# Chronometric evidence for the dual-process mental model theory of conditional

Vergauwe, Evie; Gauffroy, Caroline; Morsanyi, Kinga; Dagry, Isabelle; Barrouillet, Pierre Noël

**How to cite**

VERGAUWE, Evie et al. Chronometric evidence for the dual-process mental model theory of conditional. In: Journal of cognitive psychology, 2013, vol. 25, n° 2, p. 174–182. doi: 10.1080/20445911.2012.744743

This publication URL: https://archive-ouverte.unige.ch/unige:88206
Publication DOI: 10.1080/20445911.2012.744743

Routledge
Taylor & Francis Group

Journal of Cognitive Psychology

ISSN: 2044-5911 (Print) 2044-592X (Online) Journal homepage: http://www.tandfonline.com/loi/pecp21

# Chronometric evidence for the dual-process mental model theory of conditional

Evie Vergauwe , Caroline Gauffroy , Kinga Morsanyi , Isabelle Dagry & Pierre Barrouillet

**To cite this article:** Evie Vergauwe , Caroline Gauffroy , Kinga Morsanyi , Isabelle Dagry & Pierre Barrouillet (2013) Chronometric evidence for the dual-process mental model theory of conditional, Journal of Cognitive Psychology, 25:2, 174-182, DOI: 10.1080/20445911.2012.744743

**To link to this article:** http://dx.doi.org/10.1080/20445911.2012.744743

*Journal of Cognitive Psychology*, 2013
Vol. 25, No. 2, 174–182, http://dx.doi.org/10.1080/20445911.2012.744743

Routledge
Taylor & Francis Group

# Chronometric evidence for the dual-process mental model theory of conditional

**Evie Vergauwe, Caroline Gauffroy, Kinga Morsanyi, Isabelle Dagry, and Pierre Barrouillet**

Faculté de Psychologie et de Sciences de l'Education, Université de Genève, Geneva, Switzerland

The fact that adults exhibit a defective truth table when evaluating "If p then q" conditional statement and judge $\neg p$ cases as irrelevant for the truth value of the conditional has been considered as one of the main evidence against the mental model theory and in favour of Evans' (2007) suppositional account of conditional. If judgements of irrelevance result from some heuristic process, as the suppositional theory assumes, they should be rapid. By contrast, if they result from a demanding and time consuming fleshing out process, as our mental model theory assumes, "irrelevant" responses should be the slowest. In the present study, we analyse the time course of responses in a truth table task as a function of their nature and the interpretation of the conditional adopted by the participants. As our mental model theory predicts, "irrelevant" responses are the slowest, and response times are a direct function of the number of models each type of response involves.

***Keywords:*** Conditional reasoning; Heuristic and analytic processes; Mental models; Response times.

Understanding the processes underlying conditional reasoning is one of the most challenging questions of cognitive psychology. Accordingly, a variety of theoretical proposals have attempted to account for the way humans understand conditionals and reason from them (Braine & O'Brien, 1991; Evans & Over, 2004; Johnson-Laird & Byrne, 2002; Oaksford & Chater, 2001). In the last decades, the most influential approach has been the mental model theory (Johnson-Laird & Byrne, 1991, 2002; Johnson-Laird, Byrne, & Schaeken, 1992). The main tenet of this theory is that people interpret conditionals by constructing mental models of the states of affairs that are possible when the sentence is true. As working memory capacity is limited, people interpret an "If p then q" statement ("If the piece is red, then it's a circle") by constructing first an initial model that represents both *p* and *q* satisfied (a red circle) and leaves implicit the other possibilities (the three dots in the following diagram):

p q
...

If needed, implicit information can be made explicit by a resource demanding and time-consuming fleshing out process that can enrich the initial representation with two additional models: $\neg p$ $\neg q$ (e.g., a yellow star) and $\neg p$ $q$ (e.g., a yellow circle):

p q
¬p ¬q
¬p q

This complete three-model representation (i.e., conditional representation) represents the three possibilities compatible with the conditional.

Correspondence should be addressed to Evie Vergauwe or Caroline Gauffroy, Faculté de Psychologie et de Sciences de l'Education, Université de Genève, 40, bd du pont d'Arve, 1205 Genève, Switzerland. E-mail: Evie.Vergauwe@unige.ch or Caroline.Gauffroy@unige.ch

