Integrating the Mind

Domain general versus domain specific processes in higher cognition

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10 A competence–procedural and developmental approach to logical reasoning

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Despite several decades of debate, disagreement still exists about the nature and development of logical reasoning. The present chapter focuses on two areas that are central to this debate. The first deals with the place of a mental logic in the reasoning process. On one side of the debate this is considered essential because it provides a structure on which propositional content is affixed. Difficulties in deductive reasoning can be understood as deviations from this normative structure. On the other side, mental logic is considered unnecessary and provides nothing to the understanding of reasoning. From this perspective, performance on tasks that appear to entail deductive reasoning are explained by procedural, information-processing features of thought that are unrelated to any formal logic structure. This latter understanding leads to a second area of disagreement, which concerns whether the processes involved in reasoning are domain specific or domain general. This chapter attempts to reconcile these two debates by presenting a competence–procedural theory of reasoning and its development. According to this theory, reasoning requires the development of a domain general mental logical competence, but access and implementation of this competence are limited by procedural difficulties that may be domain general or domain specific.

Reasoning and logic

The literature on deductive reasoning is complex, and some definitional clarification is needed before beginning an analysis of the issues that frame contemporary investigations into its nature and development. This initial review of some basic concepts distinguishes logical reasoning and the structure of logic, which is critical for an unambiguous understanding of the field.

Reasoning is goal-directed thought that coordinates inferences (Johnson-Laird & Byrne, 1991). As reasoning constitutes a kind of thinking, deductive or logical reasoning is a specifically unique form because it is the only type in which general propositions lead to particular conclusions, and premises provide conclusive or necessary support for the certainty of them.

We will see later that this notion of "logical necessity" is a central feature that, unfortunately, is often ignored in various debates in the field. Deductive or logical reasoning is distinguished from other types, such as reasoning based on knowledge of context, or based on probability, as these involve induction, where inference proceeds from the particular to the general. In these latter cases, the premises provide probable, but not necessary, conclusions.

The following examples illustrate deductive and inductive reasoning.

1 All flights to Chicago have a layover in Cincinnati.
  The flight in gate 10 goes to Chicago.
  Therefore, the flight in Gate 10 has a layover in Cincinnati.

2 All the planes I have seen that fly to Chicago
    have a layover in Cincinnati.
  Therefore, all planes to Chicago have a layover in Cincinnati.

The first example (1) is a deductive inference, and the second (2) is an inductive inference. Whereas the goal of induction is to achieve a probable solution, the goal of deduction is to draw an absolutely valid ("logically necessary") conclusion from the premises.

With the distinction between deductive and inductive reasoning in hand, we move to the next critical distinction, that between logic and logical reasoning. Logic itself as a discipline is not concerned with reasoning processes *per se*. Logicians focus on the products of these, which they term *arguments*. From a psychological perspective, examples (1) and (2) involve different forms of inference, but from the perspective of logic they are deductive and inductive arguments, respectively. Logic is thus concerned with arguments that are accepted as correct or incorrect, and logical reasoning is concerned with the mental processes and structures that are in some way related to logical arguments.

From the perspective of logic, an argument is a set of propositions of which a conclusion follows from the premises, with these providing evidence for the truth of the conclusion. Deductive arguments also have the feature of being *valid* (correct) or *invalid* (incorrect). When we say that a deductive argument is valid, we are saying that it is absolutely impossible to find a situation (i.e., a possible world) in which the argument has true premises and a false conclusion. Thus, in a valid deductive argument, the conclusion *necessarily* follows from the premises. In contrast to deductive arguments, inductive arguments cannot be valid or invalid because the premises only provide probable evidence for the truth of the conclusion (see also Over, Chapter 4, this volume). No matter how many planes to Chicago I have seen that have layovers in Cincinnati, there may be some that go straight through.

Logicians use simple sentences and the "sentential connectives" that join them together (i.e., *not* called negation; *and* called conjunction; *or* called disjunction; *if . . . then* called the conditional; *if and only if* called the biconditional). They then demonstrate valid and invalid arguments related to these connectives. Elementary valid arguments are the building blocks for elementary *argument forms* or *rules of inference* that are used to analyse more complex arguments. The simplest of these forms are *modus ponens* (if p then q, p, therefore q), *modus tollens* (if p then q, not-q, therefore not-p), and hypothetical syllogism (if p then q, if q then r, therefore if p then r). Here any content can be substituted for p, q, and r and the argument remains valid.

The general deductive system that incorporates the connectives and inference rules is called a *propositional* or *sentential logic*. A more powerful system that goes beyond propositional logic is variously called *quantificational, predicate*, or *first-order logic*. Deductive propositional and predicate logics ultimately are formalisations of the commonsense correct deductive arguments that people engage in on a day-to-day basis. The logics are attempts by logicians to codify the rules according to which such arguments proceed, or, to say this in a slightly different fashion, a logic is a theory of the nature of arguments. By establishing the rules of valid deductive arguments, a logic also pinpoints the nature of error. With these distinctions concerning logic, we can turn to various theories of the relation of logic and reasoning found in the study of deductive reasoning.

Theories of deductive reasoning

There are a number of theories about the nature, origin, and development of logical reasoning. A major area of theoretical debate concerns the place of mental logic in this. If logic entails rules of arguments, then the mental logic of logical reasoning describes the mental processes associated with these rules. However, here the field has generally organised itself around two very divergent options: (1) on one hand, the broad rules of logic are taken to operate as a model of the dynamic system of psychological processes entailed by logical reasoning. In this case, the model functions as a theoretical explanation for predicted or actual behaviour; (2) on the other hand, the rule system is considered to be irrelevant to reasoning, and the appearance of the reasoning as being "logical" is considered an epiphenomenon.

