performed) and internal memories (e.g., those of events imagined or actions planned or intended to perform).

►Metacognition

Realization

Definition

Mental properties, although not identical to physical properties, are still said to be physical properties in a broad sense in virtue of being realized by physical properties, just as a machine table, for instance, is implemented by but not identical to the states of its physical implementation. A central idea is that if property F realizes property G, then G is not something distinct from or something over and above F. Unlike identity, realization is asymmetric: F realizes G only if the instantiation of F in o necessitates or determines the instantiation of G in o but not vice versa, where the necessity in question is at least nomological necessity.

►Epiphenomenalism

Reasoning

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Definition

Reasoning is a process of drawing inferences from information that is taken for granted. Formal reasoning is within the scope of mathematics and philosophy. It is the study of inferences whose validity only derives from its formal structure. Mental reasoning is a function of the human brain. It comes into play whenever people go beyond what is explicitly given. It is the cognitive activity to infer that something must be true, or is likely to be true, given that the known information is true. The problem information is given by a number of statements which are called ►premises, and the task is to find a ►conclusion that follows from these premises. The following inference is a typical reasoning problem:

If a patient's left hemisphere is damaged, then he has impaired reasoning abilities.
Alan's left hemisphere is damaged.

- -

Therefore, Alan has impaired reasoning abilities.

Although the premises (above the line) do not say anything about Alan's reasoning abilities, most people immediately agree with what is stated in the conclusion (below the line). The conclusion necessarily – logically – follows from the premises. Another inference is given in the following example.

Mammals have a nervous system.
Birds have a nervous system.
Fishes have a nervous system.

- -

All animals have a nervous system.

Although a reasoner might form the belief that the conclusion could be true, the premises do not warrant the truth of the conclusion. The reasoner is generating the ►hypothesis that the conclusion is true. The former inference is an example of ►deductive reasoning, while the latter is an instance of ►inductive reasoning.

Characteristics

Deductive and Inductive Reasoning

Mental deductive reasoning is strongly related to formal logic. The latter serves as the normative model for the former (a critical assessment of this account from a neuroscience perspective can be found in [1]). To explore deductive reasoning in the psychological laboratory, people are typically asked to draw conclusions from given premises and later their responses are evaluated for logical validity. This evaluation is based on logical correctness only and does not account for the content of the statements (the deductive inference above is logically valid, although the content concerning the role of the left hemisphere is probably wrong; see below). In ►conditional reasoning, the premises of the problem consist of an "if A then B" construct that posits B to be true if A is true. The two logically valid inferences are the Modus Ponens (if p then q; p; q, MP) and the Modus Tollens (if p then q; not-q; not-p, MT). Humans are pretty good in making inferences of the form MP, but they make many mistakes in the form MT [2], In ►syllogistic reasoning, the premises of the problem consist of quantified statements such as "All A are B," "Some A are B," "No A are B," and "Some A are not B." People often make many mistakes in syllogistic reasoning, in part because of the existence of a variety of biases [2]. The most frequently used sort of inferences in daily life (and in the psychological lab) are based on relations. In ►relational reasoning, at least two relational terms

R

A r_1 B and B r_2 C are given as premises and the goal is to find a conclusion A r_3 C that is consistent with the premises. The relations represent spatial (e.g., left of), temporal (e.g., earlier than), or more abstract information (e.g., is akin to). People are pretty good in making such inferences, but the difficulty depends on the number of premises, the order of terms and premises, the content, and the ease to envisage the content of the problem [3,4]. Moreover, in cases where a reasoning problem has multiple solutions, reasoners consistently prefer the same subset of possible answers – and often just a single solution [5].

