Developmental Review 31 (2011) 119–150

Contents lists available at SciVerse ScienceDirect

Developmental Review

journal homepage: www.elsevier.com/locate/dr

Dual systems Competence ←-→ Procedural processing: A relational developmental systems approach to reasoning

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ARTICLE INFO

Article history:
Available online 20 August 2011

Keywords:
Deductive reasoning
Relational developmental systems
Reflective competence
Algorithmic competence
Epistemic self-regulation

ABSTRACT

Many current psychological models of reasoning minimize the role of deductive processes in human thought. In the present paper, we argue that deduction is an important part of ordinary cognition and we propose that a dual systems Competence ←-→ Procedural processing model conceptualized within relational developmental systems theory offers the most coherent and productive framework for integrating and explaining the sometimes conflicting findings on the development of deductive reasoning across the lifespan. This model invokes a distinction that is quite similar to, though not identical with, the system 2–system 1 dichotomy employed in other dual systems models. In addition, the Competence ←-→ Procedural processing model maintains the more specific distinction between algorithmic and reflective subsystems of system 2. In this account, the algorithmic system is represented as a kind of mental logic while the reflective system is the seat of practical and epistemic self-regulation, including emergent epistemic and metalogical norms. While the proposed systems of mind often appear as split-off component features in other dual systems models, relational developmental systems theory conceives of them as the highly complex and relationally integrated outcome of a self-organizing and self-regulating adaptive developmental process.

Introduction

In this paper, we describe a dual-systems Competence ←-→ Procedural processing model of deductive reasoning and this model is formulated in the context of relational developmental systems theory

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0273-2297/$ - see front matter
doi:10.1016/j.dr.2011.07.005

(see Lerner & Overton, 2008; Overton, 2010). We will argue that the Competence ←-→ Procedural processing model offers the most coherent and productive framework for integrating and explaining the sometimes conflicting findings on the development of deductive inference from childhood through late adulthood. Because several influential publications (e.g., Evans, 2002; Oaksford & Chater, 2007) have allotted deductive processes a relatively limited role in ordinary cognition, we will also argue for the relevance of deductive inference to everyday reasoning and will provide a brief critique of recent accounts that seek to reduce performance on deduction tasks to inductive forms of inference. In preparation for these discussions, we begin with a general account of the dual systems approach to the study of cognition, including the recent argument by Stanovich (2009) for an additional distinction within what has been termed system 2 processes (see also Anderson, 1990, and Dennett, 1987, for earlier formulations). In a later section of the paper, we develop this distinction with respect to deductive reasoning. In our opening discussion, we identify key similarities and differences between our own Competence ←-→ Procedural processing model and other dual-systems models.

Dual-systems theories of cognition

Dual systems accounts of cognition – sometimes equated with dual-processing accounts – maintain that human thinking consists of two distinct, though interacting, systems. These systems involve distinct cognitive architectures and, in most current models, distinct functions (Oaksford & Chater, 2010). A *heuristic* (Klaczynski, 2001a) or *autonomous* (Stanovich, 2009) system – often designated as 'system 1' (Evans & Over, 2004; Stanovich, 1999; Stenning & van Lambalgen, 2008a) – operates on contextualized representations that are heavily dependent on problem content. Consequently, processing within this system is inherently domain-specific in nature. Heuristic processing is relatively automatic and non-conscious, drawing effortlessly from associative networks in semantic and episodic memory and from available routines within procedural memory. As such, heuristic processing makes few demands on processing capacity and attentional resources. Largely independent of general intelligence, heuristic processing is frequently assumed to occur within relatively independent neurological modules and to be shared with most species, having evolved relatively early. The majority of dual systems/processing theorists maintain that there are multiple heuristic or autonomous systems (Stanovich, 2009). In contrast to heuristic processing, an *analytic* system (Klaczynski, 2001a) – often designated as 'system 2' (Stanovich, 1999) – is a domain-general form of cognition and operates on more abstract, de-contextualized representations. Analytic processing is relatively conscious, effortful, deliberative, and controlled. As a consequence, it is constrained by working memory capacity and other system limitations and it is correlated with general intelligence. Analytic thinking is also primarily norm-based (but see Stanovich, this issue). Presumably, analytic thinking occurs within fairly unitary, integrative neurological networks and is less likely to be shared by other species, having evolved relatively late. Several dual systems/processing theories maintain that a crucial operation within the analytic system is the sustained decoupling of secondary representations from primary representations allowing for simulation and hypothetical thinking (Evans, 2007; Evans & Over, 2004; Stanovich, Toplak, & West, 2008; Stanovich & West, 2008).

From within the Competence ←-→ Procedural processing model to be described in this paper, the use of the term 'analytic' in referring to system 2 is problematic and potentially misleading because it implies a split (rather than relational) meta-theoretical orientation (see Overton, 2002) and as such it leans towards explanations of psychological phenomena that stress reductionism, atomism, simple (additive) complexity, and linearity to the neglect of complementary explanatory principles including holism, synthesis, organizational complexity, coaction, and non-linearity (Overton, 2010; Overton & Ennis, 2006; see also, Reyna & Brainerd, this issue, for a similar criticism of 'split' approaches). Consequently, we will generally avoid use of the term 'analytic' and refer to this system as system 2 or as a 'competence system'.

Recently, there have been suggestions that system 2 embodies both an *algorithmic* component (Anderson, 1990; Stanovich, 2008), consisting of operations, processes, rules and other cognitive structures underlying norm-based processing of reasoning and decision-making problems, and a *reflective* or *intentional* component (Dennett, 1987; Stanovich, 2008, 2009, this issue) consisting of practical and epistemic forms of self-regulation. In this paper, we argue that the best way to think of key organizational properties of the algorithmic system is as a kind of mental logic, while metalogical knowledge is an important component of epistemic self-regulation.

There are several reasons for going beyond the basic heuristic–analytic, or system 1 versus system 2, dichotomy and invoking an additional distinction within system 2. One is the need to represent the basis of human intentionality and motivation. Thus, the reflective/intentional component of system 2 is involved in goal formulation and planning, including the coordination of goals with available beliefs or knowledge states (Stanovich, 2009). This is *practical* self-regulation. Reflective processing therefore, is crucial to rationality construed as the effective attainment of goals (Evans & Over, 1996, p. 8).

In addition to practical self-regulation, it has been suggested that the reflective system is the source of *epistemic* self-regulation (Klaczynski, 2000). This involves intentional adherence to specific epistemic norms that provide criteria for judging the adequacy of knowledge claims (Kuhn, Cheney, & Weinstock, 2000; Weinstock, 2009). It also involves adherence to metalogical norms that sanction particular types of inference *from* knowledge claims (Moshman, 1990, 1998, 2009). *Epistemic norms* involve broad beliefs or understandings about the nature of knowledge, knowing (Hofer, 2002), and knowledge acquisition (learning) (Schommer-Aikins, 2004) and they have been implicated in performance on both formal and informal reasoning tasks (Klaczynski, 2000; Klaczynski & Robinson, 2000; Kuhn et al., 2000; Ricco, 2007; Stanovich, 2008, 2009; Weinstock, 2009). For example, if an individual considers knowledge to be a mere copy of properties originating in the object of knowledge, that individual is likely to understand disputes regarding knowledge claims as misunderstandings resolvable by access to the 'true' facts. One side is right and the other wrong, and current or potential data will determine this absolutely. By contrast, if the individual understands knowledge to be a construction that necessarily reflects aspects of the knower as well as the known, then she is likely to view each standpoint in a dispute as having some degree of legitimacy to it (Kuhn et al., 2000). Greater sophistication in informal reasoning goals and skills is associated with a relatively more constructivist and evaluativist personal epistemology (Kuhn, 1991; Kuhn & Franklin, 2006). Recently it has been proposed that epistemic self-regulation also includes what many have described as *thinking dispositions* (Stanovich & West, 1997, 2008) or intellectual values (Kuhn & Park, 2005), regarding, for example, whether or not one enjoys intellectual activity and whether one subjects beliefs and personal theories to scrutiny and gives priority to belief accuracy and truth preservation over stability and ego protection (Klaczynski & Lavallee, 2005; Klaczynski & Robinson, 2000).

There is now significant evidence that epistemic beliefs or levels of understanding and thinking dispositions predict reasoning performance *over and above* individual differences at either the algorithmic or the heuristic (system 1) levels (Klaczynski & Daniel, 2005; Stanovich & West, 2008). These findings make clear the need to acknowledge a reflective component to system 2 processing, at least with respect to human reasoning. For example, epistemic awareness (reflective component of system 2) contributes to the identification of informal reasoning fallacies (e.g., slippery slope, argument from ignorance) independently of either deductive reasoning competence (algorithmic component of system 2) or the application of pragmatic norms (system 1 processing) (Ricco, 2007). In addition, Stanovich and colleagues have established that measures of algorithmic processing (e.g., intelligence tests, working memory assessments) are better predictors of reasoning performance when instructions pull for *optimal* performance (norms are prescribed for the participant) than when instructions pull for *typical* performance (norms are not prescribed). Optimal performance conditions leave little room for individual variability in reflective competence to play a role. By contrast, measures of reflective processing (e.g., actively open-minded thinking, need for cognition) are better predictors of typical reasoning performance than of optimal reasoning performance (Stanovich, 2009; Stanovich, Toplak, & West, 2008, 2011). Thus appropriate modeling of reasoning performance requires both an algorithmic and a reflective level of analysis.

In addition to norms regarding the nature of knowledge, epistemic self-regulation arguably involves the use of *metalogical norms* to constrain inference and reasoning (Kuhn & Franklin, 2006; Moshman, 1998). These norms derive from metacognitive knowledge about reasoning and about the cognitive processes that support it. This knowledge includes a relatively explicit appreciation of the nature of inference, logical necessity, and indeterminacy (Morris, 2000; Morris & Sloutsky, 1998, 2001), and a specific appreciation of how inductive and deductive operations differ in their properties, applications, conditions of use, and inference rules (Heit & Rotello, 2010; Pillow, 2002; Pillow & Pearson, 2009; Rotello & Heit, 2009). In the last major section of this paper, we review empirical research suggesting that the development of deductive reasoning and of metalogical knowledge are intricately related and tend to parallel one another.

While practical self-regulation is important to rationality as effective goal pursuit, epistemic self-regulation is important to rationality construed as norm-based reasoning (Evans & Over, 1996, p. 8; Moshman, 2004, 2009). Interpreting reasoning problems as deductive or inductive per se and drawing inferences that conform to the necessary features of deductive or inductive logic requires a certain level of epistemic understanding and metalogical knowledge. Many aspects of epistemic self-regulation appear to be emergent, universal, and intricately related to the development of the algorithmic system (Boyes & Chandler, 1992; Chandler, Boyes, & Ball, 1990; Emick & Welsh, 2005; Inhelder & Piaget, 1958; Moshman, 1998, 2004; Overton & Dick, 2007; Overton & Ricco, 2010), while others are more profitably construed as individual difference variables based in epigenetic development or in specific experiential and environmental factors such as formal schooling, culture, and family system dynamics (Demetriou & Bakracevic, 2009; Ricco & Rodriguez, 2006; Stanovich & West, 2008).

The goal formulation and planning that are essential to practical self-regulation and the construction of epistemic and metalogical norms essential to epistemic self-regulation depend, in turn, upon metacognitive processes. Thus, *metacognition* – the reflection of thought upon itself – is crucial to each form of self-regulation and represents an increasingly key competence of the reflective system from childhood through adolescence (Kuhn & Franklin, 2006; Moshman, 2009; Piaget, 2001; Piaget & Garcia, 1991). Metacognition has also been proposed as an important basis for at least some of the overrides of system 1 by system 2 (Amsel et al., 2008; Stanovich, 2009; Stanovich et al., 2008; Thompson, 2009). Metacognitive processes such as monitoring and evaluation enable the individual to recognize occasions when heuristic responding is faulty. This recognition, in turn, is a crucial precondition for invoking system 2 processing as an override or for favoring products of system 2 processing in choosing an action.