Despite a variety of studies that corroborate this account (see developmental studies for the main corroboration; Barrouillet & Lecas, 1998, 2002), the mental model theory has been the subject of strong criticism (Evans, Over, & Handley, 2005). According to this latter view, if mental models represent true possibilities (i.e., the states of affairs that are possible when the sentence is true), then people who are able to construct the $p\ q$, $\neg p\ \neg q$, and $\neg p\ q$ models should deem the conditional true for the corresponding cases. However, many studies have shown that this is almost never observed. Instead, reasoners exhibit a ''defective'' truth table when asked to evaluate the truth value of conditional statements. In this interpretation, the conditional ''If the piece is red, then it's a circle'' is true for $p\ q$ cases (red circles) and false for $p\ \neg q$ cases (red stars), but the $\neg p$ cases (e. g., yellow circles or yellow stars) are considered as irrelevant for the truth value of the conditional that is deemed neither true or false. According to Evans and colleagues, the defective truth table is at odds with the mental model theory, but provides the main evidence for their hypothetical thinking theory (Evans, 2007). This theory assumes that, in line with the dual-process approach, two types of processes coexist in human thinking. Heuristic (Type 1) processes are automatic, unconscious, and pragmatically cued, and deliver the most relevant model with regard to the context. By contrast, analytic (Type 2) processes, which are controlled, conscious and resource demanding, may or may not intervene to replace or revise the output of heuristic processes. When people evaluate the truth value of a conditional, heuristic processes would strongly cue $p$ cases as relevant and $\neg p$ cases as irrelevant. Analytic processes would then be employed to process relevant cases ($p\ q$ and $p\ \neg q$) and classify them as true or false, leading to the defective truth table (Evans, 2007).

We have recently proposed to combine the mental model theory and Evans' (2006) heuristic-analytic approach within an integrative developmental theory that specifies both the role of heuristic and analytic processes in the construction of mental models for conditionals and the epistemic status of each mental model constructed (Barrouillet, 2011; Barrouillet, Gauffroy, & Lecas, 2008; Gauffroy & Barrouillet, 2009, 2011). According to Gauffroy and Barrouillet (2009), the distinction between heuristic and analytic processes can be applied to the construction of mental models for conditionals. The initial model, that comes easily to mind when understanding a conditional, and in which some part of the information is left implicit, seems to be the product of heuristic processes. By contrast, the fleshing out process by which additional models are constructed presents all the characteristics of an analytic process. It is described by Johnson-Laird and Byrne (1991) as effortful, time consuming, and resource demanding. Similarly to analytic processing, it is optional and its role is to enrich the initial representation by making explicit the information left implicit, resulting in the construction of $\neg p\ \neg q$ and $\neg p\ q$ models. Gauffroy and Barrouillet have assumed that the difference in nature between the processes underpinning the construction of initial and fleshed out models has implications on the epistemic status of the representations constructed, something that was not taken into account by the standard mental model theory. Given that heuristic processes provide individuals with a default mental model that comes easily to mind, individuals would consider that this initial model corresponds to the core meaning of the conditional. Thus, when confronted with cases that match this initial representation (i.e., $p\ q$), they would judge the conditional to be true. By contrast, the analytic fleshing out process enriches the initial representation with models that do not pertain to the core meaning of the sentence but are nonetheless compatible with it. As a consequence, when confronted with states of affairs that match fleshed out models ($\neg p\ \neg q$ and $\neg p\ q$ cases), individuals would judge the conditional neither true nor false, its truth value being left indeterminate, resulting in the ''defective'' truth table. It should be noted that our proposal strongly departs from the standard mental model theory, which assumes that indeterminate responses to $\neg p$ cases result from the fact that they are not explicitly represented in the initial model. In our theory, $\neg p$ cases are deemed irrelevant for the truth value of the conditional even when explicitly represented through fleshing out; it is precisely the fleshing out process that makes these cases irrelevant for judging the truth value of the sentence. Our account fits with data indicating that indeterminate responses become more frequent with development (Gauffroy & Barrouillet, 2009) as well as in high-capacity individuals (Evans, Handley, Neilens, & Over, 2007), because higher cognitive capacity makes possible the fleshing out process which leads in turn to indeterminate responses. Finally, possibilities that are not represented in any model, even when the fleshing out is completed, would be

considered as incompatible with the conditional and as falsifying it.

The hypotheses related to the different processes that underpin the construction of mental models and the resulting epistemological status of these models have been tested by taking advantage of developmental changes in the fleshing out process. Indeed, as analytic processes rely on working memory and general intelligence (Evans, 2006), they can be expected to develop with age. By contrast, heuristic processes are considered to be relatively independent of cognitive resources and, thus, would not strongly evolve with age. Building on these premises, there should be no age-related change in the "true" response to *p q* cases, which correspond to the initial model. By contrast, because the number of models that can be constructed though fleshing out progressively increases with age (Barrouillet & Lecas, 1998, 2002), the rate of indeterminate responses to $\neg p$ cases should increase with age. More precisely, young children who are only able to construct a single *p q* model without any fleshing out, thus exhibiting a conjunctive interpretation, should consider that *p q* cases make the conditional true and that all the other cases make it false. Adolescents, who are able to enrich the initial representation by constructing the $\neg p$ $\neg q$ model through fleshing out, should judge the *p q* cases as making the conditional true, the $\neg p$ $\neg q$ cases as leaving its truth value indeterminate, and the two other cases as making it false, adopting an interpretation known as defective biconditional. Finally, older adolescents and adults who are able to achieve a complete fleshing out leading to a three-model representation (i.e., *p q*, $\neg p$ $\neg q$, and $\neg p$ *q*) should adopt the defective conditional interpretation already described with responses of irrelevance to both $\neg p$ $\neg q$ and $\neg p$ *q* cases. In summary, a developmental pattern should emerge in truth-table tasks from a conjunctive to a defective biconditional, and finally a defective conditional pattern (Table 1). This is exactly what we observed in several studies (Barrouillet et al., 2008; Gauffroy & Barrouillet, 2009, 2011) revealing that the number of responses of irrelevance to $\neg p$ cases evolves in a definite and predictable way with the age-related increase in the number of models constructed, the "irrelevant" response to $\neg p$ $\neg q$ being accessible through the construction of a two-model representation, whereas the "irrelevant" response to $\neg p$ *q* requires a three-model representation that is only accessible later in development.