Inductive reasoning has not as much to do with logic because the conclusion goes beyond the information given in the premises. The premises only provide good reasons for accepting the conclusion. Thus, inductive reasoning is not truth-preserving but it is the most important basis of our ability to create new knowledge. This new knowledge is often based on a limited number of observations from which we formulate a law recurring to a set of phenomenal experiences. Cognitive theories of induction typically describe it as a process in which hypotheses are generated, selected, and evaluated [6,7]. Although there is no generally accepted definition of the term "induction," the majority of psychologists adopt the very broad definition that mental inductions are "all inferential processes that expand knowledge in the face of uncertainty" [6, p. 1]. Given that almost nothing is known about the neural basis of inductive reasoning this review is restricted to deductive reasoning. An easily accessible summary of behavioral findings on inductive reasoning can be found in Manktelow [8]. The main problems of research on inductive reasoning are summarized in Sloman and Lagnado [9].

Cognitive Theories of Reasoning

There are two main theories of deductive reasoning. They differ in the postulated underlying mental representations and the computational process that work on these representations. In one theory, it is believed that people think deductively by applying mental ►rules which are similar to rules in computer programs. In the other theory, deductive reasoning is conceived as a process in which the reasoner constructs, inspects, and manipulates ►mental models. The ►rule-based theory is a syntactic theory of reasoning, as it is based on the form of the argument only, whereas, the ►mental models theory is a semantic theory, because it is based on the meaning (the interpretation) of the premises.

The ►rule-based theories are primarily represented by the work of Rips [10] and Braine and O'Brian [11]. These theories claim that reasoners rely on formal rules of inference akin to those of formal logic, and that inference is a process of proof in which the rules are applied to mental sentences (but cf. Stenning and Oberlander [12]). The formal rules govern sentential connectives such as "if" and quantifiers such as "any," and they can account for relational inferences when they are supplemented with axioms governing transitivity, such as: For any a, b, and c, if a is taller than b and b is taller than c, then a is taller than c. The rules are represented in the human brain and the sequence of applied rules results in a mental proof, or derivation, which is seen as analogous to the proofs of formal logic [10].

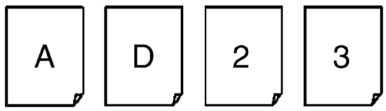
The ►theory of mental models has been developed by Johnson-Laird and colleagues [13–15]. According to the model theory, human reasoning relies on the construction of integrated mental representations of the information that is given in the reasoning problem's premises. These integrated representations are models in the strict logical sense. They capture what is common to all the different ways in which the premises can be interpreted. They represent in "small scale" how "reality" could be – according to what is stated in the premises of a reasoning problem. The model theory distinguishes between three different mental operations. In the construction phase, reasoners construct the mental model that reflects the information from the premises. In the inspection phase, this model is inspected to find new information that is not explicitly given in the premises. In the variation phase, reasoners try to construct alternative models from the premises that refute the putative conclusion. If no such model is found, the putative conclusion is considered true [14].

Reasoning and the Brain

The two reasoning theories are related to different brain areas. The rule theory implies that reasoning is a linguistic and syntactic process, and so reasoning should depend on regions located in the left hemisphere. The model theory, in contrast, postulates that a major component of reasoning is not verbal, and so the theory predicts that the right cerebral hemisphere should play a significant role in reasoning [16]. More detailed predictions are related to specific brain areas. Here the rule theory assumes that the neural computations during reasoning are implemented in the language processing regions and here specifically in the temporal cortex, while the model theory predicts that the parietal and occipital cortical areas involved in spatial working memory, perception, and movement control are evoked by reasoning [17]. The lateralization of the reasoning process has been primarily investigated in patient studies, while brain imaging techniques allow for a more detailed localization of reasoning processes.

