley, 2008; Reyna & Ellis, 1994). I have already addressed this question elsewhere (Gauffroy & Barrouillet, 2009) and I will not reiterate my arguments here, but I argued that there are good reasons to doubt such a strong developmental increase of System 1. The results evoked by some of these studies proved difficult to replicate, significant changes in heuristic use have more often been described during childhood than during adolescence, suggesting that if there is a development of System 1, this system reaches its maturity level earlier than System 2, and most of the reported developmental trends in System 1 seem to rely on social knowledge and stereotypes as they are more often related to social than non-social contents. For example, Morsanyi and Handley (2008) noted that the heuristic they studied (the conjunction fallacy, the if-only fallacy, the sunk cost fallacy or the belief bias) at least partly depend on demanding processes such as retrieving and integrating relevant knowledge in the representation of the task. They concluded that instead of challenging the idea that System 1 is immune from developmental changes, their results challenge the idea of non normative responses being necessarily the result of System 1. One of the most relevant and comprehensive developmental studies concerning the two systems is probably Klaczynski (2001) who studied normative and non normative responses through 17 different measures from a battery of reasoning and decision making tasks. It turned out that none of these measures indicated an age-related increase in non-normative responses. Factors analyses indicated that analytic reasoning related positively with age, whereas a factor related to System 1 assessing non-normative biases related negatively to age. Thus, even if age-related decline in System 1-based responses is far from being a universal phenomenon and that striking examples of development of intuitive reasoning have been provided (Brainerd, Reyna, & Ceci, 2008; Reyna & Brainerd, this issue; Reyna & Ellis, 1994), it can be safely assumed that developmental changes are more important in System 2 than in System 1 that remains relatively immune to age-related changes, at least from the elementary school period to adulthood. In the following, the main dual-process approaches are assessed in the light of these developmental trends.

The heuristic–analytic approach

Evans (1984, 1989) pioneered the domain of dual-process theories of reasoning by suggesting a distinction between heuristic and analytic processes that broadly matches the contrast outlined above
between System 1 and System 2. In Evans' (1989) theory, heuristic processes were conceived of as pre-conscious and essentially pragmatic. Their role is to direct attention and select the information that will be considered as relevant for solving the problems participants are confronted with in laboratory experiments. Analytic processes, that are assumed to underpin logical thinking, would apply to the representation constructed by these heuristic processes. The cognitive biases observed in many reasoning experiments were assumed to result from the heuristic processes that fail to select some relevant information for the task at hand or select normatively irrelevant features. Thus, whatever the quality of the analytic processes, biases would inevitably result if these analytic processes work on logically irrelevant features unconsciously selected by heuristic processes. This mechanism can be illustrated with Wason's indicative selection task. In this task, people are presented with a set of cards with a capital letter printed on one side and a single figure number printed on the other side, and are told that these cards were created according to the following rule: “If there is an A on one side of the card, then there is a 3 on the other side of the card”. Four cards are lying on the table that show an A, a D, a 3, and a 7. The task is to select the cards, and only the cards, that need to be turned over in order to know if the rule is true or false. A very frequent response consists in selecting the cards A and 3 (i.e., the \( p \) and \( q \) cards), whereas the correct response, according to formal logic, would be A and 7 because \( p \land \neg q \) (i.e., an A with another digit than 3) is the sole case that could falsify the conditional. The heuristic–analytic account of the modal response (i.e., \( p \) and \( q \) cards) proposed by Evans (1989) was to assume that card choices are dominated by heuristic processes that influence the perceived relevance of the cards, whereas analytic processes would remain silent. Among these heuristic processes, an if-heuristic would direct attention towards cases where the antecedent is true (i.e., the A card), and make them appear much more relevant than those where the antecedent is false, whereas a matching-heuristic would cue the cards that are referred to in the sentence (i.e., the A and the 3).

In an extended version of his heuristic–analytic model, Evans (2006, 2007) endorses a default-interventionist conception of the relationships between heuristic and analytic processes (Fig. 2). This means that the heuristic system is the default system, whereas the analytic processes are optional and may or not intervene to modify the representations and responses cued by the heuristic processes.\(^3\) The function of the heuristic system would be to deliver relevant content into consciousness by constructing the most plausible model according to previous knowledge, tasks features, and the goals pursued by the reasoner. It is worth noting that the default mental models constructed by heuristic processes are not semantic, as in Johnson-Laird’s mental model theory, but epistemic. Indeed, heuristic models not only represent possibilities as in the mental model theory, but are also contextualized and pragmatically rich, representing our beliefs about them and our attitudes toward them. These heuristic processes set up default responses that are selected unless the analytic system intervenes to reject, modify, or replace the default representation. Importantly, a satisficing principle determines that this default model is accepted unless there are good reasons and motivations to behave differently. This means that the intervention of analytic processes and deliberative thinking is far rarer as usually assumed by folk psychology. Among the factors that could facilitate the intervention of analytic processes are explicit instructions to reason logically, sufficient time available to carefully evaluate the default responses, and sufficient intellectual capacities to supersede their attractiveness.

### Conditionals and the heuristic–analytic theory

The heuristic–analytic model can be seen as a processing model within a larger theoretical framework called by Evans (2007) hypothetical thinking theory. Evans (2007, p. 17) defines hypothetical thinking as this “thought that requires imagining of possible states of the world”. Of course, conditional reasoning is one of the main and most important forms of hypothetical thinking. Introducing a

\(^3\) As noted by Evans (2007), the idea that the analytic system could not intervene at all is strictly incorrect. The analytic system is always involved because, even when it leaves unchanged the representation constructed by heuristic processes, some minimal analytic processing of this representation is needed to generate a response appropriate to the instructions related to the task at hand. This is what would happen when the modal response is given to the indicative selection task described above. The analytic processes accept the default selection of the \( p \) and \( q \) cards that have been cued by heuristic processes.
sentence of the form If $p$ then $q$ would necessitate to suppose $p$ and to believe that $q$ is a probable consequence of this supposition. Thus, within the hypothetical thinking theory, the conditional is suppositional in nature and based on what philosophers call the Ramsey test (Evans & Over, 2004, 2007; Evans, Over, & Handley, 2005). The Ramsey test is a procedure by which people hypothetically add $p$ to their stock of knowledge and argue on that basis about $q$. For example, for evaluating the conditional “if Queen Elizabeth dies, then Prince Charles will become King”, people would perform a kind of thought experiment in which they imagine a world in which Queen Elizabeth is dead, evaluating the likelihood of Prince Charles becoming king (Evans, 2007). In other words, the Ramsey test is a mental simulation the purpose of which is to test the relation between $p$ and $q$ either by retrieving belief about this relation from long-term memory (LTM) or by simulating the possibility of $q$ when supposing $p$. Establishing such a belief relation would result in an epistemic mental model of the conditional. In the example, the conditional “if Queen Elizabeth dies, then Prince Charles will become King” would lead to the following epistemic model

$$
\text{Queen Elizabeth dies} \rightarrow .95 \text{ Prince Charles becomes King}
$$

where $\rightarrow$ represents a conditional belief relation and .95 indicates a high degree of belief with 1 corresponding to certainty (see also Evans & Over, 2004).

There are two main arguments in favor of the suppositional conditional. First, as we have seen, adults exhibit defective truth tables of the conditional in truth table tasks. Second, when asked to evaluate the probability of the conditional, they produce the conditional probability. According to the suppositional conditional theory, the truth value gap for $\neg p$ cases in the defective truth-table (i.e., the conditional is neither true or false for these cases) occurs because of the Ramsey test, which is similar to the if-heuristic described in the first versions of the heuristic–analytic theory. Indeed, adding $p$ to the stock of knowledge, the Ramsey test acts as an if-heuristic, leading people to disregard the $\neg p$ cases that are mainly judged as irrelevant to the truth of the conditional. Thus, as illustrated in Fig. 3 reproduced from Evans (2007), the heuristic processes would strongly cue $p$ cases as relevant and $\neg p$ cases as irrelevant. When solving the truth table task, the analytic system would then process the relevant

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Fig. 2. The revised heuristic/analytic model. Reproduced by permission of the Psychonomic Society from “The heuristic–analytic theory of reasoning: Extension and evaluation”, by Evans, 2006, Psychonomic Bulletin & Review, 13.
cases (i.e., $p\ q$ and $p\ \neg q$) and classify them as true or false, leading to the defective truth table. In the same way, the Ramsey test leads directly to the prediction that people will evaluate the probability of the conditional as the conditional probability $P\ (q/p)$. Because people focus on the $p$ possibilities, the probability for the conditional to be true is the ratio between those cases that make it true (i.e., $p\ q$) and the relevant cases (i.e., $p\ q$ and $p\ \neg q$), a ratio that corresponds to the probability that $q$ occurs when $p$ occurs, that is the conditional probability $P\ (q/p)$. When evaluating a conditional, people compare the probability of the $p\ q$ cases with that of the $p\ \neg q$ cases. To the extent that $p\ q$ is judged more probable than $p\ \neg q$, the conditional probability of $q$ given $p$ is high and a high probability is assigned to the conditional $if\ p\ then\ q$. This conditional probability corresponds to the degree of belief which is part of the epistemic model provided by heuristic processes.