It is worth noting that our theory and Evans' (2007) suppositional theory differ in their account of responses of irrelevance to $\neg p$ cases in truth-table tasks. Whereas Evans assumes that the distinction between relevant and irrelevant cases result from heuristic processes and constitutes the first step of the truth evaluation process (see Evans, 2007, Fig. 3.1), we assume that responses of irrelevance rely on analytic processes. Even though the developmental findings reported previously strongly supported the hypothesis that analytic processes underlie responses of irrelevance, chronometric evidence would constitute a more direct way to decide between the two theories. Indeed, heuristic processes are assumed to operate faster than analytic processes (e.g., Epstein, 1994; Kahneman, 2000, 2011). Thus, if responses of irrelevance elicited by $\neg p$ cases are underpinned by heuristic processes constituting a first step in the evaluation process, as Evans (2007) assumes, they should be particularly fast. At the very least, they should not take longer than the "true" and "false" responses elicited by *p* cases that are assumed to result from analytic processes. By contrast, if the responses of irrelevance to $\neg p$ cases are underpinned, as we assume, by analytic processes, they should be the slowest. However, our theory goes further by making precise predictions about the time course of the different kinds of responses (i.e., "true", "false", and "indeterminate") to the different cases depending on the number of models that these responses involve.

**TABLE 1**
Response patterns corresponding to the three interpretational levels observed in development for the truth-value evaluation task (with the number of models needed to produce each response according to the mental model theory).

| | *Interpretation* | | |
|---|---|---|---|
| *Logical cases* | *Conjunctive* | *Defective biconditional* | *Defective conditional* |
| p q | True (1) | True (1) | True (1) |
| $\neg$p $\neg$q | False (1) | Indeterminate (2) | Indeterminate (2) |
| $\neg$p q | False (1) | False (2) | Indeterminate (3) |
| p $\neg$q | False (1) | False (1 or 2) | False (1 or 3) |

Consider first the defective conditional interpretation that consists in responding "true", "irrelevant", "irrelevant", and "false" to $p\ q$, $\neg p\ \neg q$, $\neg p\ q$, and $p\ \neg q$ cases respectively (i.e., the defective truth table). We have assumed that this response pattern is underpinned by a three-model representation. Responses of irrelevance to $\neg p\ \neg q$ and $\neg p\ q$ cases, that require a fleshing out of the initial model, should take longer than the responses supported by this initial model such as the "true" responses to $p\ q$ cases. However, the response of irrelevance to $\neg p\ q$ cases, which necessitates the construction of the complete three-model representation, should take longer than the same response on $\neg p\ \neg q$ cases, that can be reached with a two-model representation (i.e., $p\ q$ and $\neg p\ \neg q$). Thus, at this interpretational level, responses to $p\ q$ ("true"), $\neg p\ \neg q$ ("indeterminate"), and $\neg p\ q$ ("indeterminate") that require one, two, and three models, respectively, should take increasingly longer. Things should be different for those participants who adopt a defective biconditional response pattern and respond "true", "irrelevant", "false", and "false" to $p\ q$, $\neg p\ \neg q$, $\neg p\ q$, and $p\ \neg q$ cases, respectively. Our theory assumes that they construct only two models (i.e., $p\ q$ and $\neg p\ \neg q$). Their responses of irrelevance on $\neg p\ \neg q$ cases, which necessitate the construction of the $\neg p\ \neg q$ model through fleshing out, should take longer than the "true" responses on $p\ q$ cases. However, the two-model representation that underpins "irrelevant" responses on $\neg p\ \neg q$ cases should also lead these reasoners to produce "false" responses on $\neg p\ q$ cases that are not represented in the most complete representation they are able to construct. As a consequence, the time needed to produce the two types of responses on $\neg p$ cases should not differ. Finally, consider reasoners who adopt a conjunctive interpretation, responding "true" for $p\ q$ cases and false to all the other cases. Our theory assumes that they have only constructed a single $p\ q$ model representation. Thus, all their responses should be based on this one-model representation and, as a consequence, they should not strongly differ from each other in latencies.

