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Do Humans Have Two Systems to Track Beliefs and Belief-Like States?

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The lack of consensus on how to characterize humans' capacity for belief reasoning has been brought into sharp focus by recent research. Children fail critical tests of belief reasoning before 3 to 4 years of age (H. Wellman, D. Cross, & J. Watson, 2001; H. Wimmer & J. Perner, 1983), yet infants apparently pass false-belief tasks at 13 or 15 months (K. H. Onishi & R. Baillargeon, 2005; L. Surian, S. Caldi, & D. Sperber, 2007). Nonhuman animals also fail critical tests of belief reasoning but can show very complex social behavior (e.g., J. Call & M. Tomasello, 2005). Fluent social interaction in adult humans implies efficient processing of beliefs, yet direct tests suggest that belief reasoning is cognitively demanding, even for adults (e.g., I. A. Apperly, D. Samson, & G. W. Humphreys, 2009). The authors interpret these findings by drawing an analogy with the domain of number cognition, where similarly contrasting results have been observed. They propose that the success of infants and nonhuman animals on some belief reasoning tasks may be best explained by a cognitively efficient but inflexible capacity for tracking belief-like states. In humans, this capacity persists in parallel with a later-developing, more flexible but more cognitively demanding theory-of-mind abilities.

Keywords: theory of mind, false belief, development, comparative, adult

More than 25 years of research have taught us a great deal about theory of mind, the ability to ascribe mental states, such as beliefs, desires and intentions, to explain, predict, and justify behavior. Researchers have learned much about the age at which children reach developmental milestones, about the abilities of nonhuman animals, about the disruption of theory of mind in developmental disorders such as autism or following brain injury, and about the neural systems involved when people engage in this kind of thinking. However, we seem no nearer to reaching any consensus on the cognitive basis of theory-of-mind abilities or even of specific aspects of theory of mind, such as the paradigm case of belief ascriptions. One reason for this is that dominant accounts aim to explain the development of theory of mind or to characterize theory of mind in nonhuman animals. They give much less consideration to how inferences about mental states are achieved for the wide range of everyday functions that theory of mind is supposed to support.

A central contention in the account we develop here is that theory-of-mind abilities are subject to competing demands for efficient and flexible processing. On the one hand, theory-of-mind abilities need to be fast enough to guide competitive and cooperative activities in rapidly changing circumstances and efficient enough not to consume cognitive resources necessary for the primary task of competition or cooperation. On the other hand, theory-of-mind abilities in human adults need to be as flexible as any reasoning abilities to support the explicit explanation and prediction of action that is involved in jurisprudence, strategic negotiation, self-awareness, and understanding one's relations to other thinking agents (Harris, 1994; c.f. Heal, 1998).

Competition between demands for efficient and flexible processing is reflected in a fundamental disagreement concerning belief ascription, which dates back to some of the earliest articles on theory of mind. To one way of thinking, belief ascriptions depend on one or more modules, whose operation is fast and efficient and whose fundamental conceptual and processing structures are fixed before or during infancy (e.g., Leslie, 1994a, 1994b). The alternative view is that the ability to ascribe beliefs depends on flexible but effortful general reasoning abilities, plus knowledge learned during children's early childhood about what beliefs are, the conditions for their formation, and the role they play in cognition (e.g., Gopnik & Meltzoff, 1997). These alternatives imply very different and incompatible views about the nature of belief ascription and about the relationships between belief ascription and other cognitive processes. The conflict between these views is brought into focus by recent research on belief reasoning in infants, and it is with these developmental findings that we begin. However, the same tensions exist when considering the abilities of nonhuman animals and human adults, which we discuss in later sections. We argue that both views of belief ascription have significant evidence in their favor and that neither is likely to be fully correct. Instead, we advocate a view based on lessons from another domain, number cognition: The competing demands of efficient and flexible processing are solved by having two systems.[1]

Our central conjecture, that theory of mind involves two systems, has been canvassed in general terms by a variety of theorists