The test of development

There is no doubt that the suppositional conditional provides us with a convincing account of two main facts in conditional reasoning that are the defective truth table and the conditional probability. However, what the test of development will make clear is that the heuristic–analytic theory does not seem to be a good candidate for the role of the processing model in which the suppositional approach of the conditional could be implemented. The dual-process theory outlined above encounters three main problems. The first is that it predicts developmental trends on the truth table task and the probability task with abstract conditionals that strongly differ from what is usually observed. Second, this dual-process theory has difficulties in accounting for some frequent responses produced by adults in the probability task. The third problem results from the two others and concerns the nature of the heuristic processes involved in conditional reasoning and the precise nature of the representations they construct.

Let us begin by the developmental predictions that can be drawn from the heuristic–analytic theory of conditional. As we noted above, this theory assumes that heuristic processes cue those cases that are relevant (i.e., $p$ cases) and those that are irrelevant ($\neg p$ cases) for evaluating the conditional, as Fig. 3 makes clear. This is coherent with the theoretical framework described by Evans (2007). The distinction between what is relevant and irrelevant in the suppositional account of conditional would be a direct consequence of the Ramsey test, which is explicitly linked with the if-heuristic of the former
versions of the theory.\textsuperscript{4} However, if we assume that analytic processes should be more affected by development than heuristic processes, this theory predicts larger age-related changes in the way analytic processes classify relevant cases as true or false than in the way heuristic processes cue cases as relevant or irrelevant. Unfortunately, all the developmental studies reveal the exact opposite. As we have seen above, considering both \(\neg p\) cases as irrelevant for the truth-value of the conditional is a late developmental achievement preceded by different levels in which the partition between what is relevant and irrelevant strongly evolves with age. Such dramatic developmental changes are not expected from heuristic processes. By contrast, within the relevant cases, the partition between true and false does not evolve with age: those cases that are considered as relevant at all the ages studied (i.e., \(pq\) and \(p \neg q\)) are always classified in the same way as true and false respectively. Thus, the idea that the partition between relevant and irrelevant cases would result from heuristic processes whereas analytic processes would classify the relevant cases is contradicted by developmental studies. The same is true for the probability task. If heuristic processes cued the relevant cases to be taken into account in evaluating the probability of the conditional (i.e. \(pq\) and \(p \neg q\)), the response corresponding to the conditional probability should be observed early in development and remain quite stable through age. However, exactly in the same way as the defective truth table, this response is a late developmental achievement preceded by conjunctive responses in which both \(\neg p\) cases are considered as relevant for the evaluation, and then biconditional defective responses in which \(\neg pq\) cases are still considered as relevant and involved in the evaluation. Once more, the developmental studies contradict the idea that the relevant and irrelevant cases are cued by heuristic processes.

Second, the heuristic–analytic theory has also difficulties in accounting for a specific response given by a substantial minority of adults to the probability task. Namely, these participants give the probability of the conjunction of \(p\) and \(q\): \(P(pq)\). This conjunctive response is explained by Evans et al. (2003; Evans, 2007) as an incomplete Ramsey test. Shallow processors would cut short the Ramsey test and stop at the \(pq\) cases, while conditional probability responders would correctly compare the \(pq\) with the \(p \neg q\) frequencies. This interpretation is corroborated by the fact that conjunctive responders to the probability task are lower in general intelligence (Evans, Neileis, Handley, & Over, 2007). Though this explanation seems compelling, it is both empirically and theoretically problematic. As we have argued elsewhere (Gauffroy & Barrouillet, 2009), if conjunctive responses resulted from an incomplete Ramsey test, this incomplete test should result in a specific response when evaluating the probability for the conditional to be false. Namely, shallow processors should engage in the Ramsey test by evaluating the \(p \neg q\) frequency and stop the process at this level, giving \(P(p \neg q)\) as the probability for a conditional to be false in the same way as they give \(P(pq)\) as the probability for a conditional to be true. However, we practically never observed this response in Gauffroy and Barrouillet (2009), whereas the conjunctive response was frequent when evaluating the probability of the conditional to be true. Moreover, Evans’ explanation of the conjunctive responses is problematic at a theoretical level. If it is assumed that these responses result from an incomplete Ramsey test related with lower general intelligence, this suggests that the Ramsey test involves some controlled and demanding processes necessarily pertaining to the analytic system. However, imagining the Ramsey test as an analytic process does not fit very well with the ideas that it is related to the \textit{if-heuristic}, as Evans and Over (2004) and Evans (2007) suggest, and provides individuals with intuitions of relevance that are associated with heuristic processes in the heuristic–analytic theory.

This leads to the third problem, which concerns the nature of the epistemic model provided by heuristic processes. It remains unclear what this model is for the conditional in Evans’ theory. On the one hand, it could be assumed that this model represents the belief on a conditional relation between the antecedent and the consequent, as in the example above concerning the royal family. It can easily be imagined that associative memories and pragmatic knowledge provide us with something like a degree of belief through unconscious processes. It could also be imagined that, in the case of abstract conditionals with artificial relations that people are asked to consider as true for experimental purposes, the degree of belief is set to a high value close to 1. However, this degree of belief, which is

\textsuperscript{4} Evans and Over (2004, p. 76) present the \textit{if-heuristic}, which operates “as an unconscious and rapid process” to focus attention on \(p\) and away from \(\neg p\), as fully consistent with the suppositional theory and its Ramsey test, which is “so basic to an understanding of ‘if’ as to direct attention in this automated fashion”.

part of the epistemic model, is what the Ramsey test is intended to evaluate. As a consequence, the Ramsey test would belong to the heuristic processes, conclusion that encounters both empirical and theoretical problems. If the Ramsey test belonged to the heuristic processes, it should not be influenced by individual differences in general intelligence, as Evans et al. (2007) demonstrated. At a theoretical level, the suppositional conditional is based on the Ramsey test that permits to introduce conditionals by assessing the situations in which a conditional can be asserted or not. However, Evans (2007) assumes that conditionals are naturally introduced as result of hypothetical thinking, which "requires use of the analytic system (System 2)" (Evans, 2007, p. 17). This leads to the conclusion that the Ramsey test involves System 2. On the other hand, it could also be argued that the model provided by heuristic processes consists in a representation akin to the initial model of the mental model theory in which the affirmation of \( p \) and \( q \) co-occur. The Ramsey test, understood as an analytic process, would sequentially complete this representation by evaluating the likelihood of \( q \) within the context of \( p \). However, in this case, the suppositional theory is turned into the standard mental model theory in which "the antecedent refers to a possibility, and the consequent is interpreted in that context." (Johnson-Laird & Byrne, 2002, p. 649).

To summarize, although both theories have indisputable strengths, it seems that the suppositional theory of if (Evans & Over, 2004) and the heuristic–analytic theory (Evans, 2006, 2007) do not fit very well together. When focusing on the former, it becomes difficult to disentangle the heuristic from the analytic processes, and when focusing on the latter, the Ramsey test, which is the core of the suppositional theory, becomes an optional processing step that can be prematurely interrupted by shallow reasoners. Moreover, the developmental predictions that could be drawn from these approaches are contradicted by empirical findings that reveal a strong developmental change in the nature of the information considered as irrelevant for the conditional.

The probabilistic/mental model approach

As it became increasingly evident that the standard logic could not be considered as a normative and even a descriptive theory for human reasoning, several authors rejected the mental model theory, which was assumed to be based on standard logic, and suggested that a probabilistic approach would give a better account (Liu, Lo, & Wu, 1996; Oaksford & Chater, 2001; Oaksford, Chater, & Larkin, 2000). For example, Oaksford and Chater (2001) claimed that the inferential processes in conditional reasoning are based on estimates of the conditional probability of the conclusion given the categorical premise, and proposed a computational model simulating human inferential reasoning. These estimates of conditional probabilities would be reached by interrogating prior knowledge and beliefs about the conditional relation stored in LTM. For example, when evaluating if the conclusion Tweety flies can be drawn from the premises If an animal is a bird, then it flies and Tweety is a bird (an MP argument), people would interrogate their knowledge concerning birds to assign a probability to if \( x \) is a bird, \( x \) flies.

The conclusion Tweety flies would be endorsed with a degree of belief corresponding to this probability. In our example, this probability should be high, but the conclusion could be defeated if one learns that Tweety is an ostrich.

This theoretical proposal contrasts with the mental model theory (Johnson-Laird & Byrne, 1991, 2002) in which the inferential process is based on the search of counterexamples. People are assumed to construct mental models of what is possible given the truth of the premises, and to draw a putative conclusion by reading out these representations. If a conclusion holds in all the models constructed and that no counterexample can be found, then this conclusion is taken as certain, whereas if it only holds in some but not all models, it will be considered as only possible. Thus, from the premise If an animal is a bird, then it flies, people would construct an initial model of the form bird – fly from which it can be concluded that Tweety, which is a bird, can fly. If no counterexample to this model is found (i.e., an instance of a bird that cannot fly), the conclusion would be endorsed with certainty, and not with an associated probability, whereas if such a counterexample is found, the conclusion should be rejected and considered as possible, but uncertain.