We have until now omitted to make strong predictions about the "false" responses on $p\ \neg q$ cases. These responses have a particular status in mental model theory because they can be reached by two different routes. A fast route would consist in drawing "false" responses from the initial representation. Because $p$ is associated with $q$ in the initial model, its association with $\neg q$ can lead to the "false" response. However, a slow route would consist in deducing the "false" response by verifying that the $p\ \neg q$ case does not match any of the models constructed at the end of the fleshing out process. Because the number of models constructed depends on the kind of interpretation adopted, this slow route should take longer for defective conditional reasoners who construct three models than for defective biconditional reasoners who only construct two models. Unfortunately, the relative weight of these two routes in the evaluation process can not be predicted with certainty. Nonetheless, if the slow route underpins at least some responses, it can be predicted that the "false" responses to $p\ \neg q$ cases should take increasingly longer for conjunctive, defective biconditional, and defective conditional reasoners respectively. These predictions are summarised in Figure 1 in which it is assumed that all the responses of conjunctive reasoners are underpinned by a single model representation that underpins also the "true" responses to $p\ q$ cases of all the reasoners, whereas "indeterminate" responses to $\neg p\ \neg q$ cases require two models as well as the "false" responses to $\neg p\ q$ cases produced by biconditional reasoners, while the "indeterminate" responses to $\neg p\ q$ cases require three models (see Table 1), response times being a direct function of the number of models a given response involves.

Thus far, only a few studies have examined response times in conditional reasoning (but see Barrouillet, Grosset, & Lecas, 2000; De Neys, 2006; Evans & Newstead, 1977). We tested our hypotheses in a truth-table task in which we presented adult participants with basic conditionals like "If the star is yellow, then the circle is red" and asked them to judge for each of the four logical cases if this case made the sentence true, false, or if it is impossible to tell if the sentence is true or false (indeterminate response).

## METHOD

### Participants

A total of 46 undergraduate psychology students (mean age = 22.12) enrolled at the University of Geneva participated for course credit.

### Materials and procedure

Participants performed a computerised version of the truth table task (Barrouillet et al., 2008), and

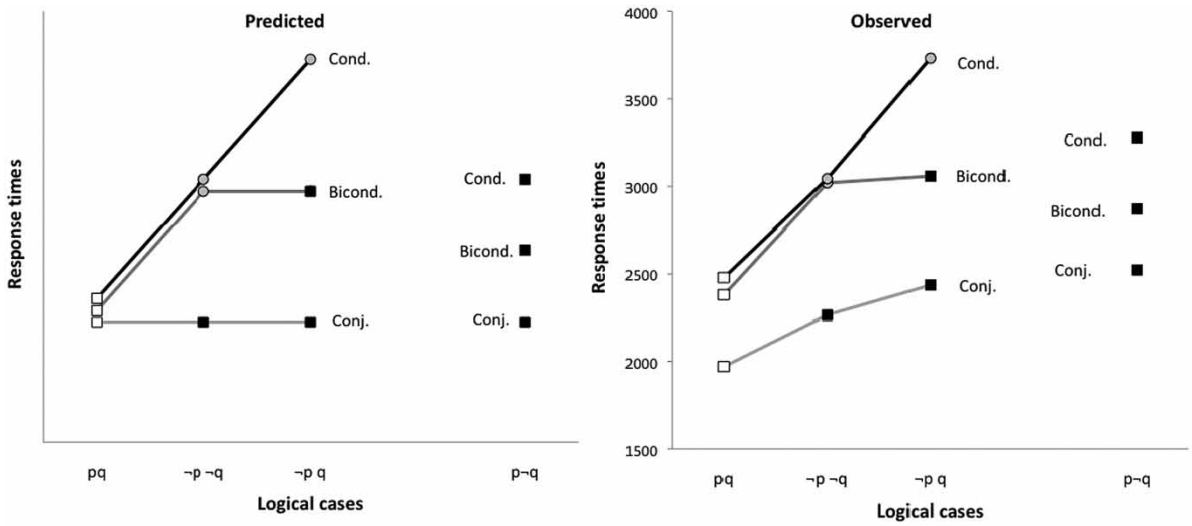


**Figure 1.** Predicted and observed mean response times as a function of logical cases and interpretation (Conj., Bicond., and Cond. for conjunctive, defective biconditional, and defective conditional interpretations, respectively). White squares, black squares, and grey circles refer to ''true'', ''false'', and ''indeterminate'' responses, respectively. Mean response times on $p\ q$, $\neg p\ \neg q$, and $\neg p\ q$ cases are predicted from the number of models they involve. Mean response times on $p\ \neg q$ cases are predicted as intermediate between the fastest and slowest responses in each group (see text for explanations about fast and slow routes for ''false'' responses in these cases).