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[1] Some authors discuss more than two systems, and we agree that it is plausible that more than one system for fast, efficient theory-of-mind processing may exist. However, for clarity, here and throughout, we refer to the "two-systems" view.

with otherwise very different convictions (including Byrne, 2002; Csibra & Gergely, 1998; Leslie, 1994a; Perner, 1991; Povinelli, Bering, & Giambrone, 2000; Russell, 2007; Tager-Flusberg & Sullivan, 2000; Suddendorf & Whiten, 2003). However, it has not been developed in any detail for the case of belief reasoning that occupies such a central position in research on theory of mind. In the current article, we examine the cognitive demands of belief reasoning; develop the hypothesis that meeting these demands requires two kinds of cognitive system; evaluate this hypothesis in the light of converging evidence from infants, adults, and nonhumans; and identify the possible future evidence that could distinguish between alternative two-system solutions. Our project of characterizing the cognitive basis of belief reasoning has implications for all of the subject areas in which theory of mind has been investigated, including typical and atypical development (e.g., Baron-Cohen, Tager-Flusberg, & Cohen, 2000; Doherty, 2008; Wellman, Cross, & Watson, 2001), cognitive psychology (e.g., Apperly, Samson, & Humphreys, 2009; German & Hehman, 2006; Keysar, Lin, & Barr, 2003), cognitive neuroscience (e.g., Apperly, Samson, & Humphreys, 2005; Frith & Frith, 2003; Saxe, Carey, & Kanwisher, 2004) and comparative psychology (e.g., Call & Tomasello, 2008; Penn, Holyoak, & Povinelli, 2008).

The Development of Belief Reasoning

Reasoning about beliefs and other mental states has a protracted developmental course, in which the acquisition of a conventional linguistic system for describing different mental states and structuring their content appears to play a critical role (Astington & Baird, 2005). One important and much-studied benchmark in this development is the ability to understand false beliefs. Children do not typically succeed on standard false-belief tasks until around 4 years of age (Wellman et al., 2001; Wimmer & Perner, 1983).[2] Further developments in children's theory-of-mind abilities occur later still. For example, children do not succeed until 5 or 6 years of age on tasks that require recognition that beliefs only represent a subset of the features of their referents (Apperly & Robinson, 1998, 2003; Hulme, Mitchell, & Wood, 2003; Sprung, Perner, & Mitchell, 2007).

However, there is evidence that 2- and 3-year-old children, who fail standard false-belief tasks, may be aware of false beliefs. For example, Garnham and colleagues asked 3-year-old children where Sam would look for some cheese, which was secretly moved while he was sleeping. Although the 3-year-olds incorrectly said that Sam would look where the cheese actually was, they nevertheless appeared to show some awareness of false beliefs by looking at the location where a character believed some cheese was hidden when prompted with "I wonder where he's going to look" (Clements & Perner, 1994; Garnham & Perner, 2001; Garnham & Ruffman, 2001). Using a modified, nonverbal version of Garnham's procedure, Southgate, Senju, and Csibra (2007) showed similar looking behavior in 2-year-olds, which is also indicative of false-belief understanding.[3]

Most strikingly, Onishi and Baillargeon (2005) provided evidence that 15-month-old infants understand that others can have false beliefs by using a violation-of-expectation paradigm. In one condition, infants were shown the following sequence of events: A watermelon slice is placed into a green box while an actor watches; then the actor's view is blocked as the watermelon slice moves to a yellow box (so the actor's belief becomes false); finally, the actor reappears and reaches into one of the boxes. Infants looked significantly longer at the display when the actor reached into the yellow box than when the actor reached into the green box. The opposite pattern of looking was found in another condition, in which the actor observed the watermelon's movement (and thus had a true belief). This and other control conditions suggest that infants' looking times may correlate with whether or not the actor acts in accordance with his or her beliefs. Related results have since been independently obtained with 13-month-olds (Surian, Caldi, & Sperber, 2007; see also Scott & Baillargeon, 2008).[4]