Verschueren, Schaeeken, and d’Ydewalle (2005) proposed to bring together the probabilistic and the mental model accounts of conditional reasoning in a dual-process perspective. They noted that the
reasoning process based on probabilities is heuristic in nature, as suggested by Oaksford and Chater (2001). These processes of likelihood estimation are fast, contextualized, relying on associative knowledge, and based on familiarity estimates rather than on conscious recollection of a range of relevant situations. By contrast, the construction of mental models strongly relies on working memory (Barrouillet & Lecas, 1999). The manipulation of these models in order to produce conclusions as well as the search for counterexamples are controlled and deliberative, reflecting analytic processes. In line with this conception, Verschueren, Schaeken, and d’Ydewalle (2005) verified with causal conditionals that when people produce fast responses, most probably based on heuristic processes, variations in their responses were better explained by variations in likelihood information, whereas slow responses, resulting most probably from the intervention of analytic processes, depended on the availability of counterexamples. They also established that when analytic processes are facilitated by the availability of strongly associated counterexamples, analytical reasoning became more important and could override the conclusions produced by probability estimates.

In a further work, Verschueren and Schaeken (2010) specified this conception by describing three different levels at which the heuristic/analytic bipolarity can be distinguished in everyday conditional reasoning. The highest level concerns the decision whether to incorporate background information or to decontextualize the problem and exclusively rely on analytic processes. If it is decided to integrate background information, the authors assume that there are two ways for taking knowledge into account, either by relying on probabilistic information or by searching for counterexamples. It can be seen that this level corresponds to the distinction proposed by Verschueren, Schaeken, and d’Ydewalle (2005) between probabilistic and mental model reasoning, which is here nested in a larger framework. At the lowest level, these counterexamples can be accessed either through strategic cue-based retrieval (i.e., through analytic processes), or automatic spreading activation (a heuristic process).

Interestingly, the idea to bring together probabilistic and mental model approaches within a dual-process account of conditional reasoning has not remained isolated. Oaksford and Chater (2010) have suggested that mental models could constitute the algorithmic level of their computational probabilistic account of conditional reasoning. As we noted above, the probabilistic approach assumes that conditional reasoning is based on conditional probabilities that are defined by the Ramsey test. However, Oaksford and Chater (2010) note that the mental processes underlying the Ramsey test have been yet poorly specified. They suggest that people interrogate their prior beliefs by clamping on or clamping off the units corresponding to the categorical premise and conclusion.5 However, a system is needed to record and store the outcomes of these retrieval processes from LTM, especially when more than one possibility has to be taken into account, as it is often the case for conditional reasoning. One way to encode and store this information would be to construct annotated mental models in working memory. When several possibilities are explored, these models could be integrated in working memory to derive a response. In this framework, the processes of activation and retrieval of associative world-knowledge from LTM can be considered as System 1 processes, whereas the storage and manipulation in working memory of the mental models constructed with the retrieved information can be considered as a System 2 process (Fig. 4). Interestingly, Oaksford and Chater (2010) assume that the level of activation of the unclamped unit (the target) in mental models can be interpreted as a real posterior probability given the activation of the clamped units. For example, when given the categorical premise $p$ for a MP inference, the level of activation of the associated unit $q$ that enters working memory through spreading activation processes reflects the conditional probability $P(q/p)$. This echoes the epistemic models described by Evans and Over (2004) in which the strength of the conditional belief relation is represented. Thus, Oaksford and Chater’s (2010) proposal provides an elegant account of the way mental models could be constructed and reflect beliefs and attitudes, as it was already suggested by Markovits and Barrouillet (2002) who assumed that mental models are constructed by activating knowledge from long-term memory, thus bringing about a rich linguistic and pragmatic experience.

5 Clamping on a given unit refers to its representation in working memory, which activates related knowledge from long-term memory, whereas clamping off consists in representing its negation. This process is akin to the construction of mental models in working memory, the tokens of these models activating knowledge from long-term memory as in Markovits and Barrouillet’s (2002) theory.
Oaksford and Chater (2010) distinguish three possibilities for interrogating the network. At a first and basic level, all people would do is to clamp on or off the unit corresponding to the categorical premise (i.e., \( p \), \( q \), \( \neg p \), and \( \neg q \) for MP, AC, DA, and MT inferences respectively). In this case, a Ramsey test is performed and the target activation read off. A second more elaborated possibility consists in clamping on or off both units corresponding to the categorical premise and to the target of the inference (i.e., \( p \) and \( q \) for MP and AC, and \( \neg p \) and \( \neg q \) for DA and MT inferences), whereas in a third possibility, people would explore the possibilities where inferences cannot be endorsed, retrieving disabling conditions for MP and MT (e.g., for the causal conditional if the key is turned, then the car starts, an empty gas tank) and alternative causes for AC and DA (e.g., for the same conditional, the car has been jump-started). In the former cases, an empty gas tank prevents concluding that the car starts from the fact that the key has been turned, and to conclude that the key has not been turned from the fact that the car does not start. In the latter case, the possibility of a jump start prevents concluding that the key has been turned.

Fig. 4. Constraint satisfaction network for two alternative conditionals and their disabling conditions according to Oaksford and Chater (2010) model. The connections with arrowheads indicate facilitatory connections and those with circular ends indicate inhibitory connections. Within the network that stores world knowledge (WK) in long-term memory (LTM), the consequent \( q \) is activated by the antecedent \( p \) as well as by the alternative cause \( r \), and inhibited by the disabling conditions \( d_1 \) and \( d_2 \). For example, turning the key \( (p) \) is related with the car that starts \( (q) \), a result that can also be produced by a jump start \( (r) \), and blocked by disabling conditions like an empty gas tank \( (d_1) \) or the battery is flat \( (d_2) \). The inhibitory relation between \( p \) and \( r \) refers to the fact that alternative causes are usually only evoked when the primary cause \( p \) is absent. When encountering the minor premise of an MP inference (i.e., \( p \)), people would clamp on the corresponding unit \( p \) in working memory (WM), which cues the \( p \)-node in the network that activates in turn the \( q \)-node. The result is represented in WM as an annotated oriented mental model relating the clamped unit \( p \) represented as normal text to the target of the inference, \( q \), in italics. The diagram represents also the interrogation of the network for cases in which the opposite conclusion can be reached. The \( q \) unit is clamped off (i.e., \( \neg q \)) while the \( p \) unit is clamped on in the second row (second model) in WM. Because the disabling conditions \( d_1 \) and \( d_2 \) are no longer inhibited by the \( q \)-node and activated by the \( p \)-node, \( d_1 \) is added to the model in WM (represented in italics as an annotation to the model). For example, the first model represents the relation between the key turned \( (p) \) and the car that starts \( (q) \), whereas the second model represents the key turned that fails to start the car \( (p \) and \( \neg q) \), thus leading to the conclusion that the gas tank can be empty \( (d_1) \). Reproduced by permission of Oxford University Press from Cognition and conditionals: Probability and logic in human thinking by Oaksford and Chater (2010), p. 315.

Oaksford and Chater (2010) distinguish three possibilities for interrogating the network. At a first and basic level, all people would do is to clamp on or off the unit corresponding to the categorical premise (i.e., \( p \), \( q \), \( \neg p \), and \( \neg q \) for MP, AC, DA, and MT inferences respectively). In this case, a Ramsey test is performed and the target activation read off. A second more elaborated possibility consists in clamping on or off both units corresponding to the categorical premise and to the target of the inference (i.e., \( p \) and \( q \) for MP and AC, and \( \neg p \) and \( \neg q \) for DA and MT inferences), whereas in a third possibility, people would explore the possibilities where inferences cannot be endorsed, retrieving disabling conditions for MP and MT (e.g., for the causal conditional if the key is turned, then the car starts, an empty gas tank) and alternative causes for AC and DA (e.g., for the same conditional, the car has been jump-started). In the former cases, an empty gas tank prevents concluding that the car starts from the fact that the key has been turned, and to conclude that the key has not been turned from the fact that the car does not start. In the latter case, the possibility of a jump start prevents concluding that the key has been turned.
from the fact that the car starts, and that the car will not start from the fact that the key has not been turned.