Those who pursue option (1), and thus favour the use of logical systems as models of the dynamic organisation of mental processes, have been referred to as a *mental logic* group (Braine & O'Brien, 1998; Rips, 1994), or as *competence theorists* (Overton, 1985, 1990). The basic position here is that the rules that have been derived to represent the structure of valid arguments may be taken as relatively adequate representations of normative, idealised, abstract operations of mind in this domain. However, as Russell suggests, this competence is not "to be regarded as 'mental representations' that the adult thinker uses when she reasons, but [as] idealisations of the system of thought to which the 'normal adult' has access.

Sometimes the access is good, sometimes poor" (1987, p. 41). Competence theorists thus argue that this logical competence is an idealised model of the dynamic organisation of the individual's capability in the domain in question. And they argue that this competence must play a central and privileged role in any account of logical reasoning.

One issue facing such theorists is how best to describe this competence. On one point, however, all competence theorists agree: The particular notation system used to describe the organisation of a mental logic does not need to correspond closely to that found in logic textbooks. For example, truth tables are a standard notation often used by logicians to describe argument forms, but no one argues that people generally reason according to truth tables or that a mental logic model should incorporate them. Piaget and his colleagues (Beth & Piaget, 1966; Inhelder & Piaget, 1958) initially described formal mental logical competence in terms of the propositional calculus; in other words, a propositional logic system that formalises compound statements in terms of the truth values of their connectives. Later, they moved towards a description of competence as a natural deductive system; in other words, a system that focuses on the validity of arguments rather than logical truth, and employs only inference rules rather than axioms (Piaget, 1986, 1987a, 1987b; Piaget & Garcia, 1991). Other influential proposals have suggested that "inference schemas" or deduction rules constitute the best description of logical competence (Braine & O'Brien, 1998; O'Brien, Braine, & Yang, 1994; Rips, 1994).

A second issue that such theorists face concerns the development of the competence system. It has been suggested that this is primarily innate (e.g., Macnamara, 1986); that it has a bioevolutionary origin (e.g., O'Brien, 2004); that it is partially innate and partially learned (Braine, 1990); that it emerges out of language (Falmagne, 1990); and finally there is the position held in the present paper, that the origins of competence are found in the *embodied actions* of the infant, the child, and the adolescent as the person coacts with the social and physical world (Lakoff & Johnson, 1999; Overton, 2003; Piaget, 1986).

In contrast to theories that incorporate a mental logical competence, those that deny the very existence of this can best be thought of as *procedural theories*. Arguing that there is no formal system of logic or mental logical rules that underlie logical reasoning, procedural theorists tend to have a strong commitment to information processing and computational models as explanatory devices. There have been a range of specific procedural theories designed to account for performance on deductive reasoning tasks. These range from simple information processing models (Griggs, 1983; Mandler, 1983), which claim that counterexamples stored in memory are sufficient to explain what appears to be "logical" reasoning, to theories that rely on domain specific reasoning via specialised schemas (e.g., Cheng & Holyoak, 1985, 1989), domain specific cognitive algorithms (Cosmides, 1989; Cummins, 1996b), or mental models (Johnson-Laird & Byrne, 1991, 2002).

In examining theories of the nature and development of deductive reasoning, we thus find two broad classes of theory – *competence* theories and *procedural* theories. Competence theories describe the nature and development of relatively enduring and universal operations of mind. When the domain of study is reasoning, this has been described in terms of the rules of deductive logic, and is thus primarily formal or syntactic in structure. In contrast, procedural or process theories focus on specific representations and procedures as these occur in real time and are related to local problems. Procedures are primarily semantic in nature, and involve specific interpreted representations. To clarify, deduction rule theories such as that proposed by Rips (1994) are not procedural in this sense because they specify particular behavioural operations that are neither independent of the syntactic structure nor context-sensitive. The rules presented by Rips simply describe a computational process directly relevant to the syntactical structures of the formal rules.

Competence and procedural theories can only be seen as incompatible to the extent that one type of theory is considered a replacement for the other. This incompatibility disappears if the two theories are seen as distinct but interrelated components of a general theory of logical reasoning. This understanding forms the basis for the construction of a general competence–procedural developmental theory of deductive/logical reasoning. From this perspective, competence serves to explain the universal and necessary features of logical reasoning. However, competence, as the dynamic organisation of mental logic, is neutral as to how this system is accessed and implemented. Procedures, on the other hand, are exactly designed to function as the real-time processing that accesses and implements the competence. This distinction is similar to the availability and accessibility distinction introduced by Tulving and Pearlstone (1966) with respect to memory. There is much more that is available for processing than can be accessed at any one moment. The discrepancy between availability of competence and its accessibility implies a critical role for procedural mechanisms necessary to access and process an available competence.

