attention to the increasingly popular dual-process approach. The word deductive in the title of this section has been put in quotation marks to indicate that individuals presented with deductive-reasoning problems often fail to use deductive processes when trying to solve them.

Mental models

Johnson-Laird (e.g., 1983; Johnson-Laird et al., 2018) argues that reasoning involves constructing mental models. What is a mental model? According to Johnson-Laird et al. (2015, p. 202), a mental model is "an iconic representation of a possibility that depicts only those clauses in a compound assertion that are true. The mental models of a disjunction, '*A* or *B* but not both' accordingly represent two possibilities: possibly (*A*) and possibly (*B*)". It is *iconic* because its structure corresponds to what it represents.

Here is a concrete example of a mental model:

Premises
The lamp is on the right of the pad.
The book is on the left of the pad.
The clock is in front of the book.
The vase is in front of the lamp.

Conclusion
The clock is to the left of the vase.

According to Johnson-Laird (1983), people use the information contained in the premises to construct a mental model like this:

book	pad	lamp
clock		vase

The conclusion the clock is to the left of the vase clearly follows from the **mental model**. The fact we cannot construct a mental model consistent with the premises (but inconsistent with the conclusions) (i.e., we cannot construct a counterexample) indicates the model is valid.

Here are the theory's main assumptions:

- A mental model describing the given situation is constructed and the conclusions that follow are generated.
- An attempt is made to construct alternative models to falsify the conclusion by finding *counterexamples* to the conclusion. If a counterexample model is not found, the conclusion is deemed valid.
- The construction of mental models involves the limited resources of working memory (see Chapter 6).
- Reasoning problems requiring the construction of several mental models are harder than those requiring only one mental model because the former impose greater demands on working memory.
- The **principle of truth**: "Mental models represent what is true, but not what is false" (Khemlani & Johnson-Laird, 2017, p. 16). This minimises demands on working memory.

KEY TERMS

Mental models
An internal representation of some possible situation or event in the world having the same structure as that situation or event.

Principle of truth
The notion that assertions are represented by forming **mental models** concerning what is true while ignoring what is false.

Findings

Several studies support the notion that working memory plays a central role in the formation of mental models. Brunyé et al. (2008) found the central executive (see Glossary) and visuo-spatial sketchpad (see Glossary) components of the working memory system were heavily involved in constructing mental models. Copeland and Radvansky (2004) found working memory capacity (see Glossary) correlated +.42 with syllogistic reasoning performance.

Khemlani and Johnson-Laird (2017) reviewed 20 studies testing the principle of truth. These studies used various reasoning tasks, in all of which individuals failing to represent what is false in their mental models would produce illusory inferences. Numerous illusory inferences were drawn. In contrast, performance was very good with similar problems where adherence to the principle of truth was sufficient to produce the correct answer. Consider the following problem:

> Only one of the following premises is true about a particular hand of cards:
>
> There is a king in the hand or there is an ace, or both.
> There is a queen in the hand or there is an ace, or both.
> There is a jack in the hand or there is a 10, or both.
>
> Is it possible there is an ace in the hand?

What is your answer? Nearly everyone says "Yes", but this is wrong! If there were an ace in the hand, both the first two premises would be true. However, the problem states that only *one* of the premises is true.

Theoretically, individuals make illusory inferences because they ignore what is false. As predicted, people are less susceptible to such inferences if explicitly instructed to falsify the premises of reasoning problems (Newsome & Johnson-Laird, 2006).

Khemlani and Johnson-Laird (2012) carried out a meta-analysis of syllogistic reasoning studies to compare seven theories. The mental model theory was best at predicting participants' responses with a 95% success rate. However, it was relatively weak at rejecting responses people do *not* produce.

According to the theory, people search for counterexamples after having constructed their initial mental model and generated a conclusion. As a result, they may construct several mental models and consider several conclusions. Newstead et al. (1999) obtained no support for this conclusion: the average number of conclusions considered with multiple- and single-model syllogisms was very low (1.12. and 1.05, respectively).