The importance of metacognition to overrides of system 1 has recently been studied through the construct of *metacognitive intercession* (Amsel et al., 2008; Klaczynski, 2006). Intercession involves inhibiting a tendency to act on the basis of the heuristic system and examining the output of heuristic processes as they become available within working memory in order to assess their accuracy, consistency, and overall adequacy as a basis for action. Intercession may also involve distinguishing between heuristic and system 2 processing and directly comparing the products of each system. Also important to intercession are aspects of epistemic self-regulation such as thinking dispositions which can determine whether or not to invoke metacognitive competencies as well as whether or not to engage the algorithmic system. For example, individuals with a disposition to engage in intellectual activity might be less inclined to use heuristic cues such as fluency to derive confidence in a potential response (Thompson, 2009). Such individuals may have the reflective capacity to distinguish between fluency and subtler, more accurate cues to whether or not a proposed answer is correct and they may appreciate the limitations of fluency as a basis for feelings of 'rightness' or of 'knowing'.

Metacognitive intercession need not consist entirely of system 2 processing and could involve system 1 heuristics (Thompson, 2009). However, more voluntary, deliberative metacognitive processes such as monitoring and evaluation belong to system 2. Further, because these processes determine whether or not algorithmic competence will be invoked, they seem best located in a component of system 2 that is partly distinct from the algorithmic system rather than in an undifferentiated system 2 (Overton & Ricco, 2010; see also Reyna & Brainerd, this issue). In this way, metacognition is primarily associated with a reflective subsystem of system 2.

Competence ←-→ Procedural processing model

Most dual system models concern adult cognition and focus on inter-individual differences rather than intraindividual ontogenetic change (but see Klaczynski and colleagues, e.g., Klaczynski, 2001a; Klaczynski, Schuneman, & Daniel, 2004). By contrast, the Competence ←-→ Procedural processing model as it operates within relational developmental systems theory is a long-standing dual systems account of the ontogenesis of cognitive development (Overton, 1990, 1991, 2006; Overton & Dick, 2007; Overton & Ennis, 2006). The Competence ←–→ Procedural processing model invokes a distinction that is quite similar to, though not identical with, the system 2 – system 1 dichotomy. In addition, the model maintains the more specific distinction between algorithmic and reflective subsystems of system 2 (Overton & Ricco, 2010). However, the Competence ←–→ Procedural processing model conceives of the system 2 components or subsystems as aspects of a *competence* system per se and represents relations between the two subsystems as fundamentally dynamic and reciprocally co-active and co-constructed across their ontogenesis.

To understand system 2 as a competence system is to maintain a strict distinction between operations of mind that are relatively enduring, universal, and applicable to a broad range of phenomena, on the one hand, and individuated, real-time action processes, on the other. The enduring operations are part of an organized complexity that constitutes *competence*, while the real-time processes are the *procedural means* by which these enduring operations are expressed or manifest in particular individuals and contexts. The competence system functions to promote understanding and entails both the discovery of, and reflection upon, coherent patterns found in representations decoupled from procedural processing. Procedures, on the other hand, are action means to an end or goal, and function to ensure success. The type-token distinction is useful here, with universal operations representing type and the multiple, contingent ways in which competence can be expressed through real time processes representing tokens. As such, the competence system describes general performance specifications, but it is neutral on how the system is to be accessed or implemented (Dennett, 1987). As a complex dynamic organization it is, in and of itself, content free and is not to be considered as the "mental representations" the adult mind uses when reasoning (Russell, 1987). Thus, for example, a deductive reasoning problem might be processed by actually thinking in terms of truth tables, by actually thinking in terms of Venn diagrams, by actually thinking in terms of natural deductive procedures, by mental models, by pragmatic methods, or by various methods employing direct experience. These procedural alternatives are independent of the competence or organizational complexity that is being implemented by way of the procedure. The claim that a type-token distinction is fundamental to understanding the nature of system 2 stands in contrast to other dual system theories that conflate competence and procedure in their accounts of this system.

There is another key consequence of the competence stance. Because the organizational properties of mind are not reducible to any particular set of real-time processes or representations, they can only be modeled by relatively abstract, dynamic, rule systems such as *logics* that represent idealizations and analogs of the competence system (Overton & Dick, 2007; Ricco, 1993, 2010). Competence refers to organizational properties of mind. Organization must be defined by rules. Competence models, however, cannot be mere additive combinations of rules as in a production system where specific sequencing and directionality of operations are an essential part of the model. Sequences of inferences in real time are purely contingent and procedural, yet they are an expression of an implied organization or competence. Logics are effective competence models because they are, themselves, rule-governed systems of operations featuring key organizational properties such as recursiveness and completeness (Haack, 1978; Kahane, 1973; Ricco, 1990, 1993; Rips, 1998). Also, logics vary in terms of their organizational properties and, as such, they are well suited to represent the different developmental levels of organizational complexity that emerge as outcomes of transformational change across the lifespan (Inhelder & Piaget, 1958; Müller, Sokol, & Overton, 1999; Overton & Ricco, 2010).

How, then, do the complementary Competence ←–→ Procedural systems compare with the system 2 – system 1 dichotomy (see Table 1)? From the perspective of the Competence ←–→ Procedural processing model, the heuristic systems (system 1) are purely procedural systems. They serve to ensure efficiency, adaptiveness, and overall success in functioning and they are context-dependent and modular in nature. System 1 processing is never competence based. By contrast, the algorithmic and reflective subsystems of system 2 are competence systems and processing within system 2 is competence-based processing. As noted previously, a competence system is not tied to any particular real-time representational or procedural act. Nonetheless, the status of the algorithmic and reflective subsystems as competence systems does carry general implications for the nature of processing within these systems. Because competence is inherently rule-based and, in our view, logical in nature, system 2 processing will be decontextualized, involving substantial decoupling of secondary from primary

Table 1
The Competence ←-→ Procedural processing model of deductive reasoning.

Competence ←→	Procedural
System 2, Domain General **Universal, enduring, organized operations of mind** Operates on de-contextualized, de-coupled, secondary and meta- representations	**System 1, Domain Specific** **Heuristic, implicit, automatized processes** Operates on contextualized representations heavily dependent on problem content
A. *Algorithmic Subsystem* Operations, processes, rules underlying norm-based reasoning. Mental logic or natural deduction system ↕ **B. *Reflective-Intentional Subsystem*** Practical & epistemic self-regulation 1. Goal formation & planning 2. Epistemic norms, thinking dispositions, and intellectual values. 3. Metalogical norms	Real time *procedural means* by which operations are expressed in particular individuals, contexts, and contents.

representations and of meta-representations from secondary representations. In addition, system 2 processing will be flexible, effortful, slow, and relatively conscious as compared to the automatic, fast, and preconscious nature of system 1 processing (Evans, 2008).

In addition to blurring the distinction between competence and procedure, contemporary dual system and dual processing accounts often lack an explicit recognition that the proposed systems of mind are highly complex and relationally integrated outcomes of a complex self-organizing and self-regulating adaptive developmental process (i.e., a relational developmental system) (Overton, 2010). In contrast to empiricist, nativist, and evolutionary linear accounts of the origins of cognitive processing, relational developmental systems theory argues that the ontogenesis of mind is embodied, nonlinear, and epigenetic. At the microscopic level, the mechanism of all developmental change is embodied action-in-the-world (Overton, 2010; van Geert & Steenbeck, 2005). As with any complex self-organizing adaptive system, the person's embodied actions in the world lead, through complex positive and negative feedback loops, to greater complexity representing epigenetic differentiations and reintegrations or intercoordinations of processing systems. Early procedural systems differentiate to face outwards towards the world of sensible objects and further differentiate into multiple modular systems. Thus, following Stanovich (2009) there appear to be a multiplicity of procedural systems. Further growth of procedural systems proceeds primarily in terms of speed and efficiency of processing. The competence system differentiates inwards to the domain-general world of reflection and forms. In contrast to the procedural systems, the competence system undergoes emergent transformational changes as well as differentiations. The competence system differentiates into two subsystems, as noted previously – an algorithmic and a reflective system. Below we describe the organization of the algorithmic subsystem as a system of rules that mirror forms of logical arguments. The reflective subsystem entails epistemic understandings, thinking dispositions, metacognition, and metalogical understanding underlying practical and epistemic self-regulation. The competence subsystems as components of the larger system process information in a bidirectional circular causal mode, as the solution of any abstract reasoning problem necessarily requires coacting reflective metacognitive skills and dispositions (Klaczynski, 2009; Kuhn & Franklin, 2006; Moshman, 2004) as well as algorithmic content-independent inference rules (Over, 2007; Overton & Dick, 2007). The development of the two competence subsystems is highly interdependent. We will discuss some aspects of this interdependence later in this paper.

Interdependence also characterizes the more general relation between change in the competence systems and change in the procedural system. We can speak of two variants of ontogenetic change (Overton, 2010). *Transformational* change concerns qualitative change in normative, universal processes or operations at the competence (type) level – change in organizational properties of thought. *Variational* change concerns both intraindividual differences across particular expressions (tokens) of competence and individual differences in these expressions. Variational change occurs at the procedural level and is generally quantifiable, as in improvements in retrieval efficiency, increases in storage capacity or processing speed, expansion of a knowledge base, or change in skill precision. Transformational and variational change interact in a bidirectional cyclical manner such that changes in organizational complexity and procedural efficiency are co-active.

The role of deductive reasoning in ordinary cognition

It is common in the contemporary adult reasoning literature to discount the role of deduction in ordinary cognition. For this reason, before presenting the Competence ←-→ Procedural processing model of the development of deductive reasoning, it is important to address the basic question of whether deductive processes have any psychological reality. That is, does ordinary cognition involve deductive reasoning to any significant extent? We begin with a definition of deduction that distinguishes it from alternative, inductive bases of inference.

Deductive and inductive inference

Deduction is the only form of inference that can support judgments of necessity (Overton, 1990; Piaget, 1986, 1987; Ricco, 1990, 1993). In a valid deductive argument, the truth of the premises guarantees the truth of the conclusion, the latter being logically necessary given the former (Haack, 1978, pp. 13–15). This is because in a valid deduction the conclusion is implicit within the premises. It is the form of a deductive inference, therefore, and not its content, that preserves the certainty of the premises in the conclusion. One important consequence of this is that deduction is monotonic (Adler, 2008). That is, the addition of new premises to a valid deductive argument cannot render the argument invalid and rejecting the conclusion of a valid argument requires rejection of at least one premise. Another key feature of deduction is that it proceeds from the general to the specific, thereby providing a basis for the application of general rules or categories to particular instances (Overton, 1990). This property is not unique to deduction, but the grounding of deduction in logical necessity provides a unique and powerful warrant for this process of instantiation (Piaget & Garcia, 1989; Ricco, 1993). Deductive systems possess important metalogical or organizational properties such as recursiveness, consistency, soundness, and completeness. Insofar as thinking conforms to the constraints that define operations within a deductive system, it acquires these organizational properties.