A competence–procedural developmental theory

A theory that proposes a distinction between a formal competence and procedures that access that competence must be explicit about how such a scheme would incorporate a developmental or change dimension. Overton and his colleagues (Müller, Overton, & Reene, 2001; Overton, 1990; Overton, Ward, Noveck, Black, & O'Brien, 1987; Ward, Byrnes, & Overton, 1990; Ward & Overton, 1990) have consistently maintained that the development of a relatively complete logical competence necessarily precedes success on reasoning problems that are fully deductive in nature, but that real-time information processing plays a key role in determining any specific performance. From this developmental perspective, some features of logical reasoning may be available quite early, and through embodied actions in the world these features become increasingly differentiated and reintegrated until a relatively complete mental logic is formed in adolescence (Müller et al., 2001) or early adulthood. Processes of differentiation and reintegration imply that there will be qualitative transformations in both mental logical competence and procedures across the course of development. Overton (1985) thus describes the person as having two cognitive systems. The competence system functions to comprehend the world. It is a dynamic system composed of the relatively stable, relatively enduring, and universal logical operations (e.g., "and", "or", "if . . . then", "negation"). The system is considered to be complete, as in the highest level of deductive competence, or incomplete, as in the sensorimotor embodied action systems found in infancy. Thus, the development of mental logic should not be characterised in terms of presence versus absence of a general competence. Rather, when it comes to classifying different conditional reasoning problems, it is better to investigate the cognitive competence that is necessary to achieve a particular interpretation (Staudenmayer & Bourne, 1977).

A second system, the procedural system, functions to assure success on problems. This is composed of individuated real-time action systems that may be sequentially ordered, but are not enduring in the way that the competence system endures. A procedure is an action means to an end or goal. It is context-dependent, and context includes both the available competence and information inputs (e.g., success at baking a cake requires stirring, mixing, and beating, but a recipe represents the underlying competence that forms the necessary context for these procedures). Procedures are considered to be sufficient or insufficient, rather than complete or incomplete. This distinction between the completeness/incompleteness of competence and the sufficiency/insufficiency of procedures is particularly important for deductive reasoning.

Competence and necessity

Within a competence–procedural theory, the development or acquisition of the concept of necessity (i.e., that which *must* be) becomes important. Competence develops first at the action level of embodiment (Overton, 1990, 2003). Thus, the infant's early understandings of *the real* (that which *is*), *the necessary* (that which *must* be), and *the possible* (that which *might* be) are constructions derived from organised embodied action and the resistance it meets in the real world. This process by which general logical competence arises through interactions with the world conforms to Piaget's assimilation/accommodation process. Assimilation is the phase of an action where current meanings or expectations (either sensorimotor or symbolic) are projected onto the world. Accommodation refers to the phase of an action that, following the partial success of an assimilation, feeds back and results in a change of the original meaning or expectation.

Necessity is the expression of assimilatory action. Possibility is the expression of accommodative action. To illustrate, consider the example of newborn sucking. This act emerges from a preadapted action organisation (preadapted sensorimotor assimilatory structures or initial competence), gives meaning to the object of action, and, thus, "creates" the object's meaning as a sensorimotor "suckable". This assimilation also yields a result (e.g., obtains milk). It is when sucking meets a resistance (in the sense of failing to yield a result) that variation occurs, and one of the variants leads to success. This variant of the original act feeds back to the initial assimilatory competence system as an accommodation. The variant thus creates a new possibility that, by modifying the initial system, becomes a new assimilation. Here then we have the first sensorimotor differentiation into necessity (assimilation), possibility (variations or accommodations), and reality (continued resistances) at a sensorimotor action level of integration.

This embodied procedural origin of necessity and possibility establishes the base for progressive (higher level conceptual and propositional) coordinations of (1) possibilities (with their flexibility) and (2) necessities (with their self-regulating system character) into increasingly complete competence systems. This means that the understanding of logical necessity that becomes evident in childhood and adolescence is never the direct product of a hardware level of explanation, as a nativist might suggest, nor is it the product of inductive generalisation drawn from direct observations of the world. Logical necessity is characteristic of a logical model (from the point of view of logic) or the deductive competence system (from the point of view of psychology). The developmental question is not how either the brain or the world generates feelings of "must". *The developmental question is how an action understanding of "must" becomes transformed into a propositional understanding of "logical necessity".*

Having *seen* a thousand planes going to Chicago and stopping in Cincinnati may yield a *contingent* truth (i.e., an assertion based on empirical knowledge), and a very strong feeling that this plane must stop at Cincinnati. It does not, however, yield logical necessity. Possessing a system of understanding that generates integrations such as "all *A*s are *B*; this is an *A*; therefore, this is a *B*" does yield logical necessity, and this is independent of any particular set of empirical observations concerning *A*s or *B*s. If all planes to Chicago stop in Cincinnati, and this is a plane to Chicago, then this plane will stop in Cincinnati. This statement is a logical necessity, and this has nothing to do with empirical observations of planes. The logical necessity comes from the formal or syntactical organisation among the parts of the sentence or, more generally, among sets of propositions. It is this dynamic organisation, beginning in sensorimotor acts as an initial pattern of action, becoming transformed, through actions in the world, into the sensorimotor "must", and undergoing transformations into symbolic representations and the integration of symbolic representations, that comes to constitute the complete deductive competence system of the adult.

An account including logical necessity requires a focus on competence and its development. The concept of logical necessity, in turn, requires an understanding of the central concepts of implication and relevance. Implication is a relation that holds between premises and conclusion, or between antecedent and consequent, as in the proposition "if *p*, then *q*". When the relation of implication holds, we can then say that *p* implies *q* (a deductive argument). This argument is defined as implication if and only if it cannot be the case that the antecedent (premise) is true and the consequent (conclusion) false. Thus, the implication relation is defined by being a logical necessity.