were tested individually, supported by the experimenter. They were presented with a statement of the form ''if $p$ then $q$'', for example, ''if the circle is red, then the star is yellow'', displayed on the top of the screen. All the statements described the content of a box in which there was a circle on the left and a star on the right. After a delay of 2000 ms following the presentation of the statement, the box containing a circle and a star appeared on screen together with the three response options (''true'', ''false'', and ''one cannot know''[1]), while the statement was still displayed. Participants were instructed to judge if the content of the box made the statement true or false, or if one could not know. The three response options were displayed as response buttons at the bottom of the screen, and participants responded by clicking on one of them with the mouse. The position of the three response options (left, middle, or right) at the bottom of the screen was counterbalanced across participants. After giving a response, the cursor automatically moved back to the centre of the screen, so that participants' response times were not affected by the type of response given in the previous trial. The next trial started upon response or when 20 s had elapsed. The correspondence between the colour of the circle and the star in the box and those stipulated in the conditional statement was manipulated to form 15 trials for each of the four logical cases (i.e., $p\ q$, $p\ \neg q$, $\neg p\ q$, and $\neg p\ \neg q$), resulting in a total of 60 trials. The presentation of the test trials was preceded by the administration of four practice trials, which included one example of each of the four logical cases. No feedback was given on these practice trials. After the practice trials, the experimenter checked that participants had no question about the task and the experiment started. In case the participants indicated that they did not understand the task, they had a chance to read the instructions again, and to work through the practice trials once more. Presentation

[1] The response ''one cannot know'' was preferred to the often used ''irrelevant'' option for several reasons. First, ''irrelevant'' can be considered as an inappropriate response option for a task in which participants are asked to judge the truth value of the conditional statement. Indeed, ''irrelevant'' is not a modality of truth or falsity of the statement and does not belong to the same dimension as ''true'' and ''false'', which qualify the statement, whereas ''irrelevant'' qualifies the case under study. From the irrelevance of the case, it is impossible to assert something about the truth value of the sentence, which remains indeterminate. The option ''one cannot know'' is a way to express this indeterminacy. Second, we used the response option ''one cannot know'' in all our previous developmental studies because ''irrelevant'' has no direct translation in French and children are not familiar with the French word for ''indeterminate'' (i.e., *indéterminé*). Finally, using this response option leads to a rate of defective conditional responses in adults that do not differ from what is usually reported in the literature (Barrouillet et al., 2008; Gauffroy & Barrouillet, 2009, 2011).

order of the test trials was randomised across participants. Response times were recorded. Participants were instructed to perform the task as correctly as possible.

# RESULTS

## Overall results

The rate at which each type of response was selected and the corresponding mean response times are given in Table 2. It can be observed that responses that did not correspond to any expected interpretation (i.e., conjunctive, defective biconditional, or defective conditional) represented only 3% of the observed responses, suggesting that the participants paid attention to the task. However, these overall mean response times remained poorly informative because a particular type of response (e.g., "false" for $\neg p\ q$ cases) could result from different processes depending on the response pattern in which it was inserted, which revealed the interpretation adopted by the reasoner.

## Response patterns analysis

Response patterns were categorised by distinguishing between the following three expected interpretations: conjunctive (true, false, false, false responses for $p\ q$, $\neg p\ \neg q$, $\neg p\ q$, $p\ \neg q$ cases, respectively), defective biconditional (true, indeterminate, false, false), and defective conditional (true, indeterminate, indeterminate, false). A given participant was considered as consistent in a given interpretation if more than two-thirds (i.e., at least 11 out of 15) of her responses for each case ($p\ q$, $\neg p\ \neg q$, $\neg p\ q$, $p\ \neg q$) were consistent with her dominant interpretation. As expected, the defective conditional interpretation was predominant (19 participants, 41% of the sample), followed by the defective biconditional interpretation (12 participants, 26%) and only few participants gave conjunctive responses (seven participants, 15%). Eight participants (17% of the sample) could not be categorised as consistent in a given interpretation and were excluded from the subsequent analyses.[2]

**TABLE 2**
Rates and response times (with standard deviations) of the different types of responses for each logical case in the entire sample of participants

| *Logical case* | *Type of response* | *Percentage* | *Response time (ms)* |
|---|---|---|---|
| p q | True | 96 | 2477 (865) |
| | *False* | *2* | *2152 (493)* |
| | *Indeterminate* | *2* | *5355 (2353)* |
| ¬p ¬q | *True* | *1* | *6238 (4649)* |
| | False | 26 | 3105 (1587) |
| | Indeterminate | 72 | 3373 (1761) |
| ¬p q | *True* | *1* | *3601 (961)* |
| | False | 52 | 3553 (1659) |
| | Indeterminate | 47 | 4293 (1596) |
| p ¬q | *True* | *1* | *2448 (994)* |
| | False | 92 | 3229 (1271) |
| | *Indeterminate* | *7* | *3353 (1117)* |

Responses that do not correspond to any identified interpretation of the conditional are indicated in italics.