**The test of development**

Most of the assumptions of the probabilistic/mental model approach echo developmental theories and findings. As we noted earlier, Markovits and Barrouillet (2002) suggested a modified mental model theory for conditional reasoning in which mental models are constructed through the retrieval from LTM of information related to the conditional relation. They assumed that both the relation between the antecedent and the consequent and the information conveyed by the minor premise would trigger retrieval from three classes of cases. The first class, named complementary, concerns those cases in which the objects or events concerned are different from those evoked in both the antecedent and the consequent. The second class, the alternative class, concerns objects/events different from \( p \) that share the same relation to \( q \) as \( p \) does. Finally, a third class could be accessed, containing disabling conditions that allow the relation between \( p \) and \( q \) to be violated. Several developmental studies showed that these three classes are accessed in this order at different developmental levels (Barrouillet & Lecas, 1998, 2002; Markovits, 1993). Moreover, it was assumed that mental models for conditional are akin to the relational schemas described by Halford, Wilson, and Phillips (1998) including a representation of the relation between the elements and its direction, as well as the structure of the represented situation in the environment. Markovits and Barrouillet (2002) observed that, at the developmental level, the complementary class was the first class to be accessed whereas retrieving cases from the other two classes often required higher developmental levels. These echoes the gradation of the three possibilities for interrogating the network evoked by Oaksford and Chater (2010), with the first possibility corresponding to the mere activation produced by the conditional relation, the second possibility corresponding to the search from the complementary class, whereas the third possibility, which consists in searching for disabling conditions and alternative cases, would be the more complex. In the same way, like Oaksford and Chater’s (2010) proposal, Markovits and Barrouillet’s (2002) approach assumes that pragmatic modulation by world knowledge affects the content of working memory in an inference by inference basis because the minor premise provides the main cue for the retrieval process. For example, the minor premise for DA (i.e., \( \neg p \)) can efficiently cue the retrieval of \( \neg p \) cases from the complementary class, but should be less efficient in activating disabling conditions of the form \( p \) \( \neg q \) or alternative cases of the form \( \neg p q \), except if the search is conducted within a context in which \( q \) is assumed to occur. Thus, in both theories, “there is no single representation built up of the conditional premise that serves to identify all the inferences someone will and will not draw” (Oaksford & Chater, 2010, p. 323).

Beyond these commonalities, one of the main limitations of the probabilistic/mental model approach is its limitation to everyday conditional reasoning. It is only when reasoning about familiar situations that mental models can be constructed by interrogating world-knowledge network and annotated with conditional probabilities. Of course, Oaksford and Chater (2010) assume that even when abstract materials are used, all inference involves accessing world knowledge in LTM, and a representation as depicted in Fig. 4 would be constructed with the parameters of the model fixed by analogy to prior conditional knowledge. However, the recourse to a process of analogy to account for reasoning with abstract material appears as a kind of sleight of hand and developmental findings do not corroborate this conception. It is possible that adults are able to use such complex analogies, but developmental studies suggest that children’s conditional reasoning is based on poorer representations when reasoning with abstract material. Whereas even young children can usually construct two models (i.e., \( p q \) and \( \neg p \neg q \)) when reasoning on familiar contents, thus producing the four inferences (see Markovits and Barrouillet (2002), for a review), their representation seems to be limited, with unfamiliar relations, to a single model \( p q \) supporting the sole MP and AC inferences (Barrouillet et al., 2000). Moreover, the developmental pattern observed in inference production with unfamiliar relations strongly reflects an increase in the number of models that can be constructed (Barrouillet et al., 2000) rather than the process of averaging the activation levels of the inference target in the different models in which it is represented, as suggested by Oaksford and Chater (2010).
Nonetheless, it should be noted that Oaksford and Chater (2010, p. 330) leave open the possibility that the working memory control system might “develop into a system capable of independent operation, which could underpin our logical abilities”, because what is stored in working memory are the representations of the permissible and impermissible possibilities according to a conditional, which corresponds to the mental model theory assumption that reasoning is thinking about possibilities (Johnson-Laird, 2006). Thus, the need to store and manipulate possibilities could explain why a reasoning system like mental models may develop over the lifespan. This is in line with the developmental study we reviewed earlier, which have repeatedly shown that developmental trends in a series of tasks conform to what could be expected from an age-related increase in the number of models that can be constructed and manipulated in working memory.

Another point that does not fit very well with developmental findings is the idea that probabilistic estimations pertain to System 1. It is coherent to assume that most of the retrievals from long-term memory rely on associative and automatic processes that pertain to System 1, whereas manipulating mental models in working memory involves System 2. However, it is less clear that these retrieval processes in themselves are sufficient to produce a representation of probabilities in working memory, as it is suggested by Verschueren, Schaeken, and d’Ydewalle (2005), at least implicitly, and more explicitly by Oaksford and Chater (2010). If this was the case, System 1 would provide, early in development, children with intuitions about what the probability of a conditional is. For example, Oaksford and Chater (2010) assume that their possibility 1 for interrogating the world-knowledge network, which is the most basic of the system 1 processes, consists in a Ramsey test providing conditional probabilities. However, we have seen that the output of the Ramsey test (i.e., the conditional probability as the probability of the conditional) is a late achievement practically never observed before adulthood, and that the task of evaluating the probability of a conditional, which is probably the better estimation of these probabilistic intuitions, develops following the same levels as other conditional reasoning tasks, but slightly later. This is not what would be expected from automatic System 1 processes implemented in basic structures with an old evolutionary history, largely independent from individual differences in fluid intelligence and working memory capacities, and benefitting from early development.

This is not to say, as Oaksford and Chater (2010) suggest, that this kind of probability is not reflected in the level of activation of the target of inferences. In many theories like ACT-R (Anderson, 1993), the probability to retrieve from long-term memory an event q that is associated with p depends on the strength of the link between the two units which determines the level of activation of the unit q in working memory. However, this does not mean that this level is explicitly represented in such a way that it is available for treatment, especially in young children. In other words, it is not because the processes underpinning the construction of mental models in everyday conditional reasoning are probabilistic in nature that the meaning of the conditional is itself probabilistic, or that people manipulate probabilities when evaluating conclusions. What the distinction introduced by Oaksford and Chater (2010) between working memory and LTM processes reveals is that the idea that the conditional is probabilistic at a psychological (i.e. algorithmic) level becomes superfluous. The fact that the System 1 processes that provide the content for the representations manipulated by System 2 are probabilistic in nature does not mean that the resulting representations are themselves probabilistic. It is possible to imagine that the capacity to make this probabilistic information explicit and interpretable is only a late achievement characterizing adulthood. We have already seen that the hypothesis of a Ramsey test pertaining to System 1 does not fit very well with the idea that shallow processors with lower intellectual capabilities would short cut the Ramsey test, thus giving conjunctive responses in the probability task.

In summary, the probabilistic/mental model approach constitutes an advance in our understanding of conditional reasoning by integrating LTM and working memory processes in a unified framework that provides us with an elegant explanation of the pragmatic effects that are ubiquitous in conditional reasoning. It permits us to understand how mental models could capture pragmatic modulations, as it was suggested by Markovits and Barrouillet (2002) and Johnson-Laird and Byrne (2002). This distinction between long-term and working memory processes maintains the idea that a more logical system, capable of independent operations of integration of mental models, production of putative conclusions, and test of these conclusions against possible counterexamples could have evolved or could develop with age. This system that could constitute the basis of our logical abilities goes far
beyond the capacity to evaluate likelihoods from stored world knowledge. Indeed, what any developmental approach has to account for is not only our capacity to reason from everyday situations, but also our more surprising capacity, specific to humans, to reason from abstract premises. Interestingly, this developmental achievement that Piaget described as the transition from concrete to formal thinking through reflective abstraction (Inhelder & Piaget, 1958) seems to be related with metacognitive advances such as the capacity to differentiate logical necessity from empirical truth and the development of a metalogic (Moshman, 1990). It is thus not surprising that metacognitive dual-process theories have been developed.

**The metacognitive approach**

Most of the dual-process theories of reasoning (e.g., Evans, 2006; Verschueren, Schaecken, & d’Ydewalle, 2005) assume that System 1 dominates reasoning as a default system that can, in certain occasions, be overridden by System 2 processes. However, because System 1 is rapid, automatic, and produces contextualized responses without effort or deliberation, the more demanding System 2 would not be engaged unless good reasons and effective triggers. One of the main questions in this respect is to identify these triggers. Both reasoner’s and task characteristics have been advocated as potential factors for a System 2 intervention. For example, as suggested by Evans (2006, see Fig. 2), empirical evidence demonstrates that instructions to reason logically (Daniel & Klaczynski, 2006; Evans, Handley, Neiilens, & Over, 2010; Evans, Newstead, Allen, & Pollard, 1994) and relaxed temporal constraints (Evans & Curtis-Holmes, 2005; see however Evans, Handley, & Bacon, 2009) are conditions susceptible to facilitate a System 2 intervention, as well as high capacities in general intelligence (Kokis, MacPherson, Toplak, West, & Stanovich, 2002; Stanovich, 1999; Stanovich & West, 2000). However, apart from explicit instructions to reason logically and use analytic processes, something that rarely occurs in natural settings, these factors facilitate System 2 intervention but do not properly trigger it. Moreover, they are external factors, whereas internal incentives are probably also needed to lead individuals to inhibit and supersede the prepotent responses elicited by heuristic processes. This is why Thompson (2009, 2010) has assumed that dual-process theories are fundamentally incomplete without a model of metacognitive processes.

Thompson (2009, 2010) proposes including metacognitive processes as a link between the heuristic and the analytic processes in order to account for the crucial questions for dual-process theories of when and why does System 2 intervene. Why, in certain occasions, is the heuristic response produced, whereas, in others, it is overridden by further analytic processes? Thompson (2010) suggests that what triggers a strong heuristic response, that is a response that will be accepted without further scrutiny, is a metacognitive experience associated with its delivery into consciousness that is named feeling of rightness (FOR). This FOR would be produced by the fluency with which the output of heuristic processes was retrieved from LTM, with high fluency associated with compelling FOR. A strong FOR is interpreted as a signal that further analysis is not required. By contrast, weak FOR would act as a triggering condition for subsequent analytic processes. For example, concluding from If an animal is a cow, then it has four legs and This animal has four legs that it is a cow would lead to a weak FOR, eliciting the search for alternative cases. This conception echoes Oaksford and Chater’s (2010) proposal that the level of activation of the target of an inference reflects the conditional probability of the relation between the categorical premise and this target. Because probability and time of retrieval are negatively correlated (Anderson, 1993), easily recoverable information comes quickly to mind with a high activation level, producing a strong FOR that prevents further analytic processes (for example, concluding from If water is heated over 100°C, then it boils and the water boils that it has been heated over 100°C).