Implication, then, is a symbolic concept entailing a necessary relation that leads from one state of affairs to another. All concepts, including implication and necessity, become transformed across the several levels of development. We have already seen that, from an embodiment perspective (Overton, 2003), an understanding of necessity originates out of the organised actions of the individual. Thus, implication as a symbolic propositional concept as, for example, in the *modus ponens* argument ("if *p*, then *q*; *p*, therefore *q*"), finds its primitive and incomplete origins in the preconceptual action level (e.g., "if I pull on the blanket, then I will bring the toy on top of the blanket closer"). At the preconceptual sensorimotor action level, the primitive analogue of implication is a clearly defined relation between actions and, thus, an intentional and intuitive sense of must. The progressive transformation of this analog to the final propositional understanding of logical necessity is a development that entails the differentiation and reintegration of competence systems beginning at the sensorimotor action level, moving to the symbolic (at around age 2), and from there to the reflective symbolic level (beginning around age 4) and finally to higher order reflective symbolic systems (beginning at approximately age 6 and again at around age 14), culminating in the relatively complete logical competence system found in adolescence or early adulthood.

Although any discussion of the development of implication and necessity demonstrates the critical role of meaning, it does not capture the full importance of meaning *in the system*. The introduction of the logical concept of *relevance* both forms an important bridge between meaning and implication and expands on the definition of implication itself. For any conditional proposition ("if *p*, then *q*") there may be some identifiable meaningful relation, linkage, or connection between the antecedent (*p*) and consequent (*q*) clauses, or there may be none. For example, for the conditional proposition, "if he is a bachelor, then he is unmarried", there is a meaning relation that is definitional in nature. This is distinguished from *material implication* in which there is no meaningful connection between antecedent and consequent (e.g., "if the moon is made of blue cheese, then oceans are full of water"). Thus, the concepts implication, logical truth, entailment, and validity require not only a necessary relation between antecedent and consequent as discussed earlier, but a relevance relation as well.

Piaget (Piaget & Garcia, 1991) used the relevance relation, which he termed "meaning implication" or "signifying implication", to establish further the central role of implication in a competence model. This, in turn, further demonstrated both that the apparent extensional system develops out of the meaning system and that primitive forms of implication precede the relatively complete form evident in formal deductive reasoning. Piaget accomplished these purposes by arguing that a relevance connection – defined as assimilation – is basic to any action sequence that involves knowing, from the sensorimotor to reflective symbolic levels.

At the sensorimotor action level, the relevance connection occurs between actual actions (e.g., "if I pull on the blanket, then I will bring the toy on top of the blanket closer"). If toy–blanket is not assimilated (given a meaning linkage) to pulling the blanket, then the action implication vanishes. At the next developmental level, the action meanings become incorporated in language and become symbolic (e.g., "if it rains, then the bicycle will get wet"). Here, the causal implication occurs only if a relevance relation is formed such that "wet bicycle" is given a meaning linkage to "rain". Finally then, at higher reflective propositional levels, the relevances and logical necessities join to form the deductive competence system that operates as a structured whole. This system, representing a developmental transformation of the earlier ones, permits the kind of logical understandings that involve genuine implication, entailment, logical truth, and validity that are evident in traditional deductive reasoning problems.

In summary, the relatively complete deductive competence system takes the form of a logical deductive model, and the system differentiates out of the embodied actions of the child. As both the competence system and the procedural system become transformed and develop to higher levels of knowing, deductive competence becomes transformed and increasingly more adequately serves the function of logical comprehension or logical understanding. Interpretative/implementation procedures increasingly serve the function of providing access to, and implementation of, the competence.

Developmental evidence

If we begin with an understanding of necessity as originating in action, two major predictions can be made about the pattern of the development of deductive reasoning. First, we would expect that a propositional reasoning competence would be a relatively late developmental acquisition. Second, we would expect that factors related to procedural information processing should influence access to and implementation of that competence. There are a number of empirical investigations that offer support for these hypotheses. For example, Overton and colleagues (Chapell & Overton, 1998; Müller et al., 2001; O'Brien & Overton, 1980, 1982; Overton, Byrnes, & O'Brien, 1985; Ward & Overton, 1990) have consistently found significant developmental advances in reasoning performance from late childhood through adolescence on a number of different formal deductive reasoning tasks, including inference and evaluation tasks. In inference tasks, participants are presented with an incomplete conditional rule, and asked to use a set of exemplars to make an inference about the missing component of the rule. In evaluation tasks, participants are given a conditional rule, and asked to evaluate a set of propositional combinations that may or may not prove the rule to be false. Successful performance on these tasks does not appear consistently before middle to late adolescence. Additionally, whereas younger adolescents do not benefit from training or the introduction of contradictory evidence, older adolescents do. Training is procedural in nature and procedures cannot access a competence that is not available (Overton et al., 1985).

Evidence for qualitative developments in deductive reasoning also comes from investigations using the Wason selection task. The original version (Wason, 1968) assessed conditional/deductive reasoning through the verification of the truth of an *abstract* conditional rule ("if there is a vowel on one side of the card, then there is an even number on the other side"). In this task participants are shown the conditional rule and an array of four cards showing, respectively, the letter E, the letter K, the number 4, and the number 7 on one side of each card. Instructions include being told that each card presents a letter on one side and a number on the other, along with the rule *if there is an "E" on one side of the card, there must be a "4" on the other side*, and the task is to select those cards that would have to be turned over to decide *whether the rule is true or false*. Selecting both the E (*p*) and the 7 (not-*q*) cards is correct because this solution provides evidence for the recognition that only a falsification strategy will provide logical certainty (i.e., a logical necessity). *Not* selecting the K (not-*p*) and 4 (*q*) along with selecting E and 7 demonstrates a *coordination* among the permissible and impermissible instances (i.e., coordination among the four argument forms *modus pollens*, *modus tollens*, denied antecedent, affirmed consequent) and this coordination defines a full understanding of the advanced logical concept of "implication". As noted above, implication is a necessary relation between premises and conclusion that is present *if and only if* it *could not* be the case that the antecedent *p* (premise) is true and the consequent *q* (conclusion) is false. In fact, when *p* implies *q*, the argument is a defined as a deductive argument.