The several forms of inductive inference (e.g., probabilistic, presumptive, plausible, pragmatic, etc.) stand in sharp contrast to deduction as just described. Inductive inference cannot guarantee the truth of the conclusion and is non-monotonic and defeasible. Although the truth of the premises may make the conclusion highly likely in inductive inference, there is always the potential for new information to render the conclusion false (Reiter, 1987). In addition, inductive inference often proceeds from the specific to the general (Kahane, 1973, pp. 248–250). Induction is a powerful form of inference that is crucial to the logic of conversation and to our ability to detect regularities and develop plans of action under uncertain circumstances. Induction has significant limitations, however, as a general logic of thought and as a purported basis for human rationality because the metalogical properties that hold within deductive systems generally fail within inductive systems.

Ascendency of induction-based accounts of reasoning

Some recent discussions of deductive reasoning within cognitive science and cognitive developmental psychology have favored the fairly extreme position that human beings typically do not engage in deduction, except, perhaps, under explicit instructions to do so (Cosmides & Tooby, 1994; Evans, 2007; Evans & Over, 2004; Oaksford & Chater, 2007; Oaksford, Chater, & Hahn, 2008; Pollock, 2008). In this view, studies of deductive reasoning have been hampered by an erroneous paradigm assumption (Evans, 2002) that lay reasoners interpret conditional and syllogistic reasoning tasks in terms of logical categories such as necessity, indeterminacy, validity, and monotonicity. On the contrary, it is claimed, such categories are not invoked by cognitively mature individuals for the simple reason that the categories have no psychological reality. Although individuals can learn logical categories and apply them when instructed, the categories are not normative to human reasoning and cannot provide the basis for claims that human beings are rational. In this view, therefore, the unique properties of deductive inference are of limited use or relevance to ordinary cognition.

Rather than assessing deductive processes per se, the paradigms used in research on deduction are now often assumed to be tapping a wide range of inductive processes (see, e.g., Evans, 2007; Oaksford & Chater, 2007). While this range extends from simple matching heuristics to hypothetical thinking based in supposition and simulation, all of these processes are fundamentally inductive in nature and they are alleged to be of the same kind as those employed on all manor of reasoning, problem solving, and decision- making tasks. Inductive inference is viewed as more central to ordinary cognition than deductive inference, and its properties are considered better analogs to the properties of thought itself.

It is clearly the case that deductive validity is too narrow a standard for assessing rationality (Pollock, 2008). Good arguments need not be deductive in nature and adequate justification for a decision or plan of action does not require deductive certainty. However, this does not mean that deductive processes play no role in human cognition and decisions by some theorists to dismiss deduction as irrelevant to human reasoning seem, to us, at least, premature. It is our contention that a natural deduction system constitutes an essential component of system 2 processing. There are many reasons for believing this to be the case. For example, scientific thinking, argumentation, and interpretive communication, though clearly drawing upon inductive processes, seem to benefit from deductive competence (Lawson, 2010; Radvansky & Copeland, 2004; Ricco, 2007; Stenning, 2002; Stenning & Monaghan, 2004). In addition, skeptical, adversarial processing in communicative settings, invoked when a default, credulous mode breaks down, appears to have many of the hallmarks of deductive reasoning (Stenning & van Lambalgen, 2008a, 2008b) including explicit formulation of assumptions, strict derivation of claims from these assumptions alone, and an exhaustive consideration of alternatives. Alternative, non-deductive systems that have been proposed as essential mindware for the algorithmic system often contain, in implicit form, some variant of propositional or predicate logic (see Evans & Over, 2004, pp. 59–69 for a critique of mental models theory in this regard; Ferguson, 2003) or lack analogs of key metalogical properties inherent in standard deductive logics that are important to explaining certain aspects of cognition such as the preservation of truth and the coherence of meaning across inferences.

While the claim that deductive validity should be the standard by which all natural language arguments are judged is not supportable, there are highly viable claims that arguers often *intend* for their arguments to be deductively valid and follow deductive metalogical norms in their construction of arguments and in identifying implicit and unstated elements in the arguments of others (Groarke, 1992, 1995, 1999, p. 2, 139; Jacquette, 2007; see also Vorobej, 2006 for the importance of considering arguers' intentions). Also, the key quality of inductive arguments, namely, that they are defeasible, can be captured, in at least some key respects, by natural deduction systems coupled with the appropriate semantics (Anderson, Chinn, Chang, Waggoner, & Yi, 1997; Ferguson, 2003; Groarke, 1999; see also Kowalski, 2010).

Although evidence for the spontaneous use of deductive reasoning in experimental contexts is sporadic, it remains the case that lay adults and adolescents (but generally not children) can reason in accordance with the norms of standard deductive logic when given explicit instructions to do so (Daniel & Klaczynski, 2006; Evans & Over, 2004, pp. 168–169; Klaczynski et al., 2004; Overton & Dick, 2007; Ricco, 2010), Further, it is specifically deductive properties of reasoning tasks, such as whether the argument to be evaluated is formally valid (e.g., modus ponens) or formally invalid (e.g., affirming the consequent), that determines whether processing will involve counterexample inhibition (valid forms) or counterexample search (invalid forms) (De Neys, 2010; see also, Verschueren & Schaeken, 2010). In addition, greater epistemic self-regulation is associated with a tendency to interpret reasoning tasks as fundamentally deductive in nature and to respond in accordance with logical norms (Klaczynski, 2000; Klaczynski & Daniel, 2005).

Evidence for two kinds of reasoning

There is new evidence that deduction and induction represent distinct and equally important aspects of human cognition. Recent findings suggest that induction-oriented instructions (emphasis on strength, plausibility, or judgments of likelihood) and deduction-oriented instructions (emphasis on validity, necessity, or categorical judgments) elicit fundamentally distinct kinds of cognitive processes, or, at the very least, pull for proportionally distinct amounts of system 1 and system 2 processes. Lay adults consider deductive validity and inductive strength to be distinct considerations in evaluating arguments (Rips, 2001) and neither adults (Markovits & Handley, 2005) nor older children (Markovits & Thompson, 2008) employ the same processing when making the former and the latter judgments in regard to a fixed content. Further, individuals are less likely to spontaneously employ an inductive strategy based in likelihood judgments in evaluating conditional arguments and are more likely to use a falsification strategy of counterexample search when sufficient working memory resources are available to them (Verschueren, Schaeken, & d'Ydewalle, 2005).

One particularly interesting set of findings in support of a psychological reality for the deductive-inductive distinction involves evidence that system 2 processing is more heavily involved than heuristic, system 1 processing under deductive instructional sets while heuristic processing is paramount under inductive sets (Heit & Rotello, 2010; Rotello & Heit, 2009). Evidence for this is that instructions orienting the participant toward induction (e.g., "strong arguments are those for which true premises make the conclusion plausible") lead to greater consideration of argument length in judging arguments while instructions that are oriented toward deduction (e.g., "valid arguments are ones for which true premises necessarily make the conclusion true") lead to greater consideration of logical validity (Rotello & Heit, 2009). Argument length is irrelevant within the assumption of monotonicity that characterizes deductive reasoning. Also, manipulations such as degrading the font or increasing time for responding that might be expected to pull for more deliberate, comprehensive, system 2 processing of arguments appear to make deductive properties of inference (e.g., validity) relatively more of a consideration for participants. In addition, the extent of similarity between categories in the premises and categories in the conclusion influences judgments following induction instructions more so than judgments following deduction instructions (Heit & Rotello, 2010). Similarity judgments, or indeed content considerations of any kind, are irrelevant in deduction. These results provide support for a claim that the distinction between deductive and inductive reasoning as described in this paper has a psychological reality in the form of distinct kinds of cognitive processing. In addition, these results are intriguing in suggesting a strong connection between system 2 and deductive processes per se (Heit & Rotello, 2010; Rotello & Heit, 2009).

The psychological findings of Heit, Rotello, Rips and others appear to have support from neuroscience research. There is neurological evidence that inductive sets are associated with different patterns of brain activity than deductive sets (Goel, Gold, Kapur, & Houle, 1997) and that deduction tasks with more familiar content, less conflict between belief and logic, and greater certainty information are associated with brain regions and pathways that differ from those associated with unfamiliar content, belief-logic conflict, and uncertainty (Goel, 2007). The former set of task properties is consistent with an inductive set while the latter are consistent with a deductive set.

Critique of mental models and bayesian theories of deductive reasoning

Two prominent approaches to explaining performance on deductive reasoning tasks are mental models theories (e.g., Johnson-Laird & Byrne, 1991; Markovits & Barrouillet, 2002) and Bayesian theories (e.g., Evans & Over, 2004; Oaksford & Chater, 2007). To this point in time, the former have provided more inherently developmental accounts of deductive reasoning than have the latter. There are also theories that attempt to integrate these two approaches. We cannot properly review and assess these two approaches here, but we would like to briefly discuss and critique them in their essentials prior to the central section of this paper devoted to the Competence ←-→ Procedural processing model account of the development of deductive reasoning. Mental models and Bayesian approaches can be taken as alternatives to the mental logic account that we seek to support in this paper and we note below the obvious incompatibilities. However, virtually any dual systems account is inherently integrative in nature and Competence-Procedural theory in particular offers a rapprochement that seeks to exploit the obvious strengths of these alternative theories. In particular, mental models theories offer a powerful representational account of how deductive processes within the competence system are manifest in real-time processing. Bayesian theories, in turn, provide rich accounts of system 1 processing.

Mental models

Mental models theories (Johnson-Laird, 2011; Johnson-Laird & Byrne, 1991) propose that both children and adults attempt to solve deductive reasoning problems by generating one or more mental models consistent with the premises. Although mental models theory was originally offered as an alternative to mental logic accounts, several analyses of the mental models approach have made it clear that it tacitly assumes the very mental logic its proponents have sought to render superfluous to performance on deduction problems (Braine, 1990; Evans & Over, 2004; O'Brien, 2004). The tokens that comprise mental models are arguably propositional tags and certain logical operators such as negation have properties that are identical to those of analogous operators in standard logic (O'Brien, 2004). Falsification or a search for counterexamples, a classic deductive reasoning strategy, is central to most presentations of mental models. In addition, mental models, when fully fleshed out, represent the full set of sixteen disjunctive normal forms for two propositions *p* and *q* familiar from standard propositional logic. Rather than focusing on proof, deducibility, and syntactic relations, mental models highlights truth, validity, and semantic relations. It derives, in principle, from model theory in standard logic (Johnson-Laird, 2008) which is concerned with the interpretation of logical variables with respect to a given domain. In standard logics, semantic and syntactic considerations are interdependent as demonstrated by completeness and soundness theorems in which each is definable in terms of the other. Similarly, mental models as a semantics or model-theoretic enterprise implies the proof theory it seeks to dispense with.

Arguably, therefore, mental models theory contains, in implicit form, various logical operators familiar from standard logic or one of its variants. Indeed, recent surveys of contemporary theories of reasoning tend to classify mental models and mental logic theories together as 'logical' theories and contrast these with probabilistic accounts (Oaksford & Chater, 2010). Both our approach and mental models theories posit genuinely deductive processes at the heart of performance on deductive reasoning tasks. We would argue, however, that those processes, along with the fundamental distinction between competence and procedures, are more explicitly acknowledged within our account.

Rather than presenting an alternative to mental logic theories, therefore, mental models theory could be seen as a plausible representational approach to how a mental logic might be applied in real-time processing (Overton & Dick, 2007). From our perspective, then, mental models considered as a procedural account is compatible with mental logic or competence accounts and provides important analyses of how the procedural and competence systems interact in determining performance on deductive reasoning problems.