This conception also relates, as noted by Thompson (2009), to Kahneman’s (2003) concept of accessibility. The idea is that some attributes of the problems under study are routinely and automatically registered by System 1 without effort and become highly accessible. Heuristic responses would then occur when people assess the target attribute of a situation (i.e., the dimension relevant for the problem) by substituting a heuristic and highly accessible attribute that comes readily to mind. This is for example what happens in the well-known conjunction fallacy problem in which participants have to
judge, after reading the description of a young woman named Linda, if it is more probable that Linda is either bank teller or bank teller and feminist (Tversky & Kahneman, 1983). The heuristic response underpinning the conjunction fallacy occurs when people substitute a judgment of similarity to stereotypes of bank tellers and feminists (i.e., a highly accessible attribute) for the required judgment of probability. Whereas it is possible for Linda to be closer to the stereotype of a feminist bank teller that to the stereotype of a bank teller, judgments of probability exclude any possibility for a conjunction (i.e., being bank teller and feminist) to be more probable than its constituents. According to Kahneman (2003), System 2 would intervene when this kind of substitution is detected, people becoming aware that they are using a heuristic.

However, even if the FOR is the main determinant of System 2 intervention, this relation is moderated by thinking dispositions, some people being more prone than others to engage in analytic processes (Stanovich, 1999). Interestingly, these thinking dispositions differ from intellectual abilities. For example, scores on measures assessing thinking dispositions such as the Actively Open-Minded Thinking Scale (AOT; Sa, West, & Stanovich, 1999) have proved to contribute unique variance in the probability of normatively correct responses above and beyond individual differences in IQ. These thinking dispositions are metacognitive abilities that probably play a major role in System 2 interventions.

Accordingly, the idea that the regulation of System 2 interventions requires a third system that is not captured by the System 1/System 2 distinction has also been advocated by Stanovich (2009, 2011) and Evans (2009). As we have seen, the factors usually considered as facilitating System 2 intervention such as high capacities in general intelligence and available time are factors that affect the capacity of System 2 to produce responses that can override heuristic responses. However, as noted by Stanovich (2009), override itself must be initiated by higher level control. This means that the analytic system (e.g., the working memory in Oaksford & Chater, 2010) would be subordinated to a higher-level system, a reflective level of processing, containing goal states and epistemic thinking dispositions. Thus, the occurrence and success of deliberative reasoning would not only depend on the computational capacities of System 2 but also on capacities that determines our dispositions to think rationally and initiate deliberative reasoning. This leads Stanovich (2009) to assume a tripartite cognitive architecture in which, in addition to System 1, labeled in this model The Autonomous Set of System (TASS), two levels are distinguished within System 2: an algorithmic level and a reflective level (Fig. 5). The key function of the algorithmic mind would be cognitive decoupling, the activity by which we are able to construct and maintain several alternative representations of a problem in working memory. This echoes the main assumption of mental model theory that deliberative reasoning involves the construction and coordination of different representations of possibilities. Cognitive decoupling would also be needed to sustain mental simulations as in the hypothetical thinking described by Evans (2007). Individual differences in this capacity are reflected by individual differences in fluid intelligence and working memory capacity. The role of the reflective mind would be to initiate decoupling by modifying and updating the content of working memory and to initiate TASS override and inhibition of heuristic responses. Individual differences in this capacity are reflected by individual differences in rational thinking dispositions. A similar proposal can be found in Evans (2009) who notes that the system responsible for recruiting working memory cannot be working memory itself, and suggests the existence of a Type 3 processing responsible for initiating working memory processes and resolving the possible conflicts between System 1 and System 2.

In summary, the metacognitive approach aims at addressing the main question inherent to any dual-process theory, which is the need for a system able to control and coordinate the relations between the two systems. Even if the characteristics of both the output of System 1 (i.e., accessibility and FOR) and the reasoner can determine System 2 intervention, it seems that a third system is needed to initiate this intervention and resolve the possible conflicts between responses. This third system of control has naturally been theorized as a metacognitive system.

The test of development

Compared with the heuristic/analytic and the probabilistic/mental model approaches, the metacognitive approach is more speculative and does not lead to clear predictions that could be empirically tested. However, some of the assumptions outlined above seem to be corroborated by developmental
findings. For example, it has been empirically demonstrated that the intervention of System 2 and the search for counterexamples is related to the degree of beliefs children and adolescents, as well as adults, have in the conditional relation. Markovits et al. (1998) have for example demonstrated that children give more normatively correct responses of uncertainty to the conditional inferences AC and DA when the antecedent and the consequent of the conditional premise are weakly than strongly associated. Markovits et al. (1998) observed that, when presented with a strong conditional relation like \( \text{If an object is a car, then it has a motor} \) and the minor premise \( \text{This object has a motor} \), young children were prone to endorse AC and conclude that the object was a car. However, with a weak relation like \( \text{If an object is a refrigerator, then it has a motor} \), children were more reluctant to conclude from the same minor premise \( \text{This object has a motor} \) that it was a refrigerator. In line with Thompson's analysis, it can be assumed that concluding that something is a refrigerator from the information that it has a motor probably involves a weak FOR triggering the search for counterexamples. Barrouillet et al. (2001) observed the same phenomena with causal relations in adolescents. Interestingly, it was observed that the effect related to the strength of the conditional relation was limited to the AC inference in young adolescents, but extended to DA inference in older adolescents. This finding could be interpreted as evidence that older children are more able to use metacognitive experiences associated with the production of fallacious inferences (e.g., endorsing the AC conclusion) for initiating deliberative thinking and searching for counterexamples. Moreover, the fact that the reliance in System 1 responses depends on their accessibility was well illustrated by Grosset, Barrouillet, and Markovits (2005) who compared weak and strong causal relations in adults. They observed that, as in adolescents, the fallacies AC and DA were more frequently endorsed with strong causal relations but, even more interestingly, that these incorrect responses were faster for strong than weak relations. This suggest that responses that come readily and easily to mind are more difficult to override.

More generally, it is usually assumed in the developmental literature that metacognitive abilities and knowledge increase with age. It is known for a long time that children are increasingly proficient at developing, using, and evaluating strategies in various domains like memory, learning, and comprehension (Bjorklund, 2005; Schneider & Bjorklund, 1998), and increasingly able to benefit from metacognitive experiences like feelings of knowing (Wellman, 1971) or source monitoring (Johnson, Hashtroudi, & Lindsay, 1993). Thus, reasoning development could be underpinned by age-related changes at the metacognitive level.

This is what Moshman (1990) assumed in his theory of metalogic development. Basically, Moshman claims that the development of deductive reasoning cannot be reduced to a mere age-related increase in performance to reasoning tasks, but that reasoning develops if it underlies systematic changes with age towards increasing rationality. Thus, he distinguishes between logic, which involves the use of basic inference schemata, and metalogic, involving a metacognitive awareness of one's logical reasoning. This metalogic can in turn be divided into two aspects: metalogical strategies and metalogical understanding. Among the metalogical strategies are strategies for generating multiple possibilities consistent with premises or actively seeking counterexamples to potential conclusions, processes that have been associated to System 2 by the dual-process theories reviewed in this article. Indeed, contrary to inference schemas that lend to immediate unconscious inferences, metalogic strategies are planful, temporally extended and susceptible to introspection. Within this framework and based on several empirical evidence, Moshman (1990) distinguishes four successive stages in the development of metalogical understanding in which he describes what is explicit in children's reasoning processes and what remains implicit. At a first level, inference schemas remain implicit, young children being only explicitly aware of the content on which they reason. A second stage, typical of elementary school children, involves awareness that conclusions are based on premises and are reached by a process of reasoning, even if the underlying logic still remains implicit. It is only at the third stage that young adolescents are explicitly aware of the logical form of their inferences. Being able to understand the necessity of the relationship between premises and conclusions, they can appreciate the validity of argument forms, independent of the empirical truth or falsity of their content. It is only in a fourth stage only reached by some individuals at the end of adolescence that metalogic itself becomes explicit. Stage 4 individuals are able to think about a formal logical system and grasp its relationships with natural language. It is this kind of ability that would be needed to produce the normative response to Wason's selection task.
It is interesting to note that developmental studies on conditional reasoning have shown that, when reasoning about unfamiliar material or relations, that is when there is no familiar content on which reasoning can be based, children remain at the most primitive level of conjunctive understanding until the beginning of adolescence. It is only around age 11 or 12, at the beginning of the stage 3 of explicit logic described by Moshman, that they become able to understand that conditional sentences can refer to other situations than those involving the co-occurrence of the antecedent and the consequent, thus adopting a biconditional reading and producing denial inferences (i.e., DA and MT) besides the inferences MP and AC that simply relate the antecedent to the consequent (Barrouillet & Lecas, 1998; Barrouillet et al., 2000). These developmental findings suggest that beyond the increase in working memory capacity (Barrouillet & Lecas, 1999), the development of conditional reasoning could be based on metacognitive development.