Patient Studies

Early studies of patients with brain-damages seemed to support the rule-based theories of reasoning. Conditional reasoning has been studied by Golding [18]. The author used the Wason-Selection-Task, which is probably the most important paradigm in behavioral research on human reasoning [19]. In the task, four



Reasoning. Figure 1 The Wason selection task.

cards are presented to the participants (see Fig. 1) and they are instructed to verify the rule "If there is a vowel on one side of the card, then there is an even number on the other side." The participants are allowed to turn over the cards in order to verify the rule. The visible letters and numbers on the card correspond to the four possible propositions p, not-p, q, and not-q. According to the propositional calculus of formal logic the only correct choices are p (according to the MP a q must be on the other side) and not-q (according to the MT a not-p must be on the other side). However, only one of the left-hemisphere-damaged patients but half of the right-hemisphere-damaged patients selected the two correct cards. Deglin and Kinsbourne [20] studied syllogistic reasoning with psychiatric patients while recovering from transitory ictal suppression of one hemisphere by electroconvulsive therapy (ECT; that simulates a short-term lesion). The premises were familiar or unfamiliar and true or false. When the right hemisphere was suppressed, the participants tended to perform deductive inferences even when the factual answer was obviously false. While their left hemisphere was suppressed, the same participants used their prior knowledge and if the content was unfamiliar they completely refused to answer. Patient studies on relational reasoning have been reported by Caramazza et al. [21] and Read [22]. Caramazza et al. [21] presented relational premises such as "Mike is taller than George" to brain-damaged patients. After reading the statements they had to answer either a congruent ("Who is taller?") or incongruent ("Who is shorter?") question. The left-hemispheric patients showed impaired performance in all problems no matter they were congruent or incongruent. Right-hemispheric patients, in contrast, showed impaired performance only in the incongruent problems. Read [22] used two relational premises and asked patients who suffered from temporal-lobectomy to generate a conclusion from these statements. Overall, the left-hemispheric patients again performed weaker than the patients with right-temporal-lobectomy, but the right-hemispheric patients were more impaired with the incongruent conclusions.

The reported findings have been frequently used by neuroscientists to support the idea that reasoning is mainly a linguistic and syntactic process, but this interpretation seems awkward to many cognitive oriented reasoning researchers. Although lesions to the left hemisphere might result in a deficit in the processing of the linguistic elements of the problem and, thus, impair overall performance, it does not necessarily follow that the damage will also affect the reasoning process. It is likely that left-hemisphere lesions lead to an inability to process the linguistic aspects of a reasoning problem, but that for the pure reasoning process the right hemisphere is important. This interpretation would also explain most of the findings. For instance, in the studies by Caramazza et al. [21] and Read [22] the patients had problems in logically deducing the converse of relations. Moreover, Whitaker et al. [23] examined conditional reasoning in patients that had undergone a unilateral anterior temporal lobectomy, one group to the right hemisphere and the other group to the left hemisphere. The content of the problems was related to the participants' prior knowledge of the world. Given the premises

If it rained, the streets will be dry.
It rained.

The right-hemisphere-damaged patients had a strong tendency to conclude "The streets will be wet" while the left-hemisphere-damaged patients concluded "The street will be dry." In other words, these right-hemispheric patients were unable to perform the deduction in isolation from their prior knowledge, while the left-hemisphere patients relied on the linguistic content of the problem.

Brain Imaging Studies

Brain imaging studies have been conducted on all the main types of deductive inferences. As with the patient studies the early findings have been frequently interpreted in favor of the rule-based theories of reasoning, as they have shown that reasoning activates a fronto-temporal neural network often just in the left hemisphere [24,25]. However, more sophisticated experimental paradigms suggest this might be due to the confounding of linguistic processing and deductive reasoning. Knauff et al. [17] studied conditional reasoning problems by presenting premises such as "If the teacher is in love, then he likes pizza" to the participants. In half of the problems the second premise was "The teacher is in love" and the participants had to conclude (by MP) "The teacher likes pizza." In the other half of problems the second premises was "The teacher does not like pizza" and the participants had to conclude (by MT) "The teacher is not in love." Both types of problems activated a bilateral occipito-parietal-frontal network, including parts of the prefrontal cortex and the cingulate gyrus, the superior and inferior parietal cortex, the precuneus, and the visual association cortex. These finding are difficult to explain based on purely linguistic processes, as the activated brain areas are implicated in the processing of visual and spatial information and visuo-spatial working memory (→) (cf. [26–28]). Similar findings have been reported from a study on syllogistic reasoning. Goel et al. [29] used problems with semantic content (e.g., "All apples are red; all red fruit are sweet; therefore all apples are sweet") and without semantic content (e.g., “All A are B; all B are C; therefore all A are C”). They found evidence for the engagement of both linguistic and spatial systems. The role of linguistic and spatial systems has been largely investigated by means of relational reasoning problems. In the study by Knauff et al. [30] such problems activated similar brain areas as the conditional problems did. However, the activity in visual association areas was even higher than during conditional reasoning. Goel and Dolan [31] addressed the question by using sentences with a spatial content. They again were either concrete (e.g., “The apples are in the barrel; the barrel is in the barn; therefore the apples are in the barn”) or abstract (e.g., “A are in B; B is in C; therefore A is in C”). They reported that all problems activated a similar bilateral occipito-parietal network no matter if they were concert or abstract.