Developmental mental models approaches have been proposed by Markovits and Barrouillet (2002) and by Gauffroy and Barrouillet (2009) (see also Barrouillet, Gauffroy, & Lecas, 2008, and Barrouillet, this issue). One key difference between these two accounts concerns the fleshing out process by which additional models are generated that go beyond an initial singularity or satisficing constraint when the resulting model is insufficient or inconclusive. The fleshing-out process is an *automatic* one in Markovits' approach (Markovits, 2004; Markovits & Barrouillet, 2002). It is largely a function of semantic memory content and the developmental status of retrieval processes. As a result, the theory seems best suited to explaining deductive reasoning with non-abstract, meaningful content problems. This is because concrete content allows, in principle, for activation of information in long-term memory and, therefore, construction of one or more of the models described in the theory, including, under the appropriate conditions, models that support norm-based responding on deductive tasks. Genuinely abstract content, i.e., content whose semantic interpretation is wholly arbitrary ("If rems are full, then braks are soft," "If there is a vowel on one side, then there is an odd number on the other") is problematic for this perspective because it provides no obvious basis for the activation of information in long-term memory. Consequently, we might expect that for abstract content, the set of mental models generated on a conditional reasoning problem would be impoverished to the point that they would support largely erroneous interpretations of the conditional such as the common bi-conditional interpretation. Yet, clearly, some individuals, including adolescents, can reason successfully with more abstract content (Overton, Ward, Noveck, Black, & O'Brien, 1987). Furthermore, success on abstract content increases across the adolescent years (Markovits & Vachon, 1990).

Gauffroy and Barrouillet (2009)(see also Barrouillet et al., 2008) provide a new mental models approach which explicitly acknowledges the importance of dual systems accounts of deductive reasoning. Though apparently eschewing a mental logic per se, they present the fleshing out process as an analytic or system 2 process that is controlled, intentional, effortful and constrained by working memory capacity. Gauffroy and Barrouillet make an important distinction between non-normative task responses that result from system 1 (e.g., semantic memory) constraints on system 2 processing and non-normative responses that result from developmental limitations in the fleshing out process occurring explicitly within system 2. An example of the former would be the impact of binary terms on the representation of conditional statements. An example of the latter would be a temporary predominance of the defective *biconditional* interpretation of 'if *p* then *q*' (limited appreciation of indeterminacy) prior to the mature, defective *conditional* interpretation (full appreciation of indeterminacy). This is consistent with a Competence ←-→ Procedural processing account which distinguishes between non-normative responding that results from system 1 override of an intact logical competence and non-normative responding that results from the absence of logical competence (system 2 failures).

Probabilistic accounts of performance on deductive reasoning tasks

Both Evans (Evans & Over, 2004) and Oaksford and Chater (2007) have argued extensively that the kind of reasoning typically employed by adults and children on a variety of deductive reasoning tasks is best construed as a non-monotonic, defeasible, and specifically probabilistic form of reasoning that proceeds from suppositions represented in terms of subjective probabilities or degrees of uncertainty rather than from categorical judgments of truth and falsehood. In this view, the ordinary language conditional ("if...then") is equivalent to the conditional probability, $P(q|p)$, i.e., the subjective probability of q given p.

One difficulty with a reliance on probabilistic accounts of system 2 thinking is that it blurs the distinction between system 1 and system 2 and weakens the argument for two distinct systems. Indeed, one of the leading probability accounts (Oaksford & Chater, 2007) originally opted for a single system model. While recent formulations of their theory (e.g., Oaksford & Chater, 2010) are arguably 'dual' with respect to cognitive architecture (LTM versus WM), they remain singular with respect to representation and function. In an early defense of a dual-process account of cognition and of the importance of rules to system 2 processing, Sloman (1996) depicts the computations of an associative system as statistical and probabilistic in nature. This is in keeping with the purpose of this system – one of representing "frequencies and correlations among the features of the world (p. 4)," thereby providing the mind with access to potential sources of "variability and covariability (p. 4)" in the environment. Sloman suggests that representations of associations among features could consist of conditional probabilities, or could be readily modeled as such. Thus heuristic system outputs provide the basis for likelihood estimates and probabilistic inference. Such inferences, however, are estimates and are not based in the rules of probability theory, nor do they represent the causal mechanisms underlying the associations being modeled. The formulation and testing of explanatory models requires rule-based processing typical of system 2, in Sloman's estimation. By this argument, probabilistic accounts of deductive reasoning may simply be reflecting system 1 or heuristic processing. Indeed, associative systems capturing statistical regularities in the environment are readily modeled via neural networks and parallel distributed processors. In considering non-monotonic reasoning in general, whether probabilistic or otherwise, there are proposals for modeling human cognition that do not require system 2 processes, being capable of implementation largely, if not entirely, on the basis of system 1 capabilities (Stenning & Lambalgen, 2008a, 2008b). Evans and Over (2004, p. 158) appear to acknowledge that assessing the conditional probability $P(q|p)$ in interpreting "if p then q" can be, at least under certain conditions, a heuristic-like procedure that involves a mix of system 1 and system 2 processes (see Barrouillet, this issue, for a discussion of the problematic nature of this mix). Thus a conditional statement will be attributed a high subjective probability if 'p, q' cases 'come to mind' more easily than 'p, $-q$' cases. According to Evans, assessing $P(q|p)$ will be a primarily system 2 process *only* where simulations are run from p or where chains of explicit probabilistic inferences are constructed from the supposition that p. However, as soon as chains of inferences are involved, probabilistic accounts run into another problem which we discuss next.

It is not entirely clear how to formalize a natural deduction system with the conditional probability interpretation of implication (Hajek, 2001). Inference systems grounded in the probability calculus do not assign truth values to conditional propositions. This means that classical validity fails in these systems since there is no sense in which the truth of the conclusion can be guaranteed by the truth of a premise set that includes conditional propositions. Probabilistic validity has been offered as an alternative to classical validity. Under the most common formulation (Adams, 1975), an argument is probabilistically valid (p-valid) if the uncertainty of the conclusion cannot be lower than the summed uncertainties of the premises. However, certain classically valid inference forms involving conditional propositions do not appear to be probabilistically valid. These include strengthening – [(if p, then q) therefore (if p and r, then q)] – as well as transitivity, and contraposition (Oaksford & Chater, 2007, p. 112; Pollock, 2008; Simone, 2009). Under some interpretations, these rules can yield consequences that are less certain than the premises. Evans and Over (2004, p. 169) maintain that an adequate probability inference system, one capable of modeling adult logical competence, must include introduction and elimination rules for 'if' and for 'or' and 'and', but not all of these rules appear to be p-valid. Other formulations of probabilistic validity are even more problematic when it comes to transferring degrees of justification or certainty from premises to conclusion (see Pollock, 2008, for such an alternative formulation and Fitelson, 2010, for a critique). In general for any probability logic, inference rules *in and of themselves* cannot provide precise estimates for the likelihood of the conclusion (Pollock, 2008). The upshot of this is that probability conditionals may well capture certain usages of ordinary language conditionals or a certain way in which we are able to interpret conditionals when asked to do so, but this comes at a price with respect to modeling how we actually construct a line of reasoning or argument containing conditional statements. An adequate formalization and corresponding competence model may be forthcoming, but we do not currently have one. For additional, and distinctly empirically-based criticisms of probabilistic accounts, see Barrouillet (this issue).

An algorithmic competence model for deductive reasoning

It is our contention that any viable account of system 2 algorithmic processing must include at its core a logical competence model or mental logic. We readily acknowledge that such models are not currently preferred by cognitive and cognitive developmental psychologists. We have suggested above that part of the reason for this is a meta-theoretical or paradigm shift toward a conception of ordinary cognition as fundamentally inductive in nature. The abandonment of a search for genuinely deductive processes in cognition seems premature to us and we offer below a re-examination of the now substantial *developmental* literature on child, adolescent, and adult performance on deductive reasoning tasks. Careful consideration of this empirical literature provides surprisingly more support for the mental logic position than might be expected.

The Competence ←–→ Procedural processing model asserts that the rules of logic bear a non-arbitrary relation to the psychological processes involved in deductive reasoning. Therefore, the rules of logical arguments – as formalized in symbolic logic – can be understood as relatively adequate models of normative, idealized, abstract operations of mind in this domain. The individual in some sense acquires and has access to the operations characterized by these rules. The rules, thus described, constitute a 'competence', and the competence is held to be a significant feature of the explanation for adequate performance on deductive reasoning tasks. It is important to note, however, that the competence is not to be thought of as mental representations (e.g., mental models) used in actual reasoning. Competence is an idealization of the system of thought that the normal adult has access to. It constitutes a universal model. The actual individual mental representations used in accessing and implementing this competence constitute a procedural model.

There are numerous variations on standard symbolic logic– some modest, and some substantially deviant – and, consequently, there are many candidates from which to choose in selecting a model for the competence system. The Competence ←–→ Procedural processing model favors a mental logic that resembles standard propositional logic, but is not isomorphic to it. Specifically, the combinatorial logic (INRC group) of Inhelder and Piaget (1958) revised as an entailment logic (Piaget & Garcia, 1991, pp. 141–158) capturing the importance of relevance and meaningful implication to human reasoning has been proposed by the Overton group as a reasonable candidate for the competence model (Overton, 1990; Ricco, 1993). The propositional-entailment logic has a developmental precursor from which it can be formally derived. In this way, the Competence ←–→ Procedural processing model and more general relational developmental systems approach provide a theoretically viable and unique account of the emergence of deductive reasoning from earlier, more limited, logical competencies. This precursor is a class and relational logic that represents the key competence system in middle childhood. The derivation of the propositional logic involves, in part, an expansion of the scope of negation in the class and relational logics (Byrnes, 1988; Byrnes & Overton, 1988; Müller et al., 1999; Piaget, 2001), and the emergence of formal deductive competence from an earlier, concrete competence can be represented as a process of increasing flexibility in the use of partial or local negations leading to the differentiation and coordination of two forms of negation – one bounded and the other unbounded (Byrnes, 1988; Piaget, 1980, pp. 297–299; Piaget & Garcia, 1991, p. 164). This theoretical claim has been supported empirically. Müller et al. (1999) provide evidence that the a priori ordering of logic problems in terms of their complexity with regard to the role of negation corresponds to a developmental progression.

Alternative mental logics have been proposed for the competence model within a Competence ←–→ Procedural account. The most influential in this regard has been the natural deduction system of Braine and O'Brien (1998). This latter model differs from the Overton/Piagetian model in several key respects. The Braine and O'Brien natural deduction system consists of relatively innate and heuristic core inference schemas and direct reasoning routines supplemented by a set of complex schemas and indirect reasoning strategies which are not innate or universal and which are particularly dependent upon formal tuition and related experiences. The primary or core schemas are employed automatically when the appropriate propositions are encountered. By contrast, the secondary or complex inference schemas are only employed under special conditions and are strategic, deliberative, and intentional. The Brain and O'Brien competence model resembles a production system more than a logic because the individual schemas and routines are not integrated into a recursive system the way logics are. The bulk of the model's utility has been in explaining relatively automatic and isolated inferences such as might be involved in language comprehension. The model has been less useful as an account of deductive reasoning construed as deliberative, intentional, system 2 cognition.

Rips (1994) psychology of proof (PSYCOP) model is another well known mental logic account of deductive reasoning offered primarily as a model of adult thinking. The model is essentially a proof theory that consists of a natural deduction system featuring both forward and backward inference rules. It is designed to model the evaluation of the validity of arguments and the derivation of valid conclusions from premises. The model also contains a theorem-prover of a heuristic nature which, for example, specifies that forward rules are to be implemented before backward rules and simpler forms of the latter precede more complex forms. Rips model is essentially a competence model in that it does not contain an account of how the mental logic interfaces with procedural systems in performance on particular tasks or problems. At the same time, the model appears to blur the distinction between competence and procedure in that the rules of the mental logic represent real time mental procedures. This is particularly evident from Rips claim that a proof theory or syntactic description, such as PSYCOP, is 'computationally relevant' while a semantic description, such as mental models purports to be, is not.