A dual-process account of the development of conditional reasoning

The previous sections revealed that each of the dual-process approaches that we reviewed have their own merits and interest in understanding reasoning processes and limitations. One of the main strengths inherent to the dual-process theories is to provide us with a comprehensive picture of cognitive structures and mechanisms. For example, both the heuristic/analytic and the probabilistic/mental model approaches reconcile a suppositional and probabilistic conception of conditional, that would characterize System 1 processes, with the more extensional conception endorsed by the mental model theory that appears as a plausible description of System 2. In the same way, the metacognitive as well as the probabilistic/mental model approaches reconcile an adaptive rationality supported by a System 1 accessing associative knowledge bases attuned to environmental regularities with a more logical rationality emerging from the operations of a decontextualized System 2. In recent works, I tried with my colleagues to take advantage from the integrative approach of the dual-process theories to propose a dual-process account of the development of conditional reasoning with two main aims (Barrouillet et al., 2008; Gauffroy & Barrouillet, 2009, 2011). The first was to characterize the output of System 1 when children and adults reason from *If p then q* sentences. The second aim was to propose a theory able to resolve the conflicts between two of the main contemporary approaches of conditional reasoning (i.e., the suppositional theory based on the Ramsey test and the mental model theory that favors an extensional approach based on the representation of possibilities), and to account for the findings these approaches are used to selectively favor. For this purpose, we proposed a model integrating the main tenets of our revised mental model theory (Barrouillet & Lecas, 1998; Markovits & Barrouillet, 2002) within the revised heuristic/analytic model of Evans (2006).

The nature of System 1 output

All the dual-process theories agree that System 1 processes are automatic, rapid, unconscious, producing an output that comes easily and immediately to mind without effort. Being not accessible to introspection, System 1 processes involved in conditional reasoning might deliver their output early in the reasoning process, in the first steps of premises comprehension. This corresponds to what is termed *initial model* in the mental model theory (Johnson-Laird & Byrne, 1991). Because System 1 processes are so basic and evolutionary old, they should not strongly develop with age. Thus, the output of System 1 should closely correspond to the primitive and spontaneous interpretations found in children. As we have seen in the section devoted to the development of conditional reasoning, the most basic and simple interpretation that has been observed in developmental studies is the *conjunctive* interpretation, by which young children seem to represent the conditional by the mere co-occurrence of the antecedent and the consequent within an oriented relation from *p* to *q* (Barrouillet & Lecas, 1998). Such a representation is akin to the initial model of the conditional postulated by the mental model theory (Johnson-Laird & Byrne, 1991, 2002), with the exception that it would not contain any implicit model pointing to alternative possibilities. This representation, which matches the explicit content of the conditional statement, would constitute what the fuzzy-trace theory (Brainerd & Reyna, 2001) describes as a verbatim representation, by opposition with *gistified* representations that
go beyond the surface form of the premises to include sense and meaning. This proposal is also coherent with a dual-process theory of conditional reasoning that we did not address before, which has been proposed by Klaczynski, Schuneman, & Daniel, 2004 and that distinguishes between experiential (instead of heuristic) and analytic systems. The experiential system would lead to endorse and produce the invited inferences to MP, AC, DA, and MT (i.e., \( q, p, \neg q, \neg p \)). Here, the conjunctive interpretation, by relying \( q \) to \( p \), supports the invited inferences for MP and AC.

In summary, our hypothesis was that when understanding a conditional sentences of the form *If \( p \) then \( q \)*, System 1 heuristic processes deliver a default model representing the relation between the antecedent and the consequent. We have assumed that this would be the case for several types of conditionals, like indicative or causal conditionals, but not necessarily for all conditionals. In line with Evans (2006), Evans & Over (2004) proposal, we also assumed that heuristic processes could deliver pragmatic implicatures susceptible to enrich System 1 output. This should be the case for conditionals like promises and threats that strongly cue invited inferences that are inherent to their meaning. For example, a promise like “if you mow the lawn, then I’ll give you five euros” would not be effective if the addressee of the message failed to understand that “if you don’t, I’ll give you nothing”, and a threat like “If you break the vase, then I’ll take your ball away” would loose any effectiveness if it was not understood at the same time that “If you don’t, I don’t take your ball away”. So, for inducements like promises and threats, we suggested that heuristic processes produce a two-model initial representation relating \( q \) to \( p \) on the one hand and \( \neg q \) to \( \neg p \) on the other (Gauffroy & Barrouillet, 2009).

**System 2 intervention**

Within this framework, System 2 intervention would be needed to enrich the initial model by the representation of other possibilities. Indeed, representing alternative possibilities would involve the process of decoupling postulated by Stanovich (2009), which requires working memory. In the same way, Evans (2007) in his hypothetical thinking theory endorses a principle of singularity stating that we can only represent one mental model at a time. Thus, maintaining ready for treatment several representations of a same premise requires some storage in working memory. The construction of these additional models can be triggered by the minor premise in inference production or evaluation, by the perception of state of affairs in truth table tasks, or even by the internal drive resulting from metacognitive processes. As we noted above, the number of models that can be constructed increases with age, determining the successive levels of interpretation and reasoning that we have described above. The first alternative model usually constructed is assumed to belong to the complementary class (i.e., a model of the form \( \neg p \neg q \)), whereas the construction of models from the alternative class (i.e., models of the form \( \neg p q \)) would involve a further processing step. This process of adding alternative representations, which is named fleshing out in the mental model theory, is thought of to be constrained by two main factors. The first concerns the availability of relevant knowledge in working memory. As we have seen, when reasoning on familiar premises, school-aged children are usually able to construct two models (i.e., \( p q \) and \( \neg p \neg q \)) and to reach a biconditional interpretation, but they are able in some occasions to retrieve relevant alternative cases and produce normatively correct responses of uncertainty on AC and DA inferences. By contrast, when reasoning from unfamiliar relations, developmental studies indicate that children are rarely able to go beyond the conjunctive interpretation before adolescence, producing conjunctive responses in truth table tasks and the sole MP and AC inferences in inference production tasks (Barrouillet et al., 2000). The second factor constraining fleshing out is the capacity of working memory, which constrains both the capacity to activate knowledge from long-term memory and the number of representations that can be held in working memory with children with higher capacities being able to construct more models (Barrouillet & Lecas, 1999; Markovits & Barrouillet, 2002). Of course, our model inherits the reasoning machinery described by the mental model theory, and we assume that analytic processes supported by System 2 are also needed to manipulate mental models in working memory, draw putative conclusions, search for counterexamples and eliminate contradictory models. The strong age-related increase in working memory capacity would account for the developmental increase in efficiency of analytic processes.

Though we framed the analytic processes of our theory onto mental models, our theory departs from the standard mental model theory concerning the epistemic status of the models, which would
depend on the way they are constructed. Evans et al. (2005) argued that Johnson-Laird and Byrne’s mental model theory was inaccurate because, when evaluating the truth-value of a conditional, people endorse a defective truth table with indeterminate responses for \( \neg p \) cases instead of the material implication interpretation allegedly favored by the mental model theory, in which all the \( p, q, \neg p q, \) and \( \neg p \neg q \) cases make the conditional true when they occur. We argued that distinguishing between heuristic and analytic processes could explain why the defective table occurs (Barrouillet et al., 2008; Gauffroy & Barrouillet, 2009). Because the output of heuristic processes comes spontaneously to mind without effort when understanding the conditional sentence, the default model constructed by these heuristic processes should be considered as the core meaning of the sentence, what makes it true. This is why the \( pq \) model constructed through heuristic processes would be universally considered as making the conditional true. By contrast, those models added by the analytic processes (i.e., the \( \neg p \) cases) are of course compatible with the conditional sentence, but should not be considered as making it true. Constructed by optional processing steps that are not needed in many occasions, the fleshed out models would not belong to the core meaning of the conditional sentence, leading to the indeterminate responses observed for \( p \) cases in truth-table tasks. Being not incompatible with the conditional, they do not make it true either, leading to the truth-value gap (i.e., the conditional is neither true nor false for \( \neg p \) cases) advocated by the suppositional approach (Evans & Over, 2004).

Our theory accounts for the age-related evolution in the indeterminate responses to \( \neg p \) cases we have described above, with adolescents considering that the \( \neg p \neg q \) case leaves indeterminate the truth-value of the conditional, while the \( \neg p q \) case still makes it false. This is because the fleshing out process in adolescents is limited to the construction of only one additional model instead of two as in adults. The same dual-process approach also accounts for the fact that incentives as promises and threats are considered as true for both the \( pq \) and \( \neg p \neg q \) cases. Because heuristic processes add pragmatic implicatures that are part of the core meaning of these conditionals, they are deemed true for both \( p q \) and \( \neg p \neg q \) cases and false for the other cases, the content of the default model blocking any further fleshing out. It is worth to note that, in line with the hypothesis of relatively unchanging heuristic processes with age, the resulting equivalence pattern (i.e., responding ‘true’ for \( p q \) and \( \neg p \neg q \) cases and ‘false’ for both \( p \neg q \) and \( \neg p q \) cases) was observed as predominant in evaluating the truth-value of promises and threats from childhood to adulthood in Gauffroy and Barrouillet (2009).