There have been two main lines of response to the evidence that infants are aware of false beliefs. Some authors argue that infants understand false belief; they therefore deny that there is a fundamental change at around 4 years of age when children first pass standard measures of false belief (Onishi & Baillargeon, 2005; Leslie, 2005), and they insist that infants' early false-belief understanding provides the "conceptual foundation" for later abilities to reason about false beliefs (Surian et al., 2007, p. 585). Opposing this view, others insist that apparent success on theory-of-mind tasks in infancy can be explained without supposing that infants have any understanding of belief at all. For example, some suggest that infants' looking times may be explained by their adopting behavioral rules, such as "people look for objects where they last set eyes on them" (Perner & Ruffman, 2005, p. 214; Ruffman & Perner, 2005, p. 462).

How might this conflict be decided? Both sides claim that parsimony favors their position (Onishi & Baillargeon, 2005, p. 257; Perner & Ruffman, 2005, p. 214). This suggests that considerations of parsimony are not decisive. In our view, both sides of this conflict are mistaken, but progress can be made by taking a broader perspective on the abilities of infants, taking into account the cognitive limitations of infants and the abilities of nonhuman

[2] For readers not familiar with standard false-belief tasks, in one typical false-belief task, a story character, Sally, places her marble in a basket, then goes outside to play. In her absence, a second character, Anne, moves the marble from the basket to a box, with the result that Sally has a false belief about the marble's location. Children are then asked test questions that require them to infer Sally's false belief to say where Sally thinks the marble is located or to predict where Sally will first look to find her marble (Baron-Cohen, Leslie, & Frith, 1985).

[3] There is also modest evidence that 2- and 3-year-old children use information about false belief in performing various intentional activities. For instance, Carpenter, Call, and Tomasello (2002; see also Happé & Loth, 2002) provided evidence that children take into account false beliefs in learning new words; there is also a range of evidence on deception-related behaviors (Newton, Reddy, & Bull, 2000; Polak & Harris, 1999; Reddy & Morris, 2004). It is possible that these findings should be interpreted in the light of a range of tasks in which children of this age intelligently exploit facts about which objects individuals are acquainted with in their interpretations of requests (Moll & Tomasello, 2007), their own communicative gestures (Liszkowski, Carpenter, Striano, & Tomasello, 2006), and their use of testimony (Koenig, Clément, & Harris, 2004). It is an open question how this evidence from intentional activities relates to the evidence from nonintentional eye movements and looking times.

[4] Although the aforementioned studies all show precocious understanding of false beliefs at very different ages, this variation may reflect differences in the sensitivity of the methods employed, rather than differences in cognitive processes that are being tested.

animals and human adults. Our first step is to draw a lesson from the case of number cognition, where there is also an apparent discrepancy between precocious abilities in infants and persisting difficulties in older children and where taking a broader perspective on infants' abilities has significantly advanced our understanding of number cognition in general.

Number Cognition

In this section, we summarize the evidence suggesting that humans have two kinds of cognitive system for processing numbers, including converging data from infants, adults, and nonhuman animals. Although there is considerable agreement on some form of two-system account, there is much debate about the form that such an account should take, and we also summarize these disagreements to show the limits of what might be learned about belief reasoning from the case of number cognition.

Reasoning about numbers has a protracted developmental course, in which the acquisition of counting with a conventional numerical symbol system plays a critical role (e.g., Baroody & Dowker, 2003). In the influential views of Piaget and coworkers (e.g., Piaget & Szeminska, 1952), infants were entirely incapable of number cognition because they lacked symbolic mental representations. Older children—even children who could count—seemed often to lack understanding of the conservation of basic numerical properties of sets over transformations that change perceptual characteristics. For example, young counters appeared not to understand that the cardinal value of a set of blocks is unaffected by changing the spacing between the blocks. Although subsequent research with improved methods was able to demonstrate success on Piaget's tasks in significantly younger children (e.g., McGarrigle & Donaldson, 1975), prior to the 1980s, there was little evidence for numerical abilities before 2 or 3 years of age, when early counting behavior appears to show some respect for abstract number properties (e.g., Gelman & Gallistel, 1978).