Khemlani et al. (2012) also found that people generate relatively few counterexamples. Participants were given this problem: They're not living adult males. *So, who could they be?* There are *seven* possibilities (e.g., dead adult males; living girls) but participants listed only *four* possibilities on average.

The theory struggles with ambiguous reasoning problems. Here is an example (Ragni & Knauff, 2013):

The Porsche is to the right of the Ferrari.
The Beetle is to the left of the Porsche.
The Dodge is in front of the Beetle.
The Volvo is in front of the Porsche.

There is no definite answer to the question "Which relation holds between the Beetle and the Ferrari?". Mental model theory does not predict which answer will be given by most participants. Ragni and Knauff (2013) argued that reasoners prefer easily constructed mental models (e.g., the Beetle is to the left of the Ferrari in the above problem). Their findings supported their theory over mental model theory.

Evaluation

The theory has several successes to its credit. First, the theory compares well against other theories of reasoning (Khemlani & Johnson-Laird, 2012; Johnson-Laird et al., 2018) and also performs well when predicting performance on Wason's selection task (Ragni et al., 2018). Second, as predicted, working memory is involved in the construction of mental models. Third, there is substantial support for the principle of truth. Fourth, as discussed later (pp. 704–705), the theory has recently been developed to account for reasoning about probabilities (Johnson-Laird et al., 2015).

What are the theory's limitations? First, most people find deductive reasoning very hard and so resort to easier forms of processing (discussed shortly). Second, most people do not typically search for counterexamples as predicted theoretically. Third, the processes involved in forming mental models are *underspecified*. It is assumed people use background knowledge when forming mental models, but the theory does not spell how we decide *which* information to include in a mental model. Fourth, mental model theory often fails to predict people's answers with ambiguous reasoning problems (e.g., Ragni & Knauff, 2013).

Dual-process theories

Several theorists (e.g., Kahneman, 2003; see Chapter 13 and Evans, 2018) have proposed dual-process (sometimes called dual-system) theoretical accounts of human reasoning and other aspects of higher-level cognition. While they differ from each other in various ways, "dual-process theories should be viewed as a *family* whose members share some features . . . it includes close relatives . . . as well as distant cousins" (Evans, 2018, p. 151). Commonalities among dual-process theories are discussed below.

Evans and Stanovich (2013a,b) provided an integrative account of dual-process theories based on a distinction between Type 1 intuitive processing and Type 2 reflective processing. One defining feature of Type 1 processing is *autonomy* (it is mandatory or necessary when the appropriate triggering stimuli are encountered). Its other defining feature is the lack of involvement of working memory (see Glossary). Note there is substantial diversity among Type 1 processes. In contrast, a defining feature of Type 2 processing is that it requires *working memory*. Its other defining feature is cognitive decoupling or mental simulation – hypothetical reasoning not constrained by the immediate environment.

Evans and Stanovich (2013a,b) also identified several features often (but not invariably) associated with the two types of processing. Features of Type 1 processing include the following: fast; high capacity; parallel; non-conscious; automatic; and independent of cognitive ability. Features of Type 2 processing include the following: slow; capacity-limited; serial; conscious; controlled; and correlated with cognitive ability.

Evans and Stanovich (2013a,b) assumed that individuals trying to solve reasoning problems initially use intuitive Type 1 processing to generate a rapid heuristic answer which may be corrected by a subsequent more deliberate answer produced via slow Type 2 processing. A key assumption is that reasoning performance will generally (but not invariably) be superior when it involves Type 2 processing in addition to Type 1 processing. This approach is often referred to as the default-interventionist model.

Why is it wrong to equate Type 1 processing with biased (and often incorrect) reasoning and Type 2 processing with correct reasoning? This question was addressed by Evans (2018). He pointed out that we have all had the experience of using effortful Type 2 processing when trying to solve a problem in mathematics without producing the correct response. In addition, correct reasoning does not always require Type 2 processing: "We often get things right via habit or reliable intuition [both involving Type 1 processing], as all dual-process authors agree" (p. 163).

We will start by considering predictions made by early dual-process theories of reasoning (e.g., Evans, 2006). According to these theories, various factors increase reasoners' use of time-consuming and effortful analytic or Type 2 processes:

(1) the reasoners are highly intelligent;
(2) sufficient time is available for Type 2 processing;
(3) reasoners do not need to perform a secondary demanding task at the same time.