## Response time analysis

For those participants whose response pattern could be categorised as conjunctive, defective biconditional, or defective conditional, response times were only considered for responses that were consistent with their interpretation (e.g., only response times for true, indeterminate, indeterminate, and false responses for the $p\ q$, $\neg p\ \neg q$, $\neg p\ q$, $p\ \neg q$ cases, respectively, for defective conditional responders). This trimming procedure led to the exclusion of 2%, 3%, and 4% of the responses given by conjunctive, biconditional, and conditional responders, respectively. A repeated measures ANOVA was performed with case ($p\ q$, $\neg p\ \neg q$, $\neg p\ q$, $p\ \neg q$) as within-subject factor and interpretation (conjunctive, biconditional, and conditional) as between-subject factor on mean response times. As expected, response times on the different cases varied as a function of the interpretation of the conditional, the interaction between case and interpretation being significant, $F(6, 105) = 2.41$, $p < .05$. As it can be seen in Figure 1 (see also Table 3), and in line with our prediction, "indeterminate" responses took longer than "false" responses for

[2] From these eight participants, three exhibited a response pattern intermediary between two interpretations (two between the defective biconditional and the defective conditional interpretations, and one between the conjunctive and the defective biconditional interpretations), whereas one participant adopted a matching interpretation usually observed in children (see Barrouillet et al., 2008; "true", "false", "indeterminate", "indeterminate" for $p\ q$, $\neg p\ \neg q$, $\neg p\ q$, and $p\ \neg q$ cases, respectively). The other four participants did not comply to any identifiable interpretation.

**TABLE 3**
Mean response times (and standard deviations) for each logical case in the conjunctive (true, false, false, and false responses for *p q*, ¬*p* ¬*q*, ¬*p q*, and *p* ¬*q* cases, respectively), defective biconditional (true, indeterminate, false, and false responses), and defective conditional (true, indeterminate, indeterminate, and false responses) interpretation

| | *Interpretation* | | |
|---|---|---|---|
| *Logical cases* | *Conjunctive* | *Defective biconditional* | *Defective conditional* |
| p q | 1970 (487) | 2381 (771) | 2479 (820) |
| ¬p ¬q | 2265 (752) | 3020 (917) | 3044 (848) |
| ¬p q | 2436 (976) | 3059 (1041) | 3735 (1362) |
| p ¬q | 2523 (1026) | 2871 (818) | 3279 (969) |

both ¬*p* ¬*q* and ¬*p q* cases. Planned comparisons revealed that the difference between ''indeterminate'' and ''false'' responses was significant for both ¬*p* ¬*q* cases, $F(1, 35) = 4.55$, $p < .05$, and ¬*p q* cases, $F(1, 35) = 6.13$, $p < .05$. Additionally, to test our more specific hypotheses concerning each interpretation, we performed a series of repeated measures ANOVAs to evaluate the effects of case in each group.

*Defective conditional responders.* Concerning defective conditional responders, the effect of cases was significant, $F(3, 54) = 20.50$, $p < .001$. As we predicted, ''true'' responses on *p q* cases were much faster than ''indeterminate'' responses on ¬*p* ¬*q* cases, $F(1, 18) = 19.75$, $p < .001$. Most importantly, and still in line with our predictions, it took even longer to respond ''indeterminate'' on ¬*p q* cases than on ¬*p* ¬*q* cases, $F(1, 18) = 15.66$, $p < .001$, with a linear trend accounting for 99.7% of the variance associated with the three cases. With regards to *p* ¬*q* cases, ''false'' response times were slower than ''true'' responses to *p q* cases, $F(1, 18) = 38.32$, $p < .001$, but faster than ''indeterminate'' responses to ¬*p q* cases, $F(1, 18) = 7.35$, $p < .05$.

*Defective biconditional responders.* The effect of cases was also significant in defective biconditional responders, $F(3, 33) = 6.01$, $p < .01$. In line with our predictions, ''indeterminate'' responses to ¬*p* ¬*q* cases were slower than ''true'' responses to *p q* cases, $F(1, 11) = 36.31$, $p < .001$, whereas the former responses did not differ from ''false'' responses to ¬*p q* cases, $F < 1$. The ''false'' responses to *p* ¬*q* cases involved intermediate responses times that were longer than the ''true'' responses to *p q* cases, $F(1, 11) = 7.64$, $p < .05$, and slightly but not significantly shorter than the ''false'' responses to ¬*p q* cases, $F(1, 11) = 1.19$, $p = .30$.