The view that infants are incapable of number cognition was profoundly altered by evidence from preferential looking and habituation paradigms showing precocious sensitivity to number properties. For example, young infants (5–8 months of age) are sensitive to the number of items in a repeatedly presented stimulus (Starkey & Cooper, 1980); they can sum over the number of items in a short sequence (e.g., Wynn, 1996), discriminate between small and large sets of objects (e.g., Xu & Spelke, 2000), and keep track of the number of items in a small set of objects following additions or subtractions (e.g., Wynn, 1992). In light of such evidence, the view that infants are entirely insensitive to number is clearly incorrect (see, e.g., Feigenson, Dehaene, & Spelke, 2004; Le Corre & Carey, 2007, for recent discussions).

If this were the end of the story, it would be natural to conclude that experimental methods more sensitive than those used by Piaget and colleagues have shown that infants do understand number after all. However, subsequent research has revealed stark limitations on infants' abilities. A proper understanding of number cognition in infants requires appreciating their limitations as well as infants' surprising competencies.

Investigations of infants' ability to process precise numerosities suggest a strict capacity limit of three items (or four items in one study; Ross-Sheehy, Oakes, & Luck, 2003). To give just one illustration, infants (age 14 months) are unlikely to search repeatedly in a box in which they have seen one item placed and are more likely to search twice for two objects and three times for three objects. However, after seeing four objects placed in a box, infants tended to search only once (Feigenson & Carey, 2003). Another distinctive limitation is observed in infants' processing of large numbers. Infants (at 6 months) are able to discriminate between large numerosities, such as 8 versus 16 dots, but they can do so only if the ratio of their discrepancy is large (e.g., 1:2) and perhaps only if the number of items in each collection is sufficiently high (e.g., above 3; Xu, 2003). Two further sets of results cast light on these findings from infants. First, a variety of other species show abilities for precise processing of very small numbers and approximate processing of large numbers, and these abilities show limitations analogous to those observed in infants (e.g., Brannon & Terrace, 1998; Hauser & Carey, 2003). This suggests that infants' abilities with numbers are not distinctively human, unlike the more flexible abilities of older children and adults.[5] Second, there is evidence that even human adults with formal education in mathematics retain abilities similar to those of infants. When such adults are required to make fast judgments, or when their ability to use strategies such as counting are disrupted experimentally, they remain able to make precise judgments about small sets and approximate comparisons of larger sets (e.g., Barth, Kanwisher, & Spelke, 2003; Trick & Pylyshyn, 1994). Adults' precise enumeration of small sets appears to show just the same limit of three or four items observed in infants, and, as in infants, adults' approximate comparison of large sets is limited by the ratio of the two sets, although this ratio gets smaller with increasing age, allowing progressively more fine-grained approximations (Halberda & Feigenson, 2008).

Thus, much evidence points to the existence of numerical judgments in participants who have limited or no access to language and executive processes and no training in numbers, as well as to the distinction between the cognitive systems supporting these abilities and the cognitive systems supporting the additional skills with numbers and mathematics that many humans acquire through education. There are, of course, a variety of characterizations of the early-developing abilities, and we describe these briefly to make clear the limits of our analogy with belief reasoning. Some authors have argued that both precise judgments for small numbers and approximate judgments for large numbers can be explained by a single system of analogue number representation that yields high discriminability (and, thus, high precision) for only comparisons of small analogue quantities (corresponding to small numbers; e.g., Gallistel & Gelman, 1992, 2000; Gelman & Gallistel, 2004). Others have argued that infants' abilities rely on distinct mechanisms that process precise and approximate numerosities independently, each having its own distinct limitations (e.g., Carey, 2004; Feigenson et al., 2004; Le Corre & Carey, 2007). In the latter camp, there is also debate about the nature of the mechanism that yields precise judgments about small sets and whether it is the same mechanism that allows parallel individuation of objects (e.g., Trick & Pylyshyn, 1994), or that subserves visual working mem-

[5] Somewhat flexible abilities have been demonstrated both in chimpanzees (e.g., Boysen & Berntson, 1989) and in an African grey parrot (e.g., Pepperberg, 2006) that have received substantial training in the symbolic representation of numerical quantity.

ory (e.g., Vogel, Woodman, & Luck, 2001), or that tracks objects through object files (e.g., Kahneman, Triesman, & Gibbs, 1992; see, e.g., Feigenson et al., 2004; Le Corre & Carey, 2007).