Findings

Much research to test the above predictions has focused on belief bias (discussed earlier, pp. 678–679; see Ball & Thompson, 2018). This bias occurs in syllogistic reasoning when a logically valid but unbelievable conclusion is rejected as invalid, or a logically invalid but believable conclusion is accepted as valid. According to dual-process theories, there will be less belief bias (and superior performance) when Type 2 processes are used. Thus, reasoners' use of Type 2 processes will generally reduce belief bias.

There is much support for the first prediction that more intelligent reasoners exhibit less belief bias than less intelligent ones (e.g., Trippas et al., 2013). More intelligent reasoners might show less belief bias because of their high cognitive ability *or* because they *choose* to adopt an analytic cognitive style. Trippas et al. (2015) found the willingness to engage in analytic thinking was more important. These findings are consistent with dual-process theory because they emphasise the role played by Type 2 processes in reducing belief bias and enhancing reasoning performance.

There is also support for the second prediction that there should be less belief bias with ample thinking time (e.g., Evans and Curtis-Holmes, 2005) because restricting thinking time reduces reasoners' ability to use Type 2 processes. In similar fashion, errors in conditional reasoning occur more often when reasoners must respond rapidly (Markovits et al., 2013; discussed earlier, p. 675).

De Neys (2006) tested the third prediction above by presenting reasoning problems on their own or with a secondary task low or high in its demands. As predicted, reasoners exhibited much more belief bias when performing a demanding secondary task.

Theoretical differences and developments

We have seen early dual-process theories of reasoning generated many predictions supported by experimental evidence. However, these theories were oversimplified. For example, as we will see, the assumption that correct reasoning performance reflects Type 2 processing whereas incorrect reasoning performance reflects Type 1 processing is only partially correct.

Another oversimplification concerns the *relationship* between Type 1 and 2 processing during reasoning tasks. As we saw earlier, several theorists (e.g., Evans & Stanovich, 2013a) proposed *serial* models for reasoning in which Type 1 processing provides a rapid intuitive answer. This is often followed by slow Type 2 processing which may lead to the initial intuitive answer being corrected and replaced by a more reflective answer.

De Neys (2012) argued the above theoretical position is too narrow and incomplete. He identified three models of how Type 1 and 2 processing combine (see Figure 14.4).

(1) The traditional theoretical approach described above (serial model) involves serial processing with intuitive (or Type 1) processing being followed by deliberate (or Type 2) processing.

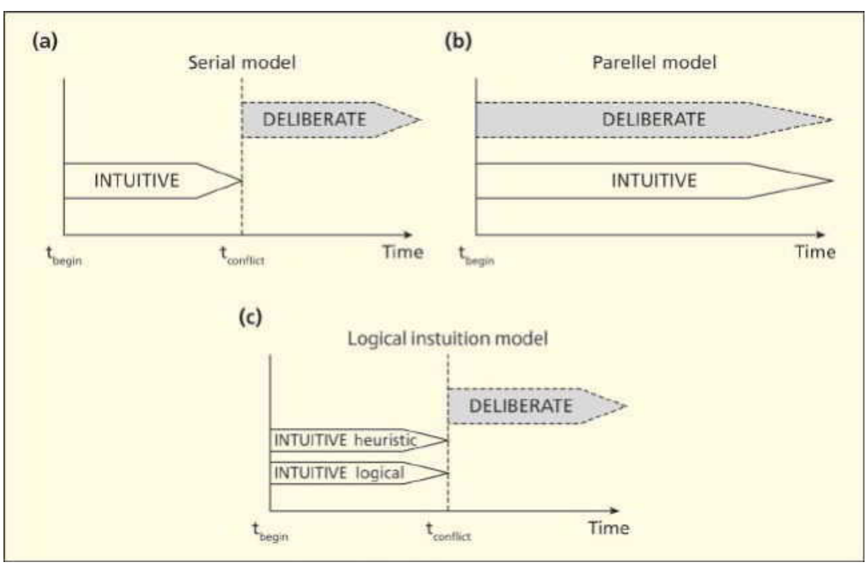

Figure 14.4
Three models of the relationship between the intuitive and deliberate systems. (a) Serial model: intuitive processing may or may not be followed by deliberate processing. (b) Parallel model: intuitive and deliberate processing are both involved from the outset. (c) Logical intuition model: deliberate processing is triggered if there is a conflict between initial intuitive heuristic and intuitive logical responses produced in parallel.