Reasoning and Visual Mental Imagery

Many of the reported experiments seem to support the model theory of reasoning. However, it is essential not to confuse mental models with visual images (→) [32,33]. Visual images are structurally similar to real visual perceptions, and can represent objects, their colors and shapes, and the metrical distances between them. They have a limited resolution, but they can be scanned and mentally manipulated [34]. They are often accompanied by neural activity in visual association areas (→) and under certain conditions also activate the primary visual cortex (→) (e.g., [30,35,36]). In contrast, mental models are likely to exclude visual detail, to represent only the information relevant to inference and to take the form of multi-dimensional arrays that maintain ordinal and topological properties [33]. Visual images represent information in a modality-specific format, whereas spatial models are abstract and not restricted to a specific modality. To clarify the role of visual images in reasoning Knauff, et al. [37] conducted a combined behavioral and brain imaging study with four sorts of relations: (i) visuo-spatial relations that are easy to envisage visually and spatially, (ii) visual relations that are easy to envisage visually but hard to envisage spatially, (iii) spatial relations that are hard to envisage visually but easy to envisage spatially, and (iv) control relations that are hard to envisage either visually or spatially. This study highlighted two important findings: First, reasoners were significantly slower with the visual relations than with the other sorts of relations. This is called the visual-impedance effect [38]. And second: On the brain level, all types of reasoning problems evoked activity in the parietal cortices and this activity seems to be a “default mode” of brain functioning during reasoning. However, only the problems based on visual relations also activated areas of the visual cortices. Obviously, in the case of visual relations, reasoners cannot suppress a spontaneous visual image but its construction calls for additional activity in visual cortices and retards the construction of a mental model that is essential for the inferential process. Interestingly, congenitally totally blind people are immune to the visual-impedance effect, since they do not tend to construct disrupting visual images from the premises [39]. For a more detailed explanation on how visual images and mental models interact in reasoning the interested reader is directed to Knauff [4].

Content Effects and Belief Biases

How easy it is to visualize is only one aspect of the content of a reasoning problem. Another aspect is how well the content agrees with the reasoners previous experiences and prior knowledge. Many behavioral studies have shown that prior knowledge can significantly influence how efficiently a reasoning problem is solved. Technically speaking, the abstract (logical) truth value of an inference can be the same as the truth value of our prior knowledge – in this case the inference is supported. Or, the formal truth value conflicts with the truth value of the prior knowledge – then the inference is more difficult, which means it results in more errors or takes significantly longer. If an inference generated by a person is biased towards the truth value of the prior knowledge or even overwritten by it, this is called belief bias [40]. Some patient studies, as described, have therefore explored the effects of brain injuries on reasoning with concrete and abstract materials. Their findings agree with the brain imaging study by Goel et al. [29] in which evidence for the engagement of both linguistic and spatial systems have been found. Reasoning with a semantic content activated a left-hemispheric temporal system, whereas problems without semantic content activated an occipito-parietal network distributed over both hemispheres. Goel and Dolan [41] brought logic and belief into conflict and found evidence for the engagement of a left temporal lobe system during belief-based reasoning and a bilateral parietal lobe system during belief-neutral reasoning. Activation of right prefrontal cortex was found when the participants inhibited a response associated with belief-bias and correctly completed a logical task. When logical reasoning, in contrast, was overwritten by a belief-bias, there was engagement of ventral medial prefrontal cortex, a region implicated in affective processing. In the dual-processing theory, Goel, et al. therefore suggests that deductive reasoning is implemented in two separate systems whose engagement is primarily a function of the presence or absence of semantic content. Content-free reasoning seems to be stronger related to visuo-spatial cortical areas in the right hemisphere, whereas content-based reasoning recruits language-related areas in the left temporal cortex. If the content of the reasoning problem results in a conflict between belief and logic, this conflict recruits additional areas in the right prefrontal cortex.