Finally, there is debate on how the abilities of infants to make limited judgments about small and large numbers relate to the abilities of educated children and adults to count and perform arithmetic and other mathematical operations. Gelman and Gallistel (1978, 2004; Gallistel & Gelman, 1992, 2000) argued that the analogue number system possessed by infants affords simple arithmetic operations (such as addition, subtraction, and ordering) and operates over symbolic, analogue number concepts. In their view, learning to count is a process of mapping such concepts and operations into natural language. Other authors have argued that infants' number abilities do not involve concepts of numbers or arithmetic operations related to counting. Thus, the principles of counting must instead be learned, and this learning may be supported by representations of the analogue number system (e.g., Dehaene, 1997; Wynn, 1992), by representations from the system that allows precise enumeration of small numbers (e.g., Carey, 2004) or by the integration of both systems (e.g., Feigenson et al., 2004). However, on any of these latter accounts, learning to count requires conceptual development, not just conceptual mapping.

The Basis for the Analogy Between Number Cognition and Belief Reasoning

Despite debate over the detailed structure of the cognitive systems for numbers, there is considerable agreement on points that are critical for the analogy we wish to make with belief reasoning. First, the original view that infants are incapable of number cognition turns out to be incorrect. In fact, infants have one or more systems that enable them to make numerical judgments. These systems remain present in adults, and there is evidence of analogous capacities in some nonhuman animals. Second, the cognitive efficiency of these systems comes at the cost of distinctive limitations on the kinds of numerical judgment that can be made. These limits are relatively specific to the domain of numerical judgment. They are not explained by facts about the nature of numbers per se or by limits on language, general intelligence, information processing or executive capacity (although the three- to four-item limit on precise enumeration may be explained by the limits of a specialized system for visual working memory). Third, these signature limits provide key evidence for the existence of distinct systems for processing numbers (and closely related functions) and for the similarity of these systems in human infants, human adults, and nonhuman animals. Fourth, it would be quite wrong to conclude that infants or nonhumans understand numbers in the same sense as educated older children or adults. The signature limits of the basic number system(s) are only overcome if and when older children acquire a conventional number system. This is a protracted process that takes several years, and the resulting numerical abilities depend rather heavily on general cognitive resources for language, information processing, and executive control. Whether or not basic number concepts exist before (see, e.g., Gallistel & Gelman, 1992, 2000), the acquisition of a conventional number system is widely agreed to transform the representational powers of children's numerical abilities, adding new concepts and enabling new operations (e.g., Carey, 2004; Feigenson et al., 2004; Gelman & Gallistel, 2004).

In sum, the case of number cognition provides a model for a two-system account that combines cognitive efficiency (achieved by one or more subsystems) with flexibility (achieved by cognitively demanding reasoning processes) and shows how it is possible to tell which system is being used on a given task by examining whether or not performance is subject to signature limits. We propose that something similar is true of belief reasoning and that the just listed points provide a powerful analogy for interpreting the existing evidence on belief reasoning and for making novel predictions.