The "abstract version" of the Wason selection task entails reasoning about indicative rules (i.e., requires reasoning about the truth of the situation; Noveck & O'Brien, 1996; Sperber, Cara, & Girotto, 1995) because it requires the identification of instances that would falsify the rule. In early research using this task, successful performance was shown to be extremely difficult for both adolescents (Girotto, Gilly, Blaye, & Light, 1989; Overton et al., 1987) and adults (Evans, Newstead, & Byrne, 1993). Only about 10% of all adults solve the abstract version correctly. The dominant pattern of response was the selection of the E (*p*) and 4 (*q*) cards, or only the card E (*p*). Wason (1983) himself pointed out that the difficulty with the abstract version is related to the heavy memory load placed on participants, with the consequence that information cannot adequately be represented and maintained as a coherent whole. This suggests that the abstract task fails to access competence because of procedural issues (i.e., working memory demands). On the other hand, when meaningful, concrete, or thematic content is used in place of abstract content, the majority of adolescents and adults exhibit successful deductive reasoning (Foltz, Overton, & Ricco, 1995; Markovits & Vachon, 1990; Müller et al., 2001; Overton et al., 1987; Ward & Overton, 1990; see Evans et al., 1993 for a review of the adult literature). This suggests that when procedural interferences are reduced (e.g., working memory demands), competence becomes more readily accessed.

One factor that has been found to be associated with access to a mature competence is the content and familiarity of the conditional rule. Work by Overton and colleagues has examined the specific role of meaningful content and performance on variations of the Wason selection task in children and adolescents (Overton et al., 1987; Ward & Overton, 1990). Overton et al. (1987) demonstrated that children have better success with meaningful and familiar social rules, but not meaningless and unfamiliar rules. However, in this study, a crucial finding for the competence–procedural theory was that familiar content did not lead to improved reasoning prior to 13 years old. Further research (Ward & Overton, 1990) focused on the meaningfulness of the relation between antecedent and consequent (i.e., logical relevance). Here, it was demonstrated that selection task problems with a meaningful relation between the two led to better performance for 14- and 17-year-olds, but not 11-year-olds, who performed equally poorly with meaningful and meaningless relations.

Developmental changes in deductive reasoning skills of older children and adolescents have also been demonstrated in other cross-sectional studies by Overton and colleagues (Byrnes & Overton, 1986, 1988; Chapell & Overton, 1998, 2002), by cross-sectional investigations in other labs (Klaczynski & Narasimham, 1998; Klaczynski, Schuneman, & Daniel, 2004; Markovits, Fleury, Quinn, & Venet, 1998; Markovits, Schleifer, & Fortier, 1989; Markovits & Vachon, 1989, 1990; Venet & Markovits, 2001), and by recent longitudinal data (Müller et al., 2001). Additional empirical evidence comes from investigations using statistical analysis of latent dimensions, such as Rasch analysis, which have reported *qualitative developmental changes* in class and propositional reasoning (Müller, Sokol, & Overton, 1999), and in deductive reasoning (Spiel, Glück, & Gössler, 2001). Unidimensional latent structure analyses are particularly helpful in identifying qualitative developmental change taking place along a theoretically uniform dimension (e.g., logical competence). Taken together, the empirical findings broadly support Overton's (1990, 1991) assertions that (1) access to, and implementation of, a deductive reasoning competence is a function of procedural determinants (e.g., working memory limitations, differences in problem representation, cognitive style, anxiety), and that (2) this formal deductive competence is not consistently available before adolescence.

Domain general versus domain specific reasoning

Along with the debate regarding competence and procedures, recent discussion has centred on the question of whether processes involved in thinking and reasoning should be considered domain-free or domain specific (Beller & Spada, 2003; Roberts, Welfare, Livermore, & Theadom, 2000). Domain-free reasoning would entail relatively global cognitive processes, while domain specific reasoning would entail more limited cognitive processes that function with specific information and specific contexts. It should be clear by now that the competence–procedural theory proposes both kinds of reasoning processes. Formal reflective symbolic competence is a domain general competence, the access to which can be influenced by the processing of domain specific information.

In contrast to competence–procedural theory, several others have favoured an exclusive understanding of reasoning as being either domain general or domain specific. All such extant theories are procedural, holding the shared assumption that a formal logical competence is irrelevant to the nature and development of deductive reasoning. We of course argue that any exclusively procedural theory either fails to account for the logical features of logical reasoning, especially logical necessity, or implicitly assumes these features as background.

One influential procedural domain general model that illustrates this problem is presented by Johnson-Laird and colleagues (Johnson-Laird & Byrne, 1991, 2002). This mental-models theory proposes that, when reasoning, people construct mental representations of the possibilities presented in the problem. The theory assumes that people represent many possibilities or outcomes captured by the problem, that these are represented iconically so that the structure of the mental model corresponds to what it represents, and that mental models represent what is true, but not what is false (Johnson-Laird & Byrne, 2002). In order to represent negation in deductive reasoning problems, the person doing the reasoning must modify the model by "tagging" this, and by fleshing out the initial model into a fully explicit one. For example, the statement *John is in Philadelphia* would be represented by a single token, say *p*. The negation of this statement (*John is not in Philadelphia*) would be "tagged" by an explicit negation sign ($\neg$) preceding the token, as in $\neg p$. Using these tokens as symbols, and with each row representing a model, a kind of mental diagram can be created. The statement *Either John is in Philadelphia or Sally is in Chicago, but not both* might be fleshed out in (1) to contain (a) in the first row, a token for *John is in Philadelphia*, and a negated token for *Sally is in Chicago*; (b) in the second row, a negated token for *John is in Philadelphia* and a token for *Sally is in Chicago*.