Finally, because our dual-process theory accounts for the evolution of the cases that are considered as relevant (i.e., either true or false) for evaluating the truth value of the conditional, it also accounts for the developmental evolution observed by Gauffroy and Barrouillet (2009) in the way adolescents and adults assess the probability for a conditional to be true, with evaluations successively based on conjunctive, defective biconditional, and then defective conditional interpretations. Thus, our theory also departs from Evans (2007) theory by assuming that the suppositional conditional based on the Ramsey test is a late developmental achievement that does not correspond to the basic understanding of conditionals.

**Developmental changes in System 1 output?**

We have previously assumed that heuristic processes remain immune to developmental changes (Gauffroy & Barrouillet, 2009). However, two aspects related with System 1 output have to be distinguished. Heuristic processes are mainly processes of retrieval from long-term memory. Thus, the output of System 1 depends both on mechanisms of retrieval and on the richness and structure of the accessed knowledge bases. If it is probable that the unconscious and automatic processes governing spreading activation and retrieval from long-term memory do not greatly evolve with age from childhood to adulthood, knowledge bases probably evolve, leading to some age-related evolution in the nature of System 1 output. Moreover, the development of metacognitive processes would enrich System 1 output by refining the metacognitive experiences that accompany memory retrieval such as feeling of retrieval fluency and FOR. It is thus possible that, with age, individuals would have access

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6 The first model \( pq \) dismisses the possibility of having \( p \neg q \), and the pragmatic implicatures \( \neg p q \) dismisses the possibility of having \( p q \). Thus, both receiving nothing after having mown the lawn \( p \neg q \) and receiving the money whereas the lawn has not been mown \( \neg p q \) make the promise “If you mow the lawn, then 1 will give you 5 euros” false.
to increasingly rich default models. These metacognitive experiences could convey information about the relation between \( p \) and \( q \) such as the frequency of \( pq \) cases.

Nonetheless, as we have seen, this default model does not probably evolve up to involving something like the Ramsey test and a representation of conditional probabilities. The fact that performing this Ramsey test depends on individual differences in fluid intelligence does not fit very well with heuristic processes, as well as the fact that giving the conditional probability when assessing the probability of the conditional is a late developmental achievement. Thus, our hypothesis is that, even in adults, the default model for indicative and causal conditionals is restricted to a representation of a directional relation between the antecedent and the consequent.

**Metacognitive development**

Our model assumes that the main development observed in conditional reasoning relies on an increase in the number of mental models that can be constructed and manipulated in working memory. However, such an increase cannot account for all the developmental phenomena. For example, Gauffroy and Barrouillet (2011) reported a developmental lag of three years between reasoning about possibilities from a conditional presented as a rule to obey on the one hand, and reasoning about the truth-value of a conditional from available cases on the other. Thus, sixth graders mainly consider \(-p \lor -q\) cases as compatible with a conditional when listing possible cases, but still deem the conditional false for the same cases when evaluating its truth-value. As we have seen earlier, it is only in adults that the defective truth table becomes the predominant pattern in truth-table tasks. This suggests that above and beyond the capacity to construct complex representations in working memory, metacognitive processes develop and allow older adolescents and adults not only to construct appropriate representations to reason from conditional statements, but also to think about the system that these representations constitute. We have argued that this final level corresponds to Moshman’s (1990) explicit metalogic stage in which individuals can think about the logical system as a system and grasp its relationships with natural language, something needed by the truth-value gap. Thus, beyond the development of System 2, the construction of meta-abilities needed to think about truth and falsity leads to higher levels of rationality only reached in adulthood, delineating a development of conditional reasoning that encompasses all the developmental period.

**Duality before dual-process theories: intuitive and operational thinking in Piaget’s theory**

The dual-process framework has proven especially heuristic in accounting for a variety of human activities such as reasoning, judgment, and social cognition (Evans, 2008). The present article was more restricted in scope and aimed at demonstrating that this framework is also suited for understanding the development of conditional reasoning. It can even been argued that the distinctions introduced by the dual-process approach are especially appropriate for understanding cognitive development, and can be traced back to the most venerable theories of cognitive development such as Piaget’s theory.

Endorsing a constructivist approach of development, Piaget rejected the idea that logic was innate in humans and designed an impressive series of studies aiming at demonstrating that even the simplest elementary logical structures were absent from child’s thinking and developed slowly through a series of levels (Piaget & Inhelder, 1954). Anticipating the “biases and heuristics” literature as well as the modern distinction between the intuitive and the reflective mind (Evans, 2010), he opposed intuition, or intuitive thinking, to rational thinking. He defined intuition as “preoperational thinking, i.e., thinking which relies only on perceptual configurations or on tentative empirical activity”. Like Kahneman (2003), Piaget envisioned that an intuition is always a process of substitution by which a rational concept is first assimilated to an undifferentiated perception or action. Long before Kahneman and Tversky (1973), Piaget provided a myriad of evidence for attribute substitution as the basis of intuitions, demonstrating that young children substitute the length of an array to the number of its constitutive objects, the shape of a ball of clay to the amount of matter it contains or to its weight, the absolute position of the extremities of a stick to its length, the result of an action
Reflective Mind
Initiate simulation via decoupling
Initiate control change in serial associative cognition
Initiate override

Algorithmic Mind

Preattentive processes
Override

Autonomous Mind

Fig. 5. The tripartite structure proposed by Stanovich. Adapted by permission of Oxford University Press from In two minds: Dual processes and beyond, by Evans and Frankish (2009), p. 67.

PERCEPTION
Fast
Parallel
Automatic
Effortless
Associative
Slow-learning
Emotional

INTUITION
SYSTEM 1

REASONING
SYSTEM 2
Slow
Serial
Controlled
Effortful
Rule-governed
Flexible
Neutral

CONTENT
Percepts
Current stimulation
Stimulus-bound

Conceptual representations
Past, Present and Future
Can be evoked by language

Fig. 6. The processes and contents involved in the two cognitive systems distinguished by Kahneman (2003). Adapted from “A perspective on judgment and choice,” by Kahneman, 2003, American Psychologist, 58, p. 698. Copyright 2003 by the American Psychological Association.
to its duration, the weight of an object to its volume, the level of water to its amount, the order of arrival to speed and, even earlier in development, the place where an object has been already retrieved to its actual location (Piaget, 1937, 1946a, 1946b; Piaget & Inhelder, 1941; Piaget & Szeminska, 1941). Preceding Kahneman’s (2003, see Fig. 6) analysis, he noticed that intuitions share many characteristics with perception and usually result from focusing on salient physical characteristics of scenes and objects. Most importantly, Piaget stressed that, though being not rational, these intuitions are notwithstanding adaptive, providing us most of the time with correct judgments: extended collections contain often more objects, the stick that sticks out is often the tallest, and the car that arrives first in a race is the fastest.

The essential problem for Piaget was to explain the transition from perceptual or image-based intuitions to the construction of an operational system. Anticipating Evans’ (2007) proposal that analytic thinking cannot operate without the heuristic system because heuristic processes provide the conscious content on which analytic processes apply, Piaget suggested that rational thinking emerges from the coordination of these intuitions, which leads to their regulation and compensation into reversible operations. However, he went probably further than the modern dual-process account by pointing out that there is a solution of continuity between intuitions and reflective thinking, for at least two reasons. First, intuitions are not mere “readings” or passive registrations of objects properties but, from the very beginning, also actions on them. This is because these intuitions are actions that they can eventually give rise to operational schemata and evolve into abstract and deductive abilities. The idea that intuitions are actions echoes the modern view of intuitions underpinned by heuristics. For example, the If-heuristic as well as the matching-heuristic described by Evans are actions in that they direct attention and select information. Second, Piaget demonstrated in several domains how intuitions gradually evolve into operations by describing the intermediary levels of this transformation. For example, Piaget and Szeminska (1941) showed how the primitive intuitions governing number understanding in young children, who assimilate number with space, evolve into what Piaget called ‘articulate intuitions’, whereby children can coordinate perceptual relationships to correctly reproduce an array of counters, manifesting some understanding of the one to one correspondence. However, as the well-known task of number conservation demonstrated, this understanding is still intuitive, and preoperational children deny the quantitative equality of the two collections as soon as the counters of one of the arrays are moved closer together. These articulate intuitions are easy to identify in the development of conditional reasoning. For example, children and adolescents who are able to coordinate the $p \land q$ and $\neg p \land \neg q$ models have gone further the most elementary conjunctive level and grasp something of the suppositional nature of the conditional. However, this biconditional level is not yet a complete understanding of the conditional, leading for example to endorse the AC and DA fallacies, and to consider that $\neg p \land q$ cases make the conditional false.