In sum, then, there are several viable mental logic accounts of deductive reasoning competence. We argue for the Competence ←–→ Procedural processing model because it is distinctly, and uniquely, developmental and it seems best positioned to explain the large body of developmental findings on reasoning. We review the model with respect to that evidence next.

Competence ←-→Procedural processing model: the development of deductive reasoning

The Competence ←–→ Procedural processing model has been successful in explaining a wide range of empirical findings on the development of deductive reasoning, and while several of these findings allow for alternative explanations, we believe that the Competence ←–→ Procedural processing model provides the most parsimonious account of the totality of evidence. The model predicts, on an a priori basis, several sets of findings. In general, the model accounts for developmental trends in both normative and heuristic-based responding on reasoning tasks. With regard to deduction paradigms per se, the model accurately predicts robust age-differences and age-changes in spontaneous falsification solutions on multiple versions of the selection task and in uncertainty responses to the indeterminate forms of conditional arguments on evaluation and inference tasks. The model provides a viable account of inconsistencies in the deduction literature between seeming evidence of early competence and adult incompetence. The Competence ←–→ Procedural processing model also accounts for age trends in the conflation of the $[-p, q]$ and $[-p, -q]$ cases of the conditional and it explains a host of findings regarding key moderators of the above age-related effects, including such factors as training, content, and SES. The Competence ←–→ Procedural processing model has been successful in accounting for the emergence of precursors to deductive competence in middle childhood and it is virtually the only developmental account of findings regarding the fate of deductive reasoning in later adulthood. Finally, the model accurately predicts recent evidence that biased, motivated reasoning remains stable across development in cases where it involves system 2 override of system 1 and declines in cases where it involves system 1 override of system 2. In the discussion to follow, each of these sets of findings will be reviewed in the context of the Competence ←–→ Procedural processing model account.

As a preamble to this review, a brief description is needed of the methodology that has been employed in empirically testing the model. Broadly, all direct tests of the model have involved two major components. The first is a developmental assessment (age differences or age changes) of the *availability of the underlying logical competence*. The criterion for a formal deductive competence is operationalized as *successful coordination* of the four elementary inference forms; the two valid forms – *modus ponens* (if *p* then *q*; *p*; therefore *q*), and *modus tollens* (if *p* then *q*; *not-q*; therefore *not-p*) – and the two invalid forms – *denied antecedent* (if *p*, then *q*; not *p*; therefore not *q*), and *affirmed consequence* (if *p*, then *q*; *q*; therefore *p*). It is the coordination of these forms that defines a full understanding of the advanced logical concept of *implication*. It is important to emphasize that testing on, or scoring of, these forms individually does not permit inference concerning the availability of the formal logical competence system. For example, the argument "If John mows the lawn (*p*), then John will be paid $10 (*q*)," "John mows the lawn (*p*)" Thus, "John gets paid $10 (*q*)" is simply a promise kept, and becomes the logical inference modus ponens, only in the context of an understanding of the remaining three forms. The second major component of all direct tests of our model is the introduction of a pro-

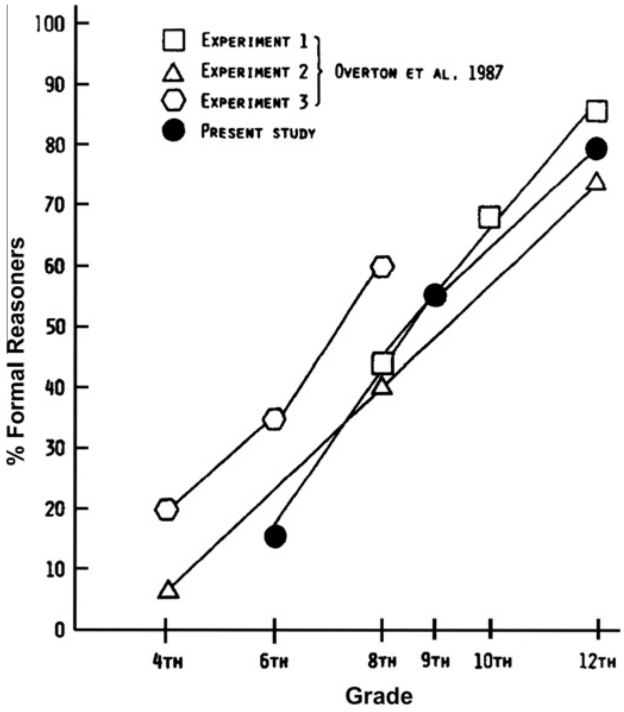

Fig. 1. Developmental availability of formal logical competence. Percentage of participants at each grade attaining the criterion for formal reasoning (complete falsification solution on at least 3 of 5 problems) on the selection task. Drawn from Ward and Overton (1990).

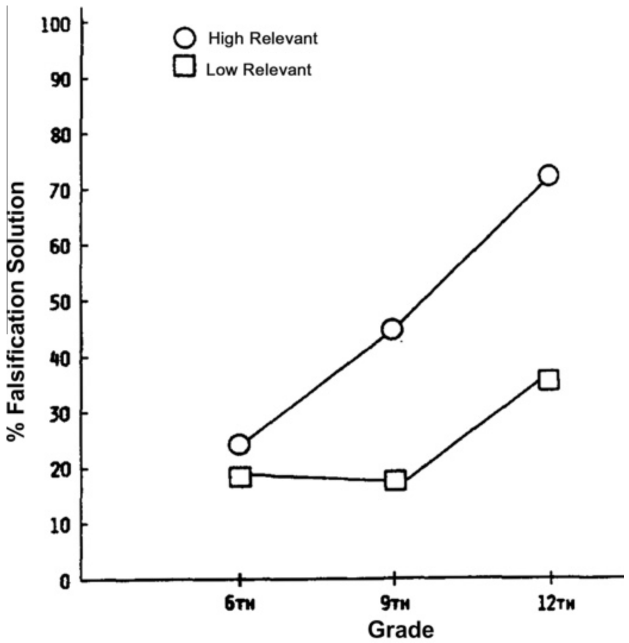

Fig. 2. Logical relevance and procedural accessibility of formal logical competence. Percentage of complete falsification solutions on the selection task at each grade for high- and low-relevant conditions. Drawn from Ward and Overton (1990).

cedural context (e.g., alternative task instructions or task materials, culturally distinct groups, supplemental problem solving strategies, etc.) designed to assess the impact of procedural processing.

An example of these two components of the general methodology is illustrated in Figs. 1 and 2 derived from a study conducted by Ward and Overton (1990). Both figures show performance on the selection task or 'four-card problem.' For each problem participants must identify cases necessary to falsify a conditional rule (if p, then q) and avoid cases irrelevant to falsification. The cases considered are presented by way of cards indicating the truth status of the rule's antecedent (p or $-p$) on one side and the rule's consequent (q or $-q$) on the other. Only one side of each card is exposed. The correct or complete falsification solution involves selecting the 'p' card and the '$-q$' cards and not selecting the '$-p$' and the 'q' cards on each problem. Fig. 1 shows the percentage of participants within various age groups achieving the complete falsification solution on at least 3 of 5 problems. The age differences depicted demonstrate the reliability of the developmental function of logical competence found in the Ward and Overton study (dark circles) aggregated with three other studies conducted in two different labs. A highly similar developmental function was found with longitudinal data (Müller, Overton, & Reene, 2001) and in studies employing 10 problems (at least 6/10 criterion) (e.g., Chapell & Overton, 1998). The Ward and Overton study also introduced high and low *logical relevance* (i.e., meaningfulness of the relation between p and q) as a procedural condition to assess the accessibility of the formal competence. The high relevance condition involved selection task problems on which the antecedent and consequent were meaningfully related (e.g., "If a person is drinking beer, then they are 21 years of age."), as judged by a fifth grade sample. In the low relevance condition, the antecedent-consequent relation was significantly less meaningful (e.g., "If a person is drinking beer, then the person goes to church."). Fig. 2 depicts the percentage of falsification solutions at each of several grades. These findings illustrate that the available formal competence (12th grade), is less procedurally accessible when relevance is low.

Age trends in normative and heuristic responding

At a general level, the Competence ←-→ Procedural processing model predicts that the most significant increase in norm-based responding across a range of tasks that arguably tap deductive reasoning competence should be evident from late childhood through middle adolescence as the algorithmic and reflective competence systems mature and consolidate affording substantially greater opportunity for override of the heuristic system. This developmental pattern has indeed been found in numerous studies of conditional and syllogistic reasoning, decision-making, scientific thinking, and argumentation. (Daniel & Klaczynski, 2006; Klaczynski, 2001a; Klaczynski et al., 2004; Kuhn & Franklin, 2006; Overton & Dick, 2007). Developmental trends regarding heuristic-based (system 1) responding on these tasks are also consistent with the Competence ←-→ Procedural processing model. Heuristic-based responding from late childhood through adolescence is generally found to decrease (Klaczynski, 2001a) or remain stable (Klaczynski, 2001b). The exceptions here are select findings of increased use of specific social heuristics and stereotypes such as might be learned at a particular point in development (e.g., the 'fat is out/thin is in' obesity stereotype of adolescence)(Klaczynski, Daniel, & Keller, 2009). By contrast, age-related *increases* in heuristic-based responding appear limited to research with children from the early to late elementary years (Brainerd, 1981; Davidson, 1995; Jacobs & Potenza, 1991; Koriat, Ackerman, Lockl, & Schneider, 2009; Markovits & Dumas, 1999; Morsanyi & Handley, 2008; Reyna & Ellis, 1994) rather than adolescence. These latter findings are consistent with the claims of the Competence ←-→ Procedural processing model because middle childhood is a period of development that precedes the emergence of full formal deductive competence.

Deduction paradigms

Focusing more specifically on deduction paradigms per se, a reasonably clear developmental pattern emerges and it is consistent with the claims of the Competence ←-→ Procedural processing model. Considering success rates (falsification solutions) on versions of the selection task, formal reasoning competence appears to be lacking in fourth through sixth grades, coming on-line in eighth/ninth grade, and readily available in tenth to twelfth grades (Chapell & Overton, 1998; Foltz, Overton, & Ricco, 1995; Overton, Ward, Noveck, Black, & O'Brien, 1987; Ward & Overton, 1990). This pattern is not limited to cross-sectional comparisons. It has been corroborated with longitudinal research as well (Müller et al., 2001). Once available, this competence appears to remain intact well into later life (Pollack, Overton, Rosenfeld, & Rosenfeld, 1995; Ricco, 2010; Takahashi & Overton, 1996). Findings from other deduction paradigms including tasks requiring evaluation of arguments or inferences from premises are consistent with claims that a formal deductive competence is an emergent capability more typically associated with adolescence than with middle childhood (Daniel & Klaczynski, 2006; Janveau-Brennan & Markovits, 1999; Klaczynski et al., 2004; Markovits & Quinn, 2002). Research with particularly complex inference tasks provide more conservative estimates regarding the age at which deductive competence is attained, but these findings confirm that the competence is emergent and associated primarily with adolescent development (O'Brien & Overton, 1980, 1982; Overton, Byrnes, & O'Brien, 1985).