(1) [p] [¬q]
[¬p] [q]

Neither situation [p] [q] nor [¬p] [¬q] is represented on this model because they are ruled out as false possibilities by the rule: mental models do not represent what is false. Models can be fleshed out to make deductive inferences, such as in the following:

John is in Philadelphia or Sally is in Chicago.

But John is not in Philadelphia.

So, Sally is in Chicago.

The fleshing-out process can require the maintenance of several representational parts, or tokens, in a limited working memory, which constitutes a procedural limitation to reasoning, making this difficult in some situations but not others. Developmentally, the mental-models approach has been expanded by Johnson-Laird (1990) and by Markovits and colleagues (Markovits & Barrouillet, 2002). Accordingly, developmental difficulties in reasoning are attributed to the immature ability to construct, maintain, and process a greater number of mental models in working memory (Markovits & Barrouillet, 2004). In this way, the modelling procedures are considered to be domain general because such cognitive processes are the source of constraints on successful reasoning.

It should be recognised that the mental models theory is, in fact, compatible with a competence theory as long as it is not seen as a substitute for logical competence. As a procedural theory, the principal value of the mental models approach has been in demonstrating procedural effects on reasoning (e.g., the facilitating effect of local content, or as an explanation for why some inferences are harder to make than others), rather than presenting a comprehensive account of deductive reasoning. In this context, mental models may represent one half of the explanation (see Roberts, 1993, for a similar discussion). Indeed, one can readily agree with Braine (1990) when he says "We think it very likely that subjects often use mental models in reasoning. It is almost certain that a complete account of deductive reasoning will need a subtheory of mental models" (p. 147). However, missing from the mental models theory is a general account of the deductive process itself. As others have pointed out, mental models have never been able to provide an account of the conception of logical understanding itself (Russell, 1987; Scholnick, 1990), or how a construction of a model of local content can lead to the understanding of the universal scope of the proposition (O'Brien, 2004). Additionally, it is difficult to see how a token-based mental-models theory could be used to describe competence in any way. Key aspects of logic cannot simply emerge from manipulating spatial tokens in working memory. In the absence of certain fundamental logical concepts, a theory that only assumes mental-models procedures is hard pressed to explain how most logical inferences would be possible. A mental-models procedural theory can be effective only if someone who has the necessary logical competence is interpreting it (see Roberts, 1993, and Rips, 1989 for similar arguments).

This same criticism is applicable to theories that attempt to provide a domain specific account of deductive reasoning. In this camp, reasoning about social situations or problems has received the most attention, and several investigators have emphasised a set of specialised principles that are derived via domain specific experiences (Cheng & Holyoak, 1985, 1989) or innately determined via evolutionary pressures operating within social situations (Cosmides, 1989; Cummins, 1996b). Those who argue that reasoning is domain specific have typically concentrated on a form of conditional reasoning, within the social domain, called deontic reasoning. As contrasted with indicative conditionals, which require reasoning about the truth of a rule, deontic conditionals require reasoning about obligations, permissions, and prohibitions, and whether these have been violated (Cummins, 1996b; Manktelow & Over, 1991).

A relatively consistent finding is that participants perform better with deontic conditionals when compared to indicative conditionals (see Cummins, 1996b; Evans, Newstead, & Byrne, 1993). Several theories have been presented to account for this difference (Chater & Oaksford, 1996; Cheng & Holyoak, 1985, 1989; Cosmides, 1989; Cummins, 1996b; Evans & Over, 1996; Johnson-Laird & Byrne, 1992; Manktelow & Over, 1991; Noveck & O'Brien, 1996; Sperber et al., 1995), but here we concentrate on two domain specific explanations of the deontic/indicative distinction. The first is pragmatic reasoning theory (Chao & Cheng, 2000; Cheng & Holyoak, 1985, 1989; Cheng, Holyoak, Nisbett, & Oliver, 1986), which claims that deductive reasoning emerges from schemas. These are sets of induced generalised rules related to specific goals and environmental situations. Cheng and Holyoak's work has primarily focused on two such structures: the permission and obligation schemas. The permission schema is relevant to social regulations where the consequent specifies a precondition that must be met in order for the action specified in the antecedent to be taken. The obligation schema deals with situations in which the consequent specifies an action that must be taken when the condition specified in the antecedent occurs. This position holds that when a specific situation invokes the permission or the obligation schema, a set of rules for dealing with all possible outcomes becomes available. Permission and obligation rules are deontic rules because they are prescriptive and not descriptive.

This prescriptive feature is usually expressed by modal verbs such as "must" and "may".

Support for pragmatic reasoning schema theory comes from performance on certain versions of the selection task. Adults perform significantly better when the rule is formulated as a permission rather than an arbitrary rule (Cheng & Holyoak, 1985). Based on this evidence, it has been argued that people produce correct solutions on these problems without logical reasoning, and that success on deductive problems only appears to follow the rules of logic, and this is merely coincidental (Girotto & Light, 1993). Theories of the origin of pragmatic reasoning schemas have argued that there are no qualitative developmental changes in deductive reasoning (Girotto & Light, 1993), and that the reasoning schemas are abstracted from everyday experience *at an early age* (Cheng & Holyoak, 1985). As noted earlier, research has already supported the contention that there are, in fact, qualitative developmental changes, and this weakens the pragmatic reasoning position. The major issue that remains is the argument for developmental precocity.