Another strength of Piaget’s theory was its capacity to give a theoretical account of the difference between concrete and abstract reasoning. The questions related to abstract reasoning were the focus of what Evans (2002) has named the deduction paradigm, in which participants are told to assume the truth of a set of premises from which they are asked to draw only conclusions that are logically necessarily. As Evans (2011a) states, researchers are now more interested in the influences of belief on reasoning than in studying logical competence in abstract reasoning. I would argue that this modern disinterest for what is probably the highest and most fascinating human capacity is at least surprising, if not regrettable. Developmental studies indicate that reasoning from unfamiliar relations is far more difficult than reasoning about familiar contents, and assuming that abstract reasoning simply relies on the establishment of analogies to prior conditional knowledge, as Oaksford and Chater (2010) did, is probably an oversimplification. In line with Piaget’s hypothesis that successive stages present the same processes of construction at a higher level (the notion of décalage vertical), studies investigating adolescent’s reasoning on truth and falsity of unfamiliar conditional relations reveal that young adolescents regress to a conjunctive understanding, and that it is not before adulthood that a complete meaning of abstract conditionals is available. Such a slow developmental process suggests that something else is needed than accessing world knowledge in long-term memory to establish an analogy. Piaget accounted for the transition from concrete to formal thinking by assuming a process of reflective abstraction by which an operation becomes the object of some higher order operation. This process that allows adolescents to go beyond the content of their inferences to reason on their form
clearly echoes both Stanovich’s (2009) hypothesis of a reflective mind that would operate on the algorithmic level of System 2 and the role of metacognitive processes hypothesized by Thompson (2010).

Finally, though logic is no longer considered as a plausible descriptive or even normative theory of human reasoning, the dual-process approach might lead us to reconsider Piaget’s solution of the question of rationality. Evans (2007) assumes that normative rationality cannot be achieved without reflective analytic thinking, but he suggests to avoid any reference to rationality in the definition of analytic thinking. What would matter is the nature of analytic thinking, which constitutes a different kind of cognitive resource available to human beings. The problem is that, contrary to intuitive thinking, the nature of analytic thinking could prove difficult to define without any reference to norms and rationality. System 1 can be defined as a set of systems that operate autonomously in response to triggering stimuli, without any control (Stanovich, 2009). These systems are adaptive as long as they properly reflect the statistical regularities of the specific class of input they are designed to process and provide individuals with well-calibrated beliefs. By contrast, the main characteristic of the analytic processes constituting System 2 is to be controlled. However, the idea of a control implies the corollary idea of a norm against which the output of these analytic processes could be assessed. As a consequence, it results from the usual description of the analytic system that it is necessarily normative in nature.

The solution adopted by Piaget in accounting for the normative rationality in humans was to assume that concrete and then formal operations were organized in structures that are isomorphic to logical structures. Concerning formal operations, these structured wholes, considered as the form of equilibrium of the subject’s operational behavior, “appear in the form of a set of virtual transformations, consisting of all the operations which it would be possible to carry out starting from a few actually performed operations” (Inhelder & Piaget, 1958). It is important to note that the formal operations described by Piaget, which are also called propositional operations, cannot be assimilated to the inference schemas postulated by the mental logic theories (Brain & O’Brien, 1998; Rips, 1994). According to these theories, individuals would have syntactic rules of inference that can be applied to the logical form of premises to produce conclusions. For example, it would exist in human mind an or elimination rule that would be triggered by premises of the logical form \( p \text{ or } q \) and \( \neg p \) and that would produce the conclusion \( q \) as output. Piaget’s conceptions differ completely from this proposal. First of all, though the subject at the formal operational stage reasons by hypothesis, this reasoning is not limited to the verbal domain but extends to physical, mathematical and even practical domains. Indeed, the structures described by Piaget were not inferred from the inferences produced by adolescents reasoning on verbal premises, but from the organization of their behavior and explanations when solving problems like equilibrating a balance, combining colored and colorless liquids to reproduce a target color, or when trying to understand and predict the oscillations of a pendulum (Inhelder & Piaget, 1958). Second, these propositional operations are not inferential mechanisms. For example, when reasoning about a system containing two propositions \( p \) and \( q \), these operations are all the possible combinations of the products \( p \cdot q \), \( p \text{ or } q \), \( \neg p \cdot q \), and \( \neg p \text{ or } \neg q \). For example, \( p \text{ or } q \) (i.e., \( p \text{ or } q \)) is an operation, as well as \( \neg p \text{ or } \neg q \) (i.e., \( \neg p \text{ or } \neg q \)). The virtual transformations evoked by Inhelder and Piaget (1958) that can result in a structured whole when properly coordinated are the four transformations of the INRC group. This means, for example, that the operation \( p \text{ or } q \) (i.e., \( p \text{ implies } q \)) which corresponds to the set \( p \cdot q \) or \( \neg p \cdot q \) or \( \neg p \text{ or } \neg q \), has an inverse \( N \) which is \( p \text{ or } \neg q \), a reciprocal \( R \) which is \( q \text{ or } p \), and a correlate \( C \) which is \( \neg p \text{ or } q \) (Piaget, 1953). Thus, it remains unclear that the idea of a mental logic is the same as Piaget’s idea, as it is often argued (e.g., Johnson-Laird, 2010). The theory of formal operational thought does not assume that adolescents construct logical operations like inference rules operating on the logical form of arguments. It does not even assume that axiomatic logic can provide an adequate formalization of the logical structure of psychological facts. As Piaget (1953) explicitly stated, adult’s, and a fortiori child’s ordinary thinking is unformalizable. As a consequence, he suggested to interpolate between psychology and axiomatic logic a “psycho-logic” or logico-psychology in the same way as the need for explanation in physics has given rise to a mathematical physics which is the application of mathematics to physics. This “psycho-logic” was not intended to base logic on psychology (or psychology on logic), but to explain some of the experimental findings of psychology using a deductive theory constructed by means of the algebra of logic. There were only two criteria for these logical schemata, which were their logical validity and applicability to empirical findings. This strategy led Inhelder and Piaget (1958) to suggest that the psychological structure of propositional...
operations corresponded to a dual structure combining a lattice (i.e., a combinatorial system) and a group (i.e., the INRC group). As we have seen above for the binary propositional operations, these operations are constructed by combining $n$ by $n$ the four basic conjunctions (i.e., $p \cdot q$, $p \cdot \lnot q$, $\lnot p \cdot q$, and $\lnot p \cdot \lnot q$) and form a system that obeys the laws of a group structure.

It can be observed that Piaget’s theory is fully compatible with the mental model approach we favored and provides us with a reasonable account of our developmental data. For example, when reasoning about abstract conditionals, it is not before the end of the formal operational stage that children understand that $\lnot q$ is the inverse of If $p$ then $q$, which is no longer confused with If $q$ then $p$, the inverse of which (i.e., $\lnot p \cdot q$) is compatible with If $p$ then $q$, creating a set of relations that reflect the virtual transformations of the INRC group. In line with the proposal that mental operations converge towards a psychological structure that can be described using algebraic schemata with logical validity, developmental studies on conditional inferences indicate that children exhibit an increasing tendency to make normative inferences when asked to reason logically from concrete premise, whether these premises are believable or not (Markovits, 2006). Moreover, we have reported in this article many studies showing that the same increase in normative inferences and judgments is observed in adolescents reasoning on abstract premises. This is not to say that the analytic system is underpinned by a mental logic. However, the development of conditional reasoning indicates that children’s reasoning progressively conforms to the prescriptions of logic, strongly suggesting that the development of System 2 results in an increasing normative rationality. Any theory of reasoning must account for this empirical finding.

Concluding comments

In this article, I have reviewed some of the prominent dual-process theories of conditional reasoning and tested these theories against developmental findings. This test revealed that all the proposed approaches have strengths and account for a part of the available developmental findings. As a consequence, I proposed a comprehensive dual-process theory that integrates Evans’ suppositional approach and Johnson-Laird’s mental model theory. This theory suggests that both the Ramsey test on which the suppositional account is based and the extensional approach favored by the mental model theory grasp something of the way adults represent and treat conditionals. However, the developmental analysis also demonstrates that both the Ramsey test and the three-model representation are developmental achievements resulting from the evolution of reflective mind, and cannot be considered as representing the basic meaning of conditional provided by the intuitive mind. As I argued above, the intuitive/reflective distinction has a long lasting history in developmental psychology that could shed some light on the contemporary dual-process theories of reasoning. After all, human beings are not born as mature undergraduate students enrolled in psychology experiments. Adult reasoning is an endpoint that cannot be properly understood without analyzing the trajectory which led to it.

References


7 The mental model theory could be understood as a fully developed functional theory of the extensional approach favored by Inhelder and Piaget (1958) in which the procedures underpinning the construction of mental model would correspond to the propositional operations described by Inhelder and Piaget. However, the mental model theory goes further by giving a detailed account of the nature of the representations constructed and of the mechanisms of inference production that remain underspecified in Piaget’s approach. For example, in Inhelder and Piaget (1958) it is assumed that there are no specific operations for deductive inferences except the N, R, and C transformations. However, it is easy to verify that these transformations allow for an exhaustive coordination of all the possibilities (e.g., from the possibilities compatible with the truth of a sentence, it is possible to infer what would happen if the sentence was false), but that they are not sufficient to underpin the manipulation of models needed to produce and evaluate conclusions.