Training, moderators, and content effects

The above developmental pattern is also indirectly supported by findings regarding training effects and the role of moderator variables. Interventions such as contradictory training, meant to discourage invited inferences on indeterminate problems, are beneficial, but only for ages at which prior research suggests the formal deductive competence is typically present (Overton, Byrnes, & O'Brien, 1985). At the same time, older adolescents are less likely than younger ones to need cues and assistance, presumably because the competence is more intact and more readily accessible (Müller et al., 2001). Moderator variables, such as SES and instructional set, have more relevance at ages where formal deductive competence is typically emerging or present (Chapell & Overton, 2002; Daniel & Klaczynski, 2006). In particular, explicit instructions to maintain a deductive set by assuming the truth of the premises, accepting only logically necessary conclusions, or working merely with the information contained in the problem, improves performance on conditional reasoning problems for adolescents (e.g., 13- and 16-years-of-age) but generally not, or less so, for pre-adolescents (e.g., 10 years) (Daniel & Klaczynski, 2006).

The Competence ←-→ Procedural processing model provides plausible explanations for a variety of *content* effects. Familiar content, meaningful content, and increased relevance of antecedent to consequent facilitate performance on deductive reasoning problems, but only subsequent to the availability of the logical competence (Müller et al., 2001; Overton, Ward, Noveck, Black, & O'Brien, 1987; Ward & Overton, 1990), and the greatest degree of variability in performance across content is found during periods of competence consolidation (Overton, Ward, Noveck, Black, & O'Brien, 1987). Abstract content is problematic at all ages, but improvement is clearly evident from eighth through twelfth grades (Overton, Ward, Noveck, Black, & O'Brien, 1987; see also Markovits & Vachon, 1990). Findings of this sort make it difficult to argue that success on deductive reasoning tasks is strictly a function of domain-specific processes (Cheng & Holyoak, 1985). Familiarity, relevance, and other aspects of content that would be expected to maximize the efficiency of processing in working memory support the application of an *existing* logical competence. Those same processes, however, are ineffective, in the absence of that competence.

The pitting of one content effect against another has also provided support for a competence account. Specifically, the perceived relevance of consequent to antecedent is a better predictor of conditional reasoning performance than mere familiarity of content, and a meaningful connection between antecedent and consequent enhances performance even in the absence of familiarity (Ward, Byrnes, & Overton, 1990). This finding is consistent with the Competence ←-→ Procedural processing model because it suggests that domain-specific processes responsible for familiarity effects are not sufficient for success on conditional reasoning problems and are secondary in importance to organizational processes in working memory. This result is to be expected from within a Competence ←-→ Procedural processing account because real-time organizations such as a semantic connection between antecedent and consequent provide optimal conditions for the application of a logical competence (Ricco, 1990; Ward et al., 1990; Ward & Overton, 1990). This is because the latter is, itself, organizational in nature. By contrast, although familiarity should generally support access to a logical competence, it could also elicit local or domain-specific inferences of a non-deductive nature (Cummins, 1996; Harris & Nunez, 1996).

Emergence of deduction from class-based competences

Three important sets of age-related effects on deductive reasoning problems can be explained by the origins of deductive competence in earlier class and relational logics, a central tenet of relational developmental systems theory and the Competence ←–→ Procedural processing model, and a tenet that is unique to this account. Prior to the differentiation and coordination of bounded and unbounded negation underlying full deductive competence, the child is likely to conflate the two possibilities for the denial of the antecedent in conditional argument, namely [$-p$, q] and [$-p$, $-q$]. This is because the negation of p is bounded (by q) in the former possibility and unbounded in the latter. Conflation involves failing to recognize that the meaning of the conditional is consistent with both possibilities, and not merely with [$-p$, $-q$]. This error amounts to interpreting the conditional as a biconditional (if p, then q AND if q, then p). For example, in evaluating the conditional statement, "If it is raining, then the street is wet," this conflation involves failing to distinguish between cases where "it is not raining and the street is wet" and "it is not raining and the street is dry". In conflation, the child represents the former case as false and the latter case as either true or indeterminate (Gauffroy & Barrouillet, 2009). Conflation is indeed significantly more common in childhood than in adolescence and represents one of the more robust effects in the conditional reasoning literature (Byrnes, 1988; Overton, 1990; Overton, Ward, Noveck, Black, & O'Brien, 1987).

The account of the emergence of conditional reasoning from class reasoning also predicts that conflation should go hand in hand with a fundamental difficulty in generating alternatives (e.g., the street has been cleaned) to p (it has rained) that could obtain along with q (the street is wet). Difficulty generating alternatives would lead to a failure to appreciate the indeterminate nature of the affirming-the-consequent (AC) and denying-the-antecedent (DA) conditional argument forms. Again, this prediction is substantially supported in the literature (Daniel & Klaczynski, 2006; Janveau-Brennan & Markovits, 1999; Markovits & Barrouillet, 2002). For the Competence ←–→ Procedural processing account, the primary restriction on the range of possibilities that the child can generate in reasoning about conditional arguments is a logical one – difficulty in appreciating that the truth of the conditional is consistent with situations where the consequent obtains despite the absence of the antecedent. While alternative, non-logic-based explanations of an increase in the generation of alternative antecedents and corresponding judgments of uncertainty on indeterminate forms are possible, there is increasing indication that these are insufficient. There is evidence that determinate responding on the two indeterminate forms – AC and DA – declines through mid-adolescence *both* for antecedents with strong connections to alternatives in semantic memory and for antecedents with weak connections to alternatives (Daniel & Klaczynski, 2006; Janveau-Brennan & Markovits, 1999; Klaczynski et al., 2004; Markovits & Quinn, 2002). These findings cannot be adequately explained on the basis of developmental changes in strength of associations within semantic memory or advances in the efficiency of retrieval processes. Based purely on these latter developmental factors, one would not expect a decline in determinate responses to the indeterminate forms for conditionals featuring antecedents that readily call to mind alternative ways in which the consequent q could obtain. Further, differential responding to 'strong' and 'weak' conditionals appears to decline with age (Barrouillet, Markovits, & Quinn, 2001). Although this could reflect advances in retrieval of alternative cases, it is also consistent with an increasing role for logical competence in responding on conditional reasoning tasks. Although Daniel and Klaczynski (2006) point to the likely importance of improved inhibitory capacities in avoiding determinate interpretations of AC and DA, they also acknowledge a role for advances in metalogical understanding.

If, as claimed by the Competence ←–→ Procedural processing model, propositional (or quantificational) logical competence develops by way of key transformations within an earlier class-based logical competence, then one would expect to see the emergence in middle childhood of specific concrete precursors to formal deductive competence. These include an appreciation of logical indeterminacy and the logic of falsification within *concrete*, problem-solving settings (Byrnes & Overton, 1986; Ricco, 1997). A logical competence based in class reasoning should be sufficient for success in this regard. Representing the set of viable alternatives on an indeterminate problem in terms of an equivalence class would provide a basis for regarding them as equally viable despite the presence of various arbitrary features that might otherwise be employed by the child to attach a greater likelihood to one alternative rather than another (Byrnes & Beilin, 1991). Consideration of alternatives from within the logical construct of an equivalence class would also promote an appreciation of the epistemic legitimacy of uncertainty, i.e., an appreciation that uncertainty is a necessary and irreducible state within logical relations. Consistent with this claim, children do not show clear evidence of an appreciation of the irreducibility of uncertainty on indeterminate problems prior to 8 or 9 years (Byrnes & Overton, 1986; Horobin & Acredolo, 1989; Ricco, McCollum, & Wang, 1997) – the age at which success on class reasoning problems is initially found – and possibly not until 11 or 12 years (Acredolo & Horobin, 1987; Scholnick & Wing, 1988). Evidence of earlier success on indeterminate problems (Fabricius, Sophian, & Wellman, 1987; Rai & Mitchell, 2006; Sodian & Wimmer, 1987; Sodian, Zaitchik, & Carey, 1991; Sommerville, Hadkinson, & Greenberg, 1979; Wollman, Eylon, & Lawson, 1979) is not accompanied by evidence that indeterminacy can be maintained in the face of task-based and internally-based cues to close prematurely on problem solutions. Similar results obtain in regard to a concrete understanding of falsification. Appreciating that a falsification strategy is the only basis for solving proof construction problems in the minimal number of moves is absent before 8 or 9 years of age (Ricco, 1997) and the capacity to *generate* conclusive tests of concrete hypotheses including a *search* for disconfirming or falsifying evidence is rarely found earlier than 8 years (Chen & Daehler, 1989; Chen & Klahr, 1999).

Preschool competence and adult incompetence

It is well recognized at this point that the deductive reasoning literature includes some strikingly inconsistent findings (Markovits & Barrouillet, 2004; Moshman, 2004). In particular, evidence of seeming deductive competence during the preschool years contrasts sharply with significant evidence of adults responding in non-normative ways on deduction paradigms. One of the more obvious strengths of the Competence ←-→ Procedural processing model is its capacity to explain this contradictory evidence (see Reyna & Brainerd, this issue, for an alternative account that focuses on developmental reversals). The Competence ←-→ Procedural processing model maintains that apparent findings of adult incompetence on deduction tasks are typically occasions where procedural obstacles to the accessing and implementation of a logical competence are present. The insufficiency of an available competence in the face of procedural obstacles is also acknowledged within other dual systems theories, as evident, for example, in the various accounts such theories provide for how algorithmic mechanisms may fail to be accessed or may be overridden by system 1 processing (Stanovich, 2009; Stanovich & West, 2008; Stanovich et al., 2008).

The Competence ←-→ Procedural processing model is also able to account for seeming evidence of precocious deductive competence. As a relational developmental systems theory it is assumed that reasoning is intentional, goal-directed, and involves some manner of organization or coordination across inferences. Any given inferential act by the child assumes and implicates various other inferences which are part of the competence, though not manifest in performance on this occasion (Markovits, 2004; Müller et al., 2001; Piaget, 1986). In this view, attributing deductive competence to individuals or groups requires evidence of a certain level of integration (and differentiation) among inference schemes. As suggested in the description of the general methodology of the Competence ←-→ Procedural processing model, any attempt to analyze inferences in isolation represents a reduction of competence to procedure. Some evidence of early success on deduction tasks consists of relatively isolated propositional inference forms such as modus ponens (MP) or valid syllogisms and obtains in the absence of success on other, logically related inferences (e.g., AC or DA). One set of findings frequently referenced as evidence of early competence concerns the use of fantasy settings or instructional sets to dissuade empirical, non-logical approaches to deduction problems. These studies are purported to provide evidence of deductive reasoning in preschool or the early school years (Dias & Harris, 1988, 1990; Hawkins, Pea, Glick, & Scribner, 1984; Kuhn, 1977; Leevers & Harris, 1999). Early success across these studies, however, is generally limited to a few isolated inference forms such as MP or valid syllogisms. Similar levels of success with indeterminate argument forms (e.g., AC or DA) is only occasionally found (Markovits, Schleifer, & Fortier, 1989; Markovits et al., 1996). From the competence perspective, therefore, such evidence of early reasoning is necessarily suspect insofar as it is limited to success with a particular type of inference in the absence of successful coordination with other, logically related inferences. In addition, children in these research settings generally fail to demonstrate an understanding of the deductive nature of the inferences they have made, suggesting that the cognitive processes involved are heuristic in nature and do not involve reasoning per se.

Other evidence of early-onset deductive competence appears to involve relatively automatic and non-intentional inferences which can readily be explained on the basis of system 1 processes. Inferences resembling deductions are common in language comprehension processes, for example, and are embedded in domain-specific or modular forms of cognition (Braine, 1978; Braine & O'Brien, 1998). Hearing that "Mom is late. She must have decided to walk," young children recognize the implication that had mother taken the car, she would have been on time. As part of domain-specific (e.g., language) processing, however, these inferences are not subject to reflection, and young children generally fail to demonstrate an understanding of their deductive nature (Moshman, 1990, 2004; Moshman & Franks, 1986).