Claims of precocious performance in preschoolers have been made (Chao & Cheng, 2000; Cummins, 1996a, 1996b; Harris & Nuñes, 1996), but problems with the method of investigation give cause to question any conclusion concerning precocity. For example, in an often-cited study by Harris and Nuñes (1996), in which the claim was made that preschool children can reason with permissions, the children were simply given an evaluation task and asked to choose the picture that would violate a given permission rule. Children were told a story and given a permission rule (e.g., "if you are going to play outside, you must put your coat on"), and then were shown two pictures and asked to point to the picture of the story character "being naughty and not doing what her mum told her" (i.e., the picture of the character without a coat on). This task requires the preschooler to point to an action that would violate an "if . . . then" rule, which is not a surprising ability even for a 3-year-old. In other words, characters who match the rule (i.e., who are wearing coats) are obeying it, and characters who don't match the rule are disobeying it. Demonstrating that children can point to violations of an "if . . . then" rule does not itself constitute evidence of deductive reasoning. As pointed out earlier, logical reasoning with conditional propositions entails an understanding of the logical concept of "implication" and this understanding is demonstrated only in cases which children demonstrate a *coordination* among the permissible and impermissible instances that define implication (i.e., *simultaneously* understanding the two valid and two invalid argument forms). The ability to pick a violation of a rule may be an early developmental precursor to the *modus tollens* argument, but it does not constitute an understanding of implication and the logical necessity implication entails.

The same criticism is relevant to the research conducted by Girotto and colleagues (Girotto et al., 1989; Light, Blaye, Gilly, & Girotto, 1989; Light, Girotto, & Legrenzi, 1990) exploring pragmatic reasoning schemas and conditional reasoning in children. In the Girotto et al. (1989) study, the selection task is formulated as a permission rule (e.g., "if one is sitting in the front of the car, then one must wear seat-belts"). The authors reported that 10-year-old children performed well with unfamiliar but plausible rules, but performance was significantly worse when the rule was unfamiliar and implausible. However, in the studies using the full Wason task, successful performance was defined as the choice of the *p* and *not-q* cards, and not as a coordination among the four argument forms (i.e., selection of the correct cards coupled with avoidance of the incorrect cards). This pattern of selection, termed *complete falsification*, implies recognition that only a falsification strategy will lead to the correct solution. In many of the reported experiments, children who selected the correct cards also selected incorrect cards. Moreover, the findings of Girotto and colleagues contradict more recent longitudinal work conducted by Overton and colleagues (Müller et al., 2001). Using the same problems from prior cross-sectional work (Ward & Overton, 1990), Müller et al. replicated the same developmental trajectory that had been found in these earlier studies (i.e., qualitative change over time). When problems are scored for complete falsification in a longitudinal study, qualitative changes in reasoning competence are revealed. That said, the discrepancy between these longitudinal findings and the cross-sectional research reported by Girotto and colleagues warrants further research.

The pragmatic reasoning schema interpretation can also be challenged on other fronts. First, only the permission rule, but not the obligation rule, reliably facilitates performance on the selection task (Müller et al., 2001; Noveck & O'Brien, 1996). Second, pragmatic reasoning schemas appear to be task specific as they are associated with improved performance on the selection task, but not on an evaluation task (Markovits & Savary, 1992; Thompson, 1995), and they have difficulty explaining good performance on other kinds of deductive reasoning tasks (see Rips, 1989). Similarly, it may be that other task features are confounded with the presence of the deontic rule, and it is thus not the deontic rule itself that is associated with improved performance (Klaczynski & Narasimham, 1998; Noveck & O'Brien, 1996; Thompson, 1995; see also Noveck, Mercier, & van der Henst, Chapter 2; Roberts, Chapter 1, this volume). For example, participants perform better in enriched contexts, regardless of whether the rule is pragmatic (Noveck & O'Brien, 1996), and they perform well with nonpragmatic rules that suggest the creation of alternative antecedents (Klaczynski & Narasimham, 1998; Thompson, 1995, 2000).

Like mental models, pragmatic reasoning schemas fall short when presenting a complete account of deductive reasoning. However, also like mental models, pragmatic reasoning schemas may account for part of the explanation. In this regard, the comments from Noveck and O'Brien (1996, p. 484) are consistent with a competence–procedural account of deductive reasoning:

> content-independent inferences of mental logic do not explain the influence of permission content on these problems; note, however, that pragmatic schemas alone also do not provide a complete account of the data reported here, and some of the features that influence performance are content-independent. More is going on with these problems than pragmatic schemas alone can explain.

Again, these different accounts are incompatible only if they are seen as substitutes for each other. From a competence–procedural approach, both are necessary pieces of an account of deductive reasoning and its development.