Systems and Concepts

As noted earlier it is a moot point whether infants or nonhumans represent numbers as such. We do not think this is critical for making a useful analogy with belief reasoning. In the literature on number cognition, we take the primary discovery to be that infants, human adults, and nonhuman animals have analogous abilities that enable them to solve number tasks with little or no recourse to general cognitive processes, such as language and executive control. It is a further question whether exercising these abilities involves representing numbers. In a similar vein, our proposal about theory of mind has two parts that we treat separately in subsequent sections. The first part concerns the existence of two types of system for belief reasoning: one that is cognitively efficient but limited and inflexible and another that is flexible but demanding of general cognitive resources. Here we follow the literature on number cognition by seeking converging evidence across infants, older children, nonhuman primates, and human adults. In this section, we make no claims about whether beliefs are represented as such; by *belief reasoning* we mean exercising an ability to deal with tasks in which belief matters. The second part concerns how a process of belief reasoning could be efficient and, in particular, whether efficient belief reasoning involves representations of beliefs, of behaviors, or of something else. As indicated in our title, we argue that it involves representing states that are like beliefs in guiding action but unlike beliefs in not having propositional content and in several further respects. In this later section, we follow the literature on number cognition by examining what can be learned from the signature limits that arise in cognitively efficient processing.

What Would Show That There Are Two Systems for Processing Beliefs?

Prima Facie Case

A primary feature of human adults' belief reasoning competence is the ability to use all cognitively available facts to ascribe any belief that the subject can themselves entertain. From this perspective, belief reasoning is an archetypal "central process" (Fodor, 1983, pp. 41–42) and is as flexible as any other type of reasoning, and in consequence, we should expect it to be demanding of general processing resources (e.g., Evans, 2003). In short, belief reasoning must be highly flexible, but we should expect this to come at the cost of cognitive efficiency.

However, belief reasoning is also supposed to play a role in guiding fast-moving activities, such as competitive and strategic interaction and communication (Grice, 1989; Sperber & Wilson, 1995). How can belief reasoning be both flexible and efficient? This tension is not unique to the problem of belief reasoning. The same problems occur in literatures as diverse as general reasoning and decision making (e.g., Evans, 2003), social cognition and person-perception (e.g., Gilbert, 1998), and, as we have just discussed, number cognition (e.g., Feigenson et al., 2004). Although the details differ, these diverse literatures all propose two types of system: one that is efficient and inflexible and one that is flexible but cognitively demanding. It seems at least reasonable to propose that the same may be true for beliefs.

Theory of Mind in Infants and Children

A large literature has examined the development of an adult-like ability to reason about beliefs flexibly and efficiently. These abilities appear to develop gradually over several years;[6] they are closely tied to developments in language and executive function (Astington & Baird, 2005; Pellicano, 2007; Perner, 1998; Perner & Lang, 1999, 2002; Sabbagh, 2006; Zelazo, Jacques, Burack, & Frye, 2002); they may be facilitated by explicit training and environmental influences, such as siblings (Clements, Rustin, & McCallum, 2000; Slaughter & Gopnik, 1996); and they may be altered by cultural background to some degree (e.g., Lillard, 1998). These are exactly the characteristics that would be expected for the development of reasoning processes that are flexible but demanding of cognitive resources.

It is against this background that recent evidence of precocious abilities in infants appears so remarkable. Put simply, if a large evidence base suggests that it takes several years and significant developments in language and executive function for children to acquire adult-like belief reasoning abilities, how are we to interpret signs of belief reasoning in infants as young as 13 months (Surian et al., 2007), who are notably lacking in language and executive abilities? One possibility is that dependence on language and executive function is an artifact of experimental designs and not an intrinsic feature of any theory-of-mind abilities; tests of infant theory of mind succeed by stripping away the extraneous dependence on language and executive function that usually obscure this competence until early childhood (e.g., Leslie, 2005; Surian et al., 2007). If this is the case, then infants' belief reasoning abilities will be limited only by experimenters' ingenuity in devising experiments to reveal infants' abilities and by the concepts they can apply (if infants fail to ascribe beliefs about global warming, quarks, or nativism, that can only be because they cannot apply such concepts). However, the case of number cognition suggests another possibility: later-developing theory-of-mind abilities involve flexible cognitive processes that, by their very nature, depend on language or executive function, whereas infants' precocious abilities are underwritten by a distinct set of cognitively efficient processes that do not depend on language and executive function. It is important to note that if this is the case, then such cognitive efficiency is likely to come at the expense of limited flexibility.