*Conjunctive responders.* The number of conjunctive responders was very low (7 participants), so the response times were only indicative. Contrary to our expectations, the effect of cases reached significance, $F(3, 18) = 4.15$, $p < .05$. The fastest responses were observed with *p q* cases, ''false'' responses taking increasingly longer with ¬*p* ¬*q*, ¬*p q*, and *p* ¬*q* cases respectively. This trend could be due to the fact that it took longer to note a mismatch than a match between the case under study and the values involved in the conditional with, among mismatches, those involving complete mismatches (¬*p* ¬*q*) taking shorter than partial mismatches (¬*p q* and *p* ¬*q*). Finally, as we predicted, ''false'' responses to *p* ¬*q* cases took increasingly longer in conjunctive, biconditional, and conditional responders respectively, though the linear trend failed short to reach significance, $F(1, 35) = 3.35$, $p = .08$.

*Additional analyses.* Another way to test our predictions was to regress the observed mean response times onto the number of models assumed to underpin each response in each group of participants (see Table 1). Because it is impossible to predict the relative weight of the slow and fast routes in producing ''false'' responses to *p* ¬*q* cases, we chose the conservative estimate of an equal repartition between the two strategies. This led to assume that these responses are underpinned by a single model in conjunctive responders, either one or two models in biconditional responders (hence a mean value of 1.5), and either one or three models in conditional responders (mean value of 2). The analysis revealed a very good fit with 90% of the variance on the mean response times accounted for by the predicted number of mental models (Figure 2).

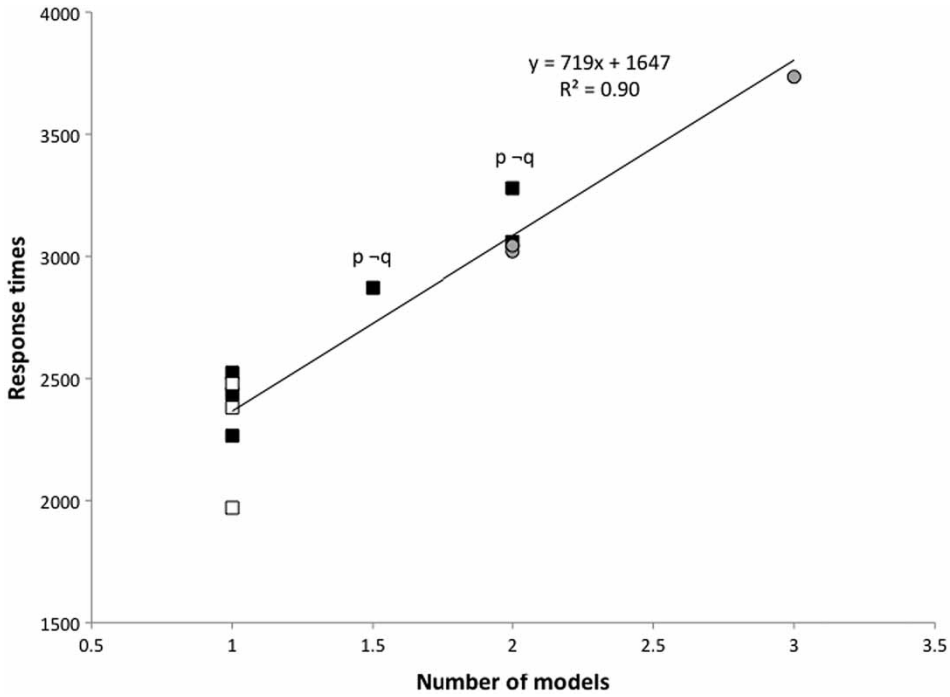


**Figure 2.** Mean response times as a function of the number of models. White squares, black squares, and grey circles refer to ''true'', ''false'', and ''indeterminate'' responses, respectively. The $p\ \neg q$ responses refer to ''false'' responses on these cases by biconditional (1.5 mental models) and conditional (2 models) responders. See text for the evaluation of the number of models on these cases.

## DISCUSSION

The present study contrasted the predictions issuing from our mental model theory of conditional and Evans' (2007) suppositional theory concerning the time course of responses in the truth table task. The results revealed that ''irrelevant'' responses to $\neg p$ cases are the slowest responses that these cases elicit. This finding is difficult to reconcile with the hypothesis that judgements of irrelevance result from heuristic processes that would precede the intervention of analytic processes, as the suppositional theory of conditional assumes. Rather, ''irrelevant'' responses seem to result from analytic processes. Two main findings corroborate this assumption. First, ''irrelevant'' responses result from a time-consuming process. Second, this process is optional, and several participants did not produce responses of irrelevance but deemed the conditional false for one or both $\neg p$ cases. When ''false'' responses were given for $\neg p$ cases, they were systematically faster than the corresponding ''irrelevant'' responses, suggesting that the process underpinning ''irrelevant'' responses was prematurely interrupted. These findings strongly point towards the conclusion that responses of irrelevance are produced by analytic processes that are time-consuming, demanding, and optional in nature. Thus, contrary to Evans' (2007) claim, the defective truth table is not a piece of evidence in favour of the suppositional theory. Many adults think that the conditional is neither true nor false for $\neg p$ cases. However, this is not due to some ''if-heuristic'' that would lead them to disregard these cases. If this was the case, there would be no reason to suppose that responses of irrelevance to $\neg p\ \neg q$ cases on the one hand and $\neg p\ q$ cases on the other would differ in their time course. However, those adults who gave ''irrelevant'' responses for both cases (i.e., defective conditional responders), took significantly longer for $\neg p\ q$ cases, as our mental model theory predicts.