Evaluation of Reasoning Theories

For a long time the psychology of reasoning was strongly committed to the assumption that reasoning should be studied in term of computational processes. How these computations are biologically implemented in the human brain has been conceived to be not sufficient, because each computational function can be computed on each hardware (and, thus, also the brain) that is equivalent to a Turing machine (e.g., [42]). However, reasoning research is a good example of where the assumption of implementation-independency fails. As there are many mappings possible between cortical regions and cognitive functions, neuroscientific data alone are certainly too weak to test cognitive theories. But, if such data are consistent with behavioral findings this can provide strong support for a cognitive theory of human reasoning. An outstanding example is the field of relational reasoning, where hardly any researchers defend an approach based on inference rules (e.g., [3]). The behavioral and neuroscientific evidence showing that people use their visuospatial system to preserve the structural properties of the world are too overwhelming. In other fields of reasoning the situation is more complicated (cf. [43]). Many researchers will agree that mental models play a key role if humans perform inferences based on conditionals and quantifiers [8]. On the other hand, there is also evidence that verbal, linguistic, and syntactic processes are also involved. The most reasonable corollary from the field of research is that human think deductively by applying different mental algorithms and that these algorithms are implemented in different brain areas. Content-free inferences are "real logical" inferences and they seem to rely on neural computations in the right parietal cortices the precuneus, and the extrastriate and (sometimes) striate cortex. They are accompanied by executive functions and control processes in the prefrontal cortex. When the logical problem is embedded into a semantic content or related to the reasoners' beliefs additional linguistic and semantic processes in the left temporal cortex come into play. Another corollary from the neuro-cognitive research is that reasoning is a multi-component process and that the diverse components strongly overlap with the components of other cognitive functions. There is no single "cheater detection module" as proposed for reasoning about social contracts [44,45] much as there are no "pragmatic schemas" [46] that completely spare human to reason.

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Rebound Bursting

Definition

Discharge of a burst of action potentials after the end of a hyperpolarizing influence, such as an inhibitory postsynaptic potential.

►Action Potential

Recall

Definition

Recall is the ability to not only recognize something as having been experienced in the past, but also to retrieve, on demand, spatiotemporal details of the context in which the stimulus or event was originally encountered.

►Recognition Memory

Receiver

Definition

In general an instrument that is able to register a signal. In communication theory, the receiver registers a signal, decodes it and reacts accordingly.

Recency

Definition

With respect to recognition, recency refers to the capacity to remember more accurately information which has just been experienced, as compared to events or items encountered further in time from retrieval.

►Recognition Memory

Marc D. Binder, Nobutaka Hirokawa and Uwe Windhorst (Eds.)

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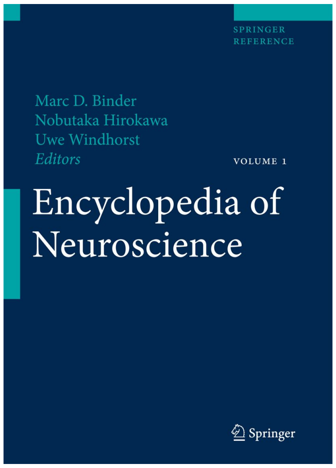

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