Age effects in biased or motivated reasoning

From a Competence ←-→ Procedural processing perspective, some forms of biased or motivated reasoning would be expected to decline across adolescence as the algorithmic and reflective subsystems of the competence system consolidate. These would be forms of bias that result from competence deficits at either the algorithmic or reflective level leading to a default to the heuristic system in the former case or failure of the algorithmic system to override the heuristic system in the latter. The belief bias effect under instructions that induce a deductive set would seem to represent this type of reasoning bias. Belief bias refers to a tendency to accept or reject the conclusion of an argument on the basis of the believability of the premises and/or conclusion, rather than the logical form of the argument. Vulnerability to belief-bias can be assessed by setting up a conflict between logic and belief. This can be accomplished by way of arguments that have an invalid form, but true premises and/or a true conclusion (e.g., All things that have a motor need oil; Automobiles need oil; Therefore, automobiles have motors). Alternatively, one could employ arguments with a valid form, but false premises and/or a false conclusion (e.g., All animals with four legs are dangerous; Poodles are not dangerous; Therefore, poodles do not have four legs). Belief bias is evident when the former argument is judged to be valid and the latter invalid. When task instructions stress the importance of a logical or formal evaluation of the argument, thus inducing a deductive set and eliciting system 2 processing if available, susceptibility to belief bias tends to decrease across later childhood and adolescence (Kokis, Macpherson, Toplak, West, & Stanovich, 2002; Markovits & Vachon, 1990). There is a similar trend with respect to scientific thinking. On hypothesis-testing tasks where the individual is not neutral with respect to the hypothesis being tested, we see fundamental problems during the middle childhood years in conceptualizing evidence as separate from theory or belief and in appreciating the falsifiable nature of the latter, and we see relatively fewer problems in adolescence and/or adulthood (Kuhn, 2002; Kuhn & Franklin, 2006). Logical and metalogical deficits would seem to be implicated in these biases.

By contrast, forms of biased reasoning that result, not from logical competence deficits, but, rather, from selective, motivated application of that competence should not show age-related changes across adolescence. Klacynzski and colleagues have studied a form of motivated reasoning in which individuals show a tendency to employ system 2 processing selectively, using it for processing belief-incongruent data, but not belief-congruent data. Thus adolescents show greater sensitivity to methodological flaws underlying research findings that refute their religious beliefs than for findings that support those beliefs (Klaczynski, 2000). This is a kind of my-side bias. Since algorithmic competence must be available in order for this type of bias to occur, a Competence ←-→ Procedural processing approach would not expect to find evidence of age differences during adolescence in displays of this type of bias. Consistent with this expectation, biases based in selective system 2 processing are generally unrelated to age during late childhood and adolescence and do not decline with advances in reasoning competence during these years (Klaczynski, 1997, 2000; Klaczynski & Fauth, 1997; Klaczynski & Lavallee, 2005; but see Klaczynski & Narasimham, 1998, for mixed findings). At the same time, reasoning biases based in selective application of system 2 processing are significantly associated with various thinking dispositions and epistemic beliefs and with vocational identity (Klaczynski, 2000; Klaczynski & Lavallee, 2005). Thus across adolescence, individual difference variables appear to be more useful than age in predicting the presence or absence of reasoning biases based in selective use of system 2 processing.

Deductive reasoning in later adulthood

Serious study of deductive processes beyond early adulthood has been occasional and unsustained. With the exception of research conducted within relational developmental systems theory broadly and the Competence ←-→ Procedural processing model specifically, the existing research is also largely atheoretical, which reflects the lack of a lifespan perspective in current theories of deductive reasoning. Relational developmental systems theory argues that deductive inference is a fundamental characteristic of mature human thought (see Overton, 2010). As inherent to thinking, deductive processes should be relatively immune to the effects of aging during the later years (Pollack et al., 1995; Takahashi & Overton, 1996). By contrast, a variety of procedural factors important to accessing and implementing this competence might be expected to be relatively more at risk for the compromising effects often found in late adulthood.

Results from the late adulthood problem-solving literature assessing relatively concrete forms of deductive reasoning, though mixed, do not present clear evidence of age related decline in deductive reasoning. To the extent that these studies employ problem-solving tasks requiring participants to engage in strictly deductive processes of proof construction (e.g., Arenberg, 1974; Haught, Hill, Nardi, & Walls, 2000; Kesler, Denney, & Whitely, 1976; Weirsma & Klausmeier, 1965; Wetherick, 1964; Young, 1971), we are less likely to find differences in performance between younger and older adults. The one possible exception to this concerns twenty questions tasks. Regarding the latter, however, there is ample evidence of success with older adults in attempts to train effective approaches to the task (Denney & Denney, 1974; Denney, Wells Jones, & Krigel, 1979; Hybertson, Perdue, & Hybertson, 1982).

The key literature regarding the question of age-related effects in deductive reasoning is clearly the relatively small set of studies of syllogistic and conditional reasoning. These studies are particularly informative because they are the least controversial measures of deduction used in research with older adults, and because they vary important potential mediators of the adult development-reasoning relation. Age-related effects in performance are found across most of these studies. However, a consistent finding is that age-related effects are absent or substantially reduced when relatively minimal training is provided (Overton et al., 1986; Pollack et al., 1995; Takahashi & Overton, 1996), or when various mediators of the development-reasoning relation are controlled (Blair, 2010; Fisk & Sharp, 2002; Gilinski & Judd, 1994; Light, Zelinski, & Moore, 1982; McKinnon & Moscovitch, 2007; Overton et al., 1986; Pollack et al., 1995; Takahashi & Overton, 1996; Viskontas, Holyoak, & Knowlton, 2005). These mediators include speed of processing, working memory demands, and demands on inhibitory processes and emotion regulation.

Taken as a whole, the relevant research findings provide reasonable support for a claim that the logical competence implicated in deductive reasoning is relatively enduring across the later years. Declines in performance on deductive reasoning tasks are generally mediated by declines in procedural factors that are important to success on these problems.

Deductive reasoning and the development of the reflective system

In this last section of the paper, we wish to discuss the reflective component of system 2 and its relation to the algorithmic component. We characterize the co-active and co-evolving nature of this relation and argue that increasing organizational complexity at the algorithmic level is paralleled by progressively more explicit conceptual knowledge about logical categories (metalogical knowledge) at the reflective level. Finally, we speculate about how advances in logical competence at the algorithmic and reflective levels could be related to various aspects of self-regulation.

The algorithmic and reflective competence systems as co-constructed and co-active

Relational developmental systems theory (Lerner & Overton, 2008; Overton, 2010) and closely related developmental theories (Mascalo & Fischer, 2010; Raeff, 2011) maintain that all features of mind (i.e., cognitive, affective, and motivational systems) increase in hierarchical complexity across the lifespan. With respect to reasoning, the orthogenetic development of logico-mathematical organization is evident at both the algorithmic and reflective levels of competence. Consider first the algorithmic system. Complexity refers to the system's capacity to express operations or transformations in terms of combinations of other operations within the system. This is a kind of *recursiveness*. Logical equivalences or entailments among operations, and the inferences these entailments support, are relations of logical necessity. Therefore, the richness of such internal relations characterizing the organization of thought at a given level of development is an index of the scope and complexity of the necessary relations the child (at that level) can construct among meanings.

Inhelder and Piaget's (1958, 1964) familiar logico-mathematical organizations proposed as algorithmic competence models for middle childhood and adolescent thinking can be compared in terms of recursiveness. Consider the four transformations comprising Inhelder and Piaget's (1958, p. 134) model of formal deductive reasoning – the INRC group (identity, negation, reciprocity, and correlativity). These transformations apply to propositions in the logic, altering the truth values of atomic components and/or changing the logical operator – $I(p \vee q) = (p \vee q)$, $N(p \vee q) = (-p \,\&\, -q)$, $R(p \vee q) = (-p \vee -q)$; $C(p \vee q) = (p \,\&\, q)$. The key property of the INRC group is that each transformation is definable in terms of each of the other transformations (e.g., N = RC, R = NC, etc.). This degree of recursiveness contrasts with the more limited forms of recursion we find in the class and relational groupings (Byrnes, 1988; Ricco, 1990). In the additive combination of classes, for example, relations of logical equivalence among transformations are confined to immediate vertical relations within the hierarchical structure of the logic.

The increasing recursiveness of logical–mathematical operations within the algorithmic component of system 2 from childhood through adolescence is paralleled by key developments in the reflective subsystem. The reflective equivalent of recursion is metalogical knowledge or understanding. As logical transformations or inference schemes become increasingly coordinate yielding richer entailments among schemes or combinations of schemes, metalogical understanding emerges. Children acquire ever more explicit knowledge regarding logical categories such as inference, consistency, indeterminacy, necessity, and validity as well as proof tactics or strategies such as reductio ad absurdum, systematic generation of possible states of affairs consistent with the premises, and a search for counterexamples. Increasing metalogical knowledge, in turn, brings greater control over the inference process by way of the intentional use of explicit logical categories as norms or constraints on thinking (Moshman, 1990, 1998, 2004). Demetriou and colleagues (Demetriou & Kazi, 2006; Demetriou, Mouyi, & Spanoudis, 2010) provide evidence of this interdependence between expanding knowledge of reasoning processes and emerging reasoning competence. Increasing awareness of reasoning processes "becomes part of the very functioning of the processes concerned (Demetriou et al., 2010, p. 330)".

The relation between these two parallel changes – increasing complexity, (i.e., recursion, within the algorithmic system) and increasing explicitness of metalogical knowledge within the reflective system – is not linear or causal (in the efficient causal sense). It is more accurately conceived of as co-active and co-constructing. The parallel sets of changes are simply different aspects of the same developmental process. That process has been viewed by several theorists (e.g., Demetriou et al., 2010; Kuhn & Franklin, 2006; Moshman, 1998; Overton & Ricco, 2010; Piaget, 2001) as one of reflection of logical forms implicit in action and in domain-specific or concrete forms of thinking onto a more abstract plane of representation. Through this reflective process, relatively isolated or bounded inference patterns can be compared and similarities abstracted leading to the coordination of these patterns into more content- and context-independent schemes (algorithmic level). At the same time, this reflective process yields increasingly explicit knowledge of the properties of deductive inference with a resulting capacity to invoke these properties as norms or constraints on reasoning (reflective level).

Development of metalogical knowledge

Metalogical knowledge is a component of the reflective system and an important basis of epistemic self-regulation. The development of metalogical knowledge and its association with success on deductive reasoning paradigms is well understood at this point and has been documented extensively by Moshman (1998, 2004, 2009). The course of development for conceptual knowledge about logic, suggested by the evidence reviewed below (Komatsu & Galotti, 1986; Markovits, Schleifer, & Fortier, 1989; Miller, 1986; Miller, Custer, & Nassau, 2000; Morris, 2000; Morris & Sloutsky, 2001; Moshman

& Franks, 1986), is entirely consistent with the emergence of a class-based mental logic at the algorithmic level supporting concrete precursors to deductive competence in middle childhood followed by the emergence of a propositional mental logic supporting a mature formal competence in early to mid-adolescence.