The entire pattern of response times almost perfectly fitted the predictions issuing from the mental model theory according to which response times are a function of the number of models each response involves. However, it can be observed that a perfect fit was obtained when considering conditional and biconditional reasoners, whereas conjunctive responders did not exactly produced the expected pattern. This could be due to the fact that conjunctive interpretations are quite unusual

in adults who do not constitute the appropriate population to study the time course of conjunctive responding (only 15% of the adults in our sample adopted this interpretation). Developmental studies focusing on age groups in which conjunctive interpretations are predominant, such as early adolescence (Gauffroy & Barrouillet, 2009, 2011), would constitute a necessary complement to the present study.

## REFERENCES


Barrouillet, P. (2011). Dual-process theories of reasoning: The test of development. *Developmental Review*, *31*, 151–179.

Barrouillet, P., Gauffroy, C., & Lecas, J. F. (2008). Mental models and the suppositional account of conditionals. *Psychological Review*, *115*(3), 760–771.

Barrouillet, P., Grosset, N., & Lecas, J. F. (2000). Conditional reasoning by mental models: Chronometric and developmental evidence. *Cognition*, *75*, 237–266.

Barrouillet, P., & Lecas, J. F. (1998). How can mental models account for content effects in conditional reasoning? A developmental perspective. *Cognition*, *67*, 209–253.

Barrouillet, P., & Lecas, J. F. (2002). Content and context effects in children's and adults' conditional reasoning. *Quarterly Journal of Experimental Psychology*, *55*(3), 839–854.

Braine, M. D. S., & O'Brien, D. P. (1991). A theory of if: A lexical entry, reasoning program, and pragmatic principles. *Psychological Review*, *98*, 182–203.

De Neys, W. (2006). Automatic-heuristic and executive-analytic processing during reasoning: Chronometric and dual-task considerations. *Quarterly Journal of Experimental Psychology*, *59*, 1070–1100.

Epstein, S. (1994). Integration of the cognitive and psychodynamic unconscious. *The American Psychologist*, *49*, 709–724.

Evans, J. St. B. T. (2006). The heuristic-analytic theory of reasoning: Extension and evaluation. *Psychonomic Bulletin and Review*, *13*(3), 378–395.

Evans, J. St. B. T. (2007). *Hypothetical thinking: Dual processes in reasoning and judgment*. Hove, UK: Psychology Press.

Evans, J. St. B. T., Handley, S. J., Neilens, H., & Over, D. E. (2007). Thinking about conditionals: A study of individual differences. *Memory and Cognition*, *35*, 1772–1784.

Evans, J. St. B. T., & Newstead, S. E. (1977). Language and reasoning: A study of temporal factors. *Cognition*, *5*, 265–283.

Evans, J. St. B. T., & Over, D. E. (2004). *If*. Oxford, UK: Oxford University Press.

Evans, J. St. B. T., Over, D. E., & Handley, S. J. (2005). Suppositions, extensionality and conditionals: A critique of the mental model theory of Johnson-Laird and Byrne (2002). *Psychological Review*, *112*, 1040–1052.

Gauffroy, C., & Barrouillet, P. (2009). Heuristic and analytic processes in mental models for conditional: An integrative developmental theory. *Developmental Review*, *29*, 249–282.

Gauffroy, C., & Barrouillet, P. (2011). The primacy of thinking about possibilities in the development of reasoning. *Developmental Psychology*, *47*, 1000–1011.

Johnson-Laird, P. N., & Byrne, R. M. J. (1991). *Deduction*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Johnson-Laird, P. N., & Byrne, R. M. J. (2002). Conditionals: A theory of meaning, pragmatics, and inference. *Psychological Review*, *109*, 646–678.

Johnson-Laird, P. N., Byrne, R. M. J., & Schaeken, W. (1992). Propositional reasoning by model. *Psychological Review*, *99*, 418–439.

Kahneman, D. (2000). A psychological point of view: Violations of rational rules as a diagnostic of mental processes. *Behavioral and Brain Sciences*, *23*, 681–683.

Kahneman, D. (2011). *Thinking, fast and slow*. New York, NY: Farrar, Straus, & Giroux.

Oaksford, M., & Chater, N. (2001). The probabilistic approach to human reasoning. *Trends in Cognitive Sciences*, *5*, 349–357.