From De Neys (2012). Reprinted by permission of SAGE Publications.

(2) In the parallel model, intuitive (Type 1) and deliberate (Type 2) processes occur at the same time. This model is wasteful of cognitive resources because effortful processes are always used.
(3) According to the logical intuition model (advocated by De Neys, 2012, 2014), two types of intuitive responses (intuitive heuristic and intuitive logical) are activated in parallel. If these two responses conflict, deliberate (Type 2) processes resolve matters. The notion of intuitive logical processing sounds paradoxical. However, De Neys argued that traditional logical principles can be activated fairly automatically.

Findings

Evidence consistent with the logical intuition model was reported by De Neys et al. (2010) using a syllogistic reasoning task involving conflict (or no conflict) between the logical validity and believability of the conclusions. There was strong belief bias – accuracy was only 52% on conflict (belief bias) trials compared to 89% on non-conflict trials.

The very poor performance on conflict problems (marginally greater than chance) suggests reasoners failed to detect their logical structure. However, De Neys et al. (2010) found participants had greater physiological arousal on conflict trials suggesting conflict was registered within the processing system below the conscious level. The implication is that some logical processing can be intuitive rather than analytic.

Further support for the logical intuition model was reported by Trippas et al. (2016). Participants simply decided how much they liked various sentences. Sentences following logically from preceding sentences were rated more likeable than those that did not. Since the task made no reference to logical validity, this finding suggests participants had an implicit sensitivity to logical structure based primarily involving Type 1 processes.

Bago and De Neys (2017) presented participants with various syllogistic reasoning problems involving conflict between the believability and validity of the conclusion. The participants provided two responses to each problem: (1) a fast, intuitive response; and (2) a much slower and more deliberate response.

According to the default-interventionist model (e.g., Evans & Stanovich, 2013a; discussed earlier, pp. 683–684), we would predict low levels of accurate fast responses and substantially more correct deliberate responses than intuitive ones. Neither prediction was supported. On average, 44% of the fast responses were accurate, and only 7% of initially inaccurate fast responses were followed by accurate slow responses.

In one of their experiments, Bago and De Neys (2017) used the same syllogistic reasoning task described above. However, there was an additional requirement on participants – they performed a secondary demanding task at the same time to reduce their engagement in Type 2 analytic processing. Nevertheless, 49% of fast responses on conflict problems were correct. Overall, these findings support the logical intuition model in that fast (and presumably Type 1) processes often produce logically correct responses.

Similar findings to those of Bago and De Neys (2017) have been reported in research on conditional reasoning (see Glossary; see pp. 673–676). Newman et al. (2017) used conditional-reasoning problems involving belief bias (see Glossary). Reasoners provided a fast and a slow response to each problem. Contrary to the predictions of early dual-process theories, fast responses were often correct based on logical validity and slow responses were often incorrect and exhibited belief bias. These findings suggest a blurring of the distinction between Type 1 and Type 2 processes – there was a mixture of logically correct and belief-based responses regardless of whether Type 1 processes (fast responses) or Type 2 processes (slow responses) were involved.

Imagine we presented reasoners with conditional-reasoning problems involving a conflict between logical validity and believability (e.g., "If a child is happy, then it cries; suppose a child laughs; does it follow that the child is happy?"). According to logic, the correct answer is "No". According to beliefs and our knowledge of the world, the answer is "Yes". Trippas et al. (2017) used problems like that but with the novel twist that reasoners were sometimes told to answer the question based on their beliefs rather than logic.

According to early dual-process theories (e.g., the default-interventionist model), responding on the basis of belief should involve Type 1 processing and so should be faster than responding on the basis of logic (involving Type 2 processing). In addition, the believability of the conclusion (accessed rapidly) should interfere with logic-based responses (accessed slowly) but the reverse should not be the case.