A detailed look at the development of specific logical constructs reveals a pattern of purely intuitive or implicit understandings preceding more explicit understanding. Consider children's understanding of *logical necessity*. Implicit knowledge of this construct is evident in the ability of 6-year-old children to discriminate between logical falsehoods (contradictions) and contingent statements (Ruffman, 1999; Russell, 1982; see also Nesdale, Tunmer, & Clover, 1985 and Tunmer, Nesdale, & Pratt, 1983). That this knowledge is merely implicit at this point is suggested by findings that a comparable capacity to discriminate between logical truths (tautologies) and contingent statements is not simultaneously present and emerges later (Nicholls & Thorkildson, 1988; Russell, 1982). In addition, an appreciation that the truth or falsehood of logically determinate statements can be known a priori while the truth status of contingent statements cannot does not appear to be present until 8–9 years at the earliest (Cummins, 1978; Morris & Sloutsky, 2001; Osherson & Markman, 1975). More evidence that children's understanding of logical necessity proceeds from implicit to explicit involves findings that while 7-year-olds recognize that logical truths are true everywhere and will never change, they do not appreciate that logical truths *cannot* be imagined to be different and are distinct from social conventions and physical laws in this and other respects. This latter, more explicit understanding is absent for several additional years (Komatsu & Galotti, 1986; Miller, 1986; Miller et al., 2000). Thus a fully explicit or formal understanding of logical necessity may be a relatively late development. This seems to parallel findings for closely related logical constructs such as logical indeterminacy and falsification both of which are sufficiently explicit by 8 or 9 years of age to be evident in children's performance on concrete problem solving tasks but are not yet evident in performance on deductive reasoning paradigms.

Children's understanding of *inference* also proceeds from relatively implicit to relatively explicit. The beginnings of an explicit understanding of inference are evident around 6 years of age. It is at this time that we see a basic appreciation that inference can be a source of knowledge (Pillow, 1999; Sodian & Wimmer, 1987) and that premise information is important to inference (Rai & Mitchell, 2006). Six year olds also attribute greater certainty to deductive inference than to guessing with regard to their own cognitive activity (Pillow, 2002). At the same time, much of the young child's knowledge of inference remains implicit. Six year olds do not clearly appreciate when there is sufficient information present for inference and when not (Miller, Hardin, & Montgomery, 2003), and distinguishing between deduction and guessing with respect to another person's thinking, may not be present until 8–9 years (Pillow, Hill, Boyce, & Stein, 2000). Attributing greater certainty to deductive inference than to inductive inference, even with respect to the child's own thinking, is also absent until about 8–10 years (Galotti, Komatsu, & Voelz, 1997; Pillow, 2002) particularly for stronger forms of induction (Pillow & Pearson, 2009). A full appreciation of the deductive–inductive distinction in inference forms appears to be associated with adolescence when we see explicit awareness that inferential validity is a function of argument form and independent of the truth and falsehood of the premises (Markovits et al., 1989; Morris & Sloutsky, 1998; Moshman & Franks, 1986; Venet & Markovits, 2001; but see Morris, 2000, for evidence of training effects in preadolescents).

If the emergence of deeper conceptual understanding of logical forms is the result of a reflective process involving abstraction or metarepresentation of these as embedded in relatively bonded forms of cognition, then one would expect to see a pattern of progression from implicit to explicit understanding for various logical categories. As indicated in the above discussion of logical necessity and inference, this expectation has been largely supported by the available findings. In addition, this trend at the reflective level toward increasing metalogical knowledge closely parallels the complementary trend of increasing recursiveness of logical forms at the algorithmic level.

Developmental interdependence of logical competence and self-regulation

As noted in the previous discussion, changes in logical competence at the algorithmic level and corresponding advances in metalogical knowledge at the reflective level are linked in an intricate, co-active and co-constructive fashion. Arguably, these developments in logical competence also entail relatively universal changes in self-regulation. Associations between deductive reasoning and performance on various measures of executive functioning have been found across several studies (e.g., Emick & Welsh, 2005; Hooper, Hooper, & Colbert, 1985; Shute & Huertas, 1990) and reasoning and executive control measures are sometimes found to share considerable variance across the adult years, suggesting that they load on a single factor (Salthouse, 2005). The development of logical competence may also be related to non-logical aspects of epistemic self-regulation such as the emergence of new epistemic norms or levels of understanding. Chandler and Birch (2010) and colleagues have suggested that the emergence of deductive competence is crucial in initiating deep levels of epistemic doubt to which adolescents must adjust, eventually emerging with a capacity to appreciate the limits of human knowledge while formulating criteria by which rational consensus can be achieved. In particular, the development of deductive reasoning has been linked to advances in appreciating the constructive or subjective nature of knowledge leading to the transition from a realist stance to the radical relativism or, in some cases, reactive dogmatism, typical of early- to mid-adolescence (Boyes & Chandler, 1992; Chandler et al., 1990).

There is evidence as well that deductive reasoning strategies, once available, can contribute to developmental increases in other processes at the reflective level such as monitoring accuracy and cognitive self-efficacy. Problem-solving strategies associated with deductive competence provide more diagnostic cues in support of a specific response option. Predictive strategies, for example, are more diagnostic than confirmatory strategies (Mitchum & Kelly, 2010). Strategies that generate more diagnostic cues yield more accurate monitoring of whether one is selecting the correct response option, a better basis for confidence judgments about one's response, and greater confidence in one's response. Similarly, Demetriou and colleagues (Demetriou & Kazi, 2006; Demetriou et al., 2010) provide evidence that estimates of one's own task performance and judgments of one's competence as a reasoner are increasingly related to reasoning performance across childhood and adolescence. As newly emergent reasoning capabilities consolidate and the individual gains experience with these, self-assessments become more accurate.

Just as logical competence carries implications for epistemic self-regulation beyond the emergence of metalogical knowledge, non-logical aspects of epistemic self-regulation may contribute to the development of logical competence. The work of Kuhn (2001, 2002) and colleagues provides a framework for conceiving of this manner of influence. Advances in epistemological understanding proceed from an interpretation of knowledge that favors the objective aspect at the expense of the subjective to an interpretation and appreciation that integrates the two (Kuhn et al., 2000). In Kuhn's model, this advance promotes interest in, and sustained valuing of, knowledge acquisition strategies such as inquiry, analysis, inference, and argument that represent engagement of system 2 in the coordination of existing beliefs with new data and experiences (Kuhn & Franklin, 2006; Kuhn & Park, 2005). Use of the knowledge acquisition strategies, in turn, can contribute to the development of at least some aspects of metalogical knowledge including an appreciation of the purposes and uses of deductive inference and knowledge of specific deductive reasoning strategies and their application in problem-solving settings (Kuhn, 2001).

Summary and conclusions

In our contribution to this special issue, we have had several aims in mind. Our principle purpose was to defend a Competence ←-→ Procedural processing model of deductive inference as it operates within a relational developmental systems perspective. The Competence ←-→ Procedural processing model shares with other dual systems approaches the basic claim that both child and adult cognition are best understood as a complex interplay between two distinct processing systems which differ in their phylogeny, ontogeny, and function. Where our model differs from other dual-systems accounts is in the claim that system 2 is a competence system per se and that its algorithmic subsystem contains a mental logic plausibly modeled by a variant of classic symbolic logic. Another important and relatively unique attribute of our perspective is that the general theory represents mind and the development of mind as a complex relational self-organizing, self-regulating adaptive system, and the ontogenesis of this system as nonlinear, epigenetic, and constituted by embodied action-in-the-world.

In our discussion of the literature on the development of deductive reasoning, we have attempted to demonstrate that the Competence ←–→ Procedural processing model operating in the context of a relational developmental systems theory provides a plausible and parsimonious explanation for a wide range of phenomena including developmental trends in normative and heuristic-based responding across a variety of reasoning paradigms, including, in particular, deduction paradigms, and age differences/changes in specific response patterns on conditional reasoning tasks. The model and theory also provide a framework for reconciling inconsistencies in the literature involving apparent precocity in children and apparent lack of competence in adults (see also Reyna & Brainerd, and Stanovich, this issue) and it is consistent with the limited findings regarding the fate of deductive reasoning in late adulthood. In addition, the theory is generally accurate in predicting performance outcomes in middle childhood based on whether the task involved requires class-based reasoning or full-blown formal deductive competence.

Although we would argue that the totality of findings on the development of deductive reasoning favor the Competence ←–→ Procedural processing model over alternative accounts, we also acknowledge that any given set of findings is consistent with more than one model. There is, therefore, no decisive test of competing accounts. For this reason, we believe that it may be profitable to seek some means of reconciling competing claims (Overton, 2006; Overton & Ennis, 2006). In this regard, a rapprochement afforded by relational developmental systems theory generally and the Competence ←–→ Procedural processing model specifically offers a promising basis for resolving differences and preserving the obvious strengths of each approach. The specific nature of the rapprochement offered by the Competence ←–→ Procedural processing account is to interpret the findings from research conducted within alternative models as providing important elaborations of the procedural component of the model while, at the same time, rejecting interpretations that blur distinctions between competence and procedural processing or that reduce aspects of competence to procedural factors. The roles of encoding, retrieval, executive, and pragmatic-interpretive processes in age, task, and content effects in deductive reasoning have been significantly clarified by research within domain-specific, mental models, and probabilistic theories of reasoning. The Competence ←–→ Procedural processing model is also compatible with metacognitive models of deductive reasoning (Kuhn & Franklin, 2006; Moshman, 2004) that stress reflective processes. We have argued above for the need to posit a reflective competence system that is co-active with the algorithmic system and that provides the basis for epistemic self-regulation.

In exploring the algorithmic-reflective distinction within the competence system (system 2), we have argued that across childhood and adolescence the algorithmic system features an increasingly inter-coordinated set of distinctly logical operations, processes, or rules underlying norm-based responding on reasoning tasks. Paralleling this, the reflective system displays increasingly mature levels of metalogical and epistemic understanding.

In support of the proposed rapprochement, it is important to point out that the central claim of the Competence ←–→ Procedural processing model – i.e., that thought is inherently logico-mathematical – does not preclude the development of a variety of inductive or non-monotonic forms of reasoning. In addition, the claim is reasonably consistent with a view that analysis in terms of logical relations is not the default mode of responding even on most deductive reasoning problems, and that logical analysis represents an override of more heuristic responding as the default (Daniel & Klaczynski, 2006; Evans, 2002; Klaczynski, 2000; Klaczynski & Robinson, 2000). Further, although not favored by most dual-systems accounts, there is no reason, in principle, why system 2 as depicted by Evans, Stanovich, and others cannot include a logical competence model. Some dual-process theorists have acknowledged the importance of an "appreciation of the logic of necessity and indeterminacy" (Daniel & Klaczynski, 2006, p. 351) to success on deductive reasoning tasks.

An additional, secondary purpose of our contribution, preparatory to our discussion of the development of deductive reasoning, has been to address the recent trend to discount the role of deduction in ordinary cognition. We have offered a brief defense of the relevance of deductive processes to everyday reasoning. This discussion was intended to identify key arguments for taking deduction seriously, but was not meant to 'prove the case' which certainly would require a paper in its own right (see Over, 2007 for an extended argument for taking deduction seriously). The Competence ←-→ Procedural processing model gives a central and fundamental status to deductive processes in mature thought (Overton, 1990; Piaget, 1986; Ricco, 1993; Rips, 2001). By contrast, most alternative theories of reasoning tend to view deduction as less significant or epiphenomenal (Evans, 2002; Kuhn & Franklin, 2006) and represent performance on deductive reasoning paradigms as reflecting distinctly non-deductive processes (Markovits & Barrouillet, 2002). We have pointed to recent evidence that lay adults routinely distinguish between deductive and inductive norms when engaged in reasoning and deliberately and flexibly adopt one or the other set of norms as a function of task demands. These and other findings discussed in this article suggest that it is premature to rule out a significant role for deductive reasoning in human cognition. While acknowledging the recent accomplishments of induction-based accounts of reasoning, and of probabilistic models in particular, we have also raised some concerns about these accounts as models of performance on deductive reasoning paradigms.

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