The above theoretical and empirical arguments concerning factors unrelated to the deontic status of the rule may also pose a problem for another class of domain specific theories: those that emerge from an evolutionary perspective. Such theories argue that the architecture of human reasoning is innate and results from selective pressures to solve adaptive problems within specific domains. Cosmides (1989; Cosmides & Tooby, 1992, 2005), for example, proposed that differences in performance between deontic and indicative versions of the selection task could be explained by social contract theory. According to this, there are domain specific cognitive processes dedicated to reasoning about social contracts in social situations, and these specific processes are modular in their organisation. The theory proposes that reasoning will be better in situations in which it is beneficial to detect violators of a social contract (or to detect cheaters; Gigerenzer & Hug, 1992), such as in situations where a person accepts a benefit without paying a cost. Detection of violators in such social situations would be adaptive and advantageous, and thus specific cognitive algorithms would be selected for that would allow our ancestors to detect cheaters efficiently (Cosmides & Tooby, 1992; Gigerenzer & Hug, 1992). Following this logic, other modular reasoning processes have been proposed, such as a special system for reasoning about risk reduction in hazardous situations (Fiddick, Cosmides, & Tooby, 2000) or reasoning about sharing-rules (Hiraishi & Hasegawa, 2001).

Variants of this evolutionary approach have also been presented. For example, Cummins (1996b) has argued that reasoning about social contracts describes a piece of a larger adaptive system for reasoning about social norms. Thus, enhanced reasoning about deontic conditionals is taken to reflect enhanced reasoning about any rules that violate them, and not just reasoning about violations of reciprocity. Again, a focus of support for evolutionary psychological theories stems from research that finds early differences between deontic and indicative reasoning in children (Chao & Cheng, 2000; Cummins, 1996a, 1996b; Harris & Nuñes, 1996), or little qualitative change in reasoning competence across the lifespan (Girotto & Light, 1993).

As noted earlier, all domain specific theories falter, and evolutionary theory is domain specific, when confronted by the ample evidence that reasoning improves across the lifespan, especially when this improvement is qualitative in nature. However, there are additional causes to question the viability of evolutionary explanations. For example, Fodor suggests that the indicative–deontic distinction is related to the nature of the rules and is an artifact of the structure of the task (Fodor, 2000a, 2000b). The result is that the deontic conditional promotes a strategy of searching for violators, a strategy that is most appropriate in the assessment of a formal logical understanding.

There is also evidence that successful performance can be elicited in nondeontic contexts (Almor & Sloman, 1996, 2000; Girotto, Kemmelmeier, Sperber, & van der Henst, 2001; Griggs, 1989; Liberman & Klar, 1996; Platt & Griggs, 1993; Sperber et al., 1995), and in contexts that do not involve social exchange (Cheng & Holyoak, 1985). There is considerable evidence that cheating detection content is neither necessary nor sufficient to elicit the logically correct responses on the selection task (Liberman & Klar, 1996). For example, in the classic example of facilitation with unfamiliar content, the cassava root selection problem (Cosmides, 1989), subjects are presented with the rule:

> If a man eats cassava root, then he must have a tattoo on his face.

The rule is preceded by a story in which cassava root is explained to be reserved for married men, who are distinguished from unmarried men by the presence of a tattoo. The task is to determine who is breaking the law, and the four selection cards are presented (i.e., [*p*] "eats cassava root", [*not-q*] "no tattoo", [*not-p*] "eats molo nuts", [*q*] "tattoo"). Cosmides (1989) and Gigerenzer and Hug (1992) reported very good performance on this version of the selection task, with poor performance in similar no-cheating versions, and this finding was replicated by Liberman & Klar (1996). However, Liberman and Klar implemented two other conditions that eliminated confounds related to task interpretation. In one problem, an unconfounded no-cheating version of the cassava root problem, the same rule was presented with the rationale that people without tattoos cannot digest cassava roots. Despite the lack of a cheater detection context or a social contract, performance was equivalent to cheating contexts (71%, on average, across five different scenarios of both unconfounded no-cheating and original cheating versions of the task). Thus, a cheating context is clearly not a necessary condition for successful performance. This finding is particularly troublesome for evolutionary theories because there is no specific adaptive reason to expect successful performance in non-cheating versions. There is no social context, nor is there a cheater or violator of any social contract (Cosmides, 1989; Gigerenzer & Hug, 1992).

On both theoretical and empirical grounds neither mental-models nor domain specific theories provide complete explanations for the development of, and successful performance of, deductive reasoning. First, these theories fail to predict the qualitative changes in the development of deductive reasoning. Second, evolutionary theories must explain empirical results that conflict with the theory, including the finding that social contexts and social contracts are not necessary preconditions for facilitated performance in reasoning tasks. Finally, while accounting for many of the facts of logical reasoning, these theories skirt the core issue of logical necessity. An account including logical necessity requires a focus on competence and the development of competence.

Conclusion

In this chapter we have argued that neither domain specific nor domain general models are adequate accounts of logical reasoning, as each fails to handle various critical empirical data. Rather, a comprehensive understanding of logical reasoning requires, on one hand, a theory that can explain the universal features of the logic that competent adults express. On the other hand, this theory also needs to include procedural explanations of how this available competence is accessed and implemented. From our perspective, the most adequate approach to construction of such a competence–procedural theory must entail recognition that ultimately reasoning is the reflection of an embodied development, and not the result of isolated biological mechanisms or isolated cultural influences.

The competence–procedural approach described in this chapter begins from an embodiment assumption (Overton, 2003), and describes the development of reasoning as a series of differentiations and integrations of knowledge structures. These begin with actual physical actions and at each new major level of integration the structures become transformed into richer and more complete propositional systems. With respect to offering a comprehensive theory of deductive reasoning, a key feature of this approach is that it recognises the necessity of both competence and procedural systems. Procedural approaches without a formal competence, as we have described in the present chapter, are unable to explain how one achieves a universal understanding of logical necessity, implication, and relevance.

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