Neither prediction was supported (Trippas et al., 2017). Response times were comparable on belief-based and logic-based trials, and the logical validity of the conclusion interfered with belief-based responding. However, these findings are entirely consistent with parallel-processing theories.

Thompson et al. (2018) carried out a similar study. Participants differing in cognitive ability received incongruent reasoning problems involving a conflict between belief and logic and had to respond on the basis of belief or logic. There were two main findings (see Figure 14.5):

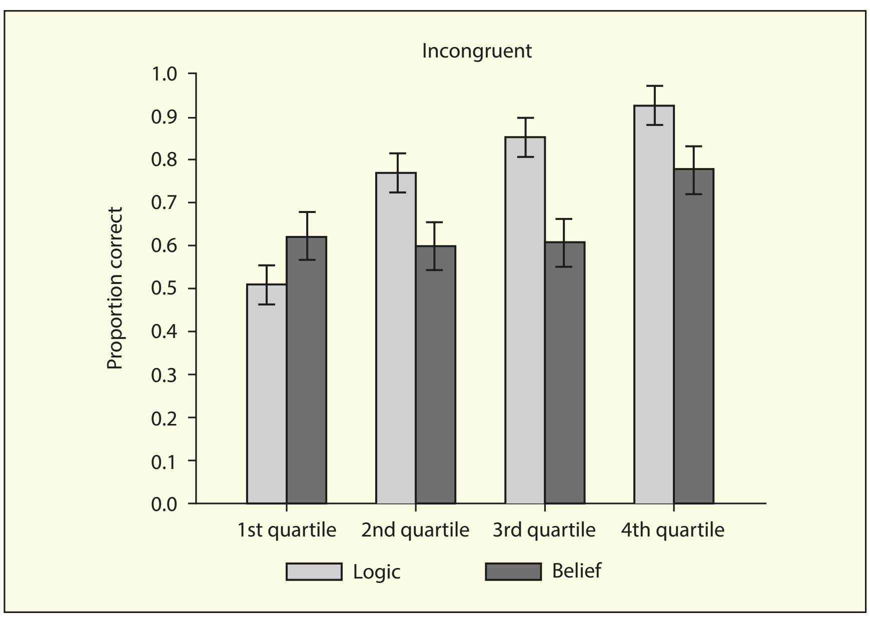

Figure 14.5
Proportion correct on incongruent syllogisms as a function of instructions (respond on the basis of logic or belief) and cognitive ability (1st quartile = lowest; 4th quartile = highest).
From Thompson et al. (2018).

KEY TERM

Meta-reasoning
Monitoring processes that influence the time, effort and strategies used during reasoning and problem solving.

(1) The more intelligent reasoners had greater difficulty resolving conflict when providing belief-based responses rather than logic-based responses.
(2) The less intelligent reasoners exhibited the opposite pattern.

These findings suggest more intelligent individuals generate logic-based responses faster than belief-based ones, whereas less intelligent individuals generate belief-based responses faster.

What conclusions should we draw? First, rather than arguing belief-based responses involve fast Type 1 processing whereas logic-based responses involve slow Type 2 processing, we need to consider individual differences. Second, "If responses (belief- or logic-based) can be generated either quickly and effortlessly or slowly and deliberately, perhaps these responses merely differ on a single dimension, namely, complexity" (Newman et al., 2017, p. 1165).

What causes Type 2 processing?

What determines whether reasoners' responses are based on analytic (Type 2) processing or whether they reflect only intuitive (Type 1) processes? The theories discussed above address this issue. Traditional serial models assume that Type 2 processes *monitor* the output of Type 1 processes and it is this monitoring process that determines whether reasoning performance is based on Type 2 processes. In similar fashion, many parallel models assume Type 2 reasoning is triggered when conflict monitoring (involving Type 2 processing) leads to conflict detection. What is puzzling about all these theories is that, "They assume that Type 2 processing is effectively caused by itself" (Pennycook et al., 2015, p. 36).

Ackerman and Thompson (2017, p. 607) provided a detailed account of **meta-reasoning**: "The processes that monitor the progress of our reasoning and problem-solving activities and regulate the time and effort devoted to them" (see Figure 14.6). Monitoring processes assess the probability of success before, during and after performing a reasoning task. The most important monitoring feature is the feeling of rightness: "the degree to which the first solution that comes to mind feels right" (p. 608). Only when this feeling is weak do reasoners engage in substantial Type 2 or analytic processing.

Thompson et al. (2011) studied the role of feeling-of-rightness ratings on the use of Type 2 processes with syllogistic and conditional-reasoning tasks. Participants provided an initial answer immediately after reading each problem (intuitive, or Type 1, answer) followed by an assessment of that answer's correctness (feeling of rightness). Participants then had unlimited time to reconsider their initial answer and provide a final analytic, or Type 2, answer. As predicted, participants spent longer reconsidering their intuitive answer and were more likely to change it when they had low feelings of rightness.

What determines feeling-of-rightness ratings? Thompson et al. (2013b) addressed this issue in a study on syllogistic reasoning. Participants produced the first response that came to mind, provided a feeling-of-rightness rating, and then produced a slower, more deliberate response. Feeling-of-rightness

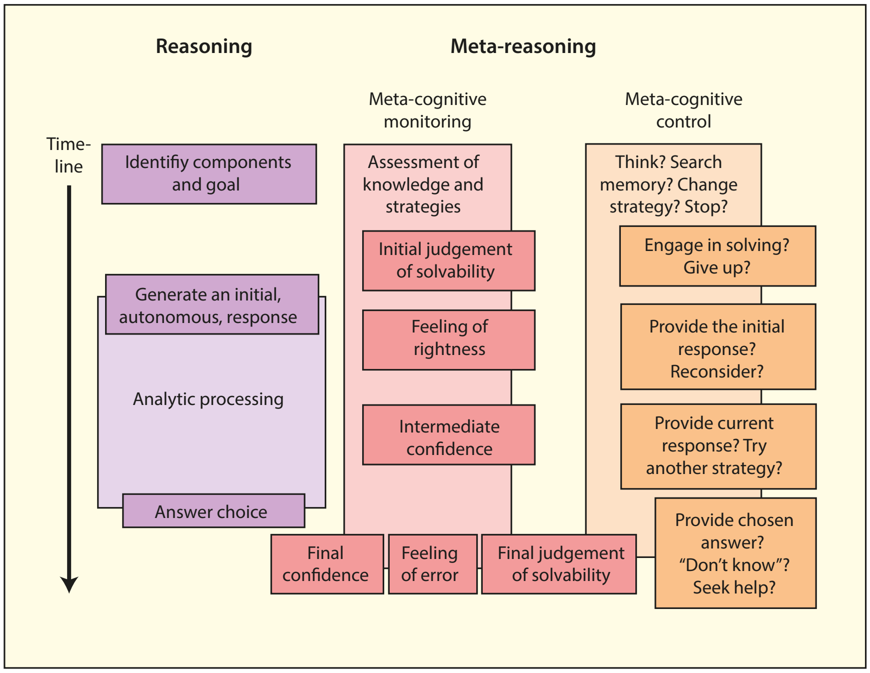

Figure 14.6
The approximate time courses of reasoning and meta-reasoning processes during reasoning and problem solving.
From Ackerman & Thompson (2017).

ratings were higher when the first response was produced rapidly rather than slowly, indicating the importance of response fluency.

Most research indicates response fluency is a fallible measure of response accuracy. For example, people give higher feeling-of-rightness ratings to reasoning problems having familiar rather than unfamiliar content even when the former problems are harder (Ackerman & Thompson, 2017).

Evaluation

What are the strengths of the contemporary dual-process approach? First, dual-process theories have become increasingly popular and wide-ranging. For example, they provide explanations for syllogistic reasoning and conditional reasoning (Verschueren et al, 2005, discussed earlier, pp. 674–675). In addition, such theories account for findings in problem solving (see Chapter 12), judgement and decision-making (see Chapter 13). Second, "Dual-process theory . . . provides a valuable high-level framework within which more specific and testable models can be developed" (Evans, 2018, p. 163).

Third, there have been increasingly sophisticated attempts to clarify the relationship between Type 1 and Type 2 processes (e.g., whether they are used serially or in parallel). Fourth, we have an enhanced understanding of meta-reasoning processes (especially those involved in monitoring). Fifth, recent theory and research are starting to take account of the *flexibility* of processing on reasoning problems due to the precise form of the problem and individual differences (Thompson et al., 2018).

What are the limitations with the dual-process approach? First, the processes used by reasoners vary depending on their abilities and preferences, their motivation and their task requirements. Melnikoff and Bargh (2018; see Chapter 13) identified two ways many dual-process theories are over-simplified: (1) they often imply that Type 1 processes are "bad" and error-prone, whereas Type 2 processes are "good"; and (2) they assume many cognitive processes can be assigned to just two types.

Second, "The absence of a clear and general definition of a Type 1 or Type 2 *response* does create difficulty for researchers wishing to test [dual-process] theories" (Evans, 2018, p. 163). For example, it is often assumed theoretically that fast responses reflect Type 1 processing and are error-prone whereas slow responses reflect Type 2 processing and are generally accurate. However, we have discussed various studies disconfirming those assumptions.

Third, there has been a rapid increase in the findings that require to be explained theoretically, and theories have not kept pace with this increase. For example, meta-reasoning often plays an important role in influencing reasoners' processing strategies and performance. As yet, however, no theorists have integrated meta-reasoning processes into a comprehensive dual-process theory of reasoning.

BRAIN SYSTEMS IN REASONING

Interactive feature: Primal Pictures' 3D atlas of the brain

In recent years, there has been increased research designed to identify the brain regions associated with deductive reasoning. Prado et al. (2011) reported a meta-analytic review of 28 neuroimaging studies on deductive reasoning (see Figure 14.7). They obtained evidence for a core brain system centred in the left hemisphere involving frontal and parietal areas. Specific brain areas activated during deductive reasoning included the inferior frontal gyrus, the medial frontal gyrus, the precentral gyrus and the basal ganglia.

Coetzee and Monti (2018) reported findings broadly consistent with those of Prado et al. (2011). They used fMRI to assess brain activation while participants performed deductive-reasoning tasks. There were two key findings. First, core regions (left rostrolateral cortex, in BA10; medial prefrontal cortex, in BA8) were more strongly activated with complex (rather than) simple deductive reasoning. Second, the main language areas

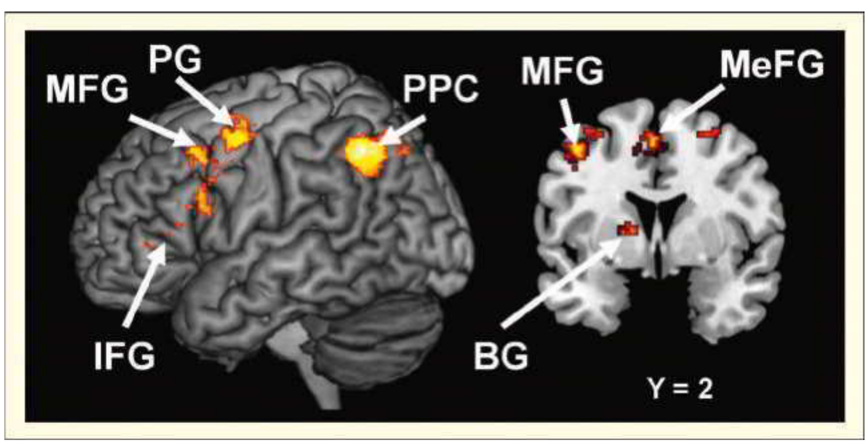

Figure 14.7
Brain regions most consistently activated across 28 studies of deductive reasoning. PG = precentral gyrus; MFG = middle frontal gyrus; PPC = posterior parietal cortex; IFG = inferior frontal gyrus; BG = basal ganglia; MeFG = medial frontal gyrus.

From Prado et al. (2011). © Massachusetts Institute of Technology, by permission of the MIT Press.