The way to determine whether infants' belief reasoning involves cognitive processes distinct from those that support adults' flexible belief reasoning is to look for apparently arbitrary signature limits analogous to the three-item and ratio limits on infant number cognition. But what would count as an arbitrary limit on the flexibility of belief reasoning? To answer this question, we need to consider the nature of belief. In standard accounts, a belief is an attitude to a content that plays a certain psychological role. Typically, in explicit adult theory-of-mind reasoning, the content is propositional (i.e., sentence-like), and the psychological role includes being caused and justified by perceptions, interacting with other beliefs and desires, and causing and justifying actions. Infants' theory-of-mind abilities may be limited with respect to content, psychological role, or both.

In terms of content, all experiments involving infants mentioned so far required only that infants could track attitudes to objects' locations. Other experiments (Moll & Tomasello, 2007; Scott & Baillargeon, 2008) may have required that infants and young children understand attitudes toward objects that bear certain distinguishing features (including shape or color). No study has yet suggested that infants track beliefs involving both the features and the location of an object (e.g., "The red ball is in the cupboard"); or that they track beliefs whose contents can be represented only using quantifiers (e.g., "There is no red ball in the cupboard"); or that, in tracking beliefs, they are sensitive to modes of presentation as would be necessary for Level 2 perspective taking (e.g., appreciating whether an agent sees an object as a duck or a rabbit). If infants' belief reasoning were shown to be limited in these or similar ways, we could conclude that whatever they represent, it is not a state with propositional content.

Infants' belief reasoning may also be limited with respect to psychological role. Infants and young children do show some correct expectations about the causes of belief states. For example, they do not expect a person to acquire beliefs when obviously disengaged (e.g., when he or she is facing a wall). They do not expect people to acquire beliefs about an object merely by virtue of standing on it, and they do not take close proximity to an object to be a necessary condition for having a belief about it; instead, some kind of purposive interaction with the object appears to be required (Dunham, Dunham, & O'Keefe, 2000; Moll & Tomasello, 2006, 2007; O'Neill, 1996). Nonetheless, children may struggle with Level 1 perspective-taking (e.g., appreciating that an agent does not see an object that you see) before 24 months of age (Moll & Tomasello, 2006; but see Luo & Baillargeon, 2007; Sodian, Thoermer, & Metz, 2007), and not much is yet known about infants' understanding of inference or testimony as causes of belief (see, e.g., Song, Onishi, Baillargeon, & Fisher, 2008). One potential limitation in psychological role concerns interactions among beliefs and with other states. Infants may not understand that what you already believe modulates causes of beliefs but may instead think of beliefs as independent of each other, in much the way that perceptions are sometimes thought to be. And instead of understanding how beliefs interact with desires in influencing the means we select to achieve a goal, they may think of beliefs as fixing parameters on basic object-directed actions (e.g., where someone will reach or walk to). If infants' belief reasoning were shown to be limited in some such ways, we could conclude that

[6] For example, 5- and 6-year-old children (who are old enough to pass false-belief tasks) still have problems understanding how beliefs are acquired (Carpendale & Chandler, 1996; Robinson & Apperly, 2001), how beliefs interact with desires (Leslie et al., 2005; Leslie & Polizzi, 1998), and the emotional consequences of false beliefs (e.g., Harris, Johnson, Hutton, Andrews, & Cooke, 1989; Ruffman & Keenan, 1996).

whatever they represent does not involve the causal and justificatory structure that is constitutive of adults' flexible belief reasoning (Davidson, 1989, 1995).

In sum, although there is evidence that infants have some abilities to solve tasks involving beliefs, the evidence falls well short of establishing several criteria for saying that infants ascribe beliefs as such. We should emphasize that our aim is not to downplay the impressive findings from existing studies of infants' belief reasoning; indeed, we think it likely that current evidence underestimates the sophistication of infants' abilities. Rather, our point is to question whether it is plausible that infants' abilities are limited *only* by their general knowledge and the concepts they can apply. Our contention is that infants' belief-reasoning abilities may, in fact, be subject to arbitrary limits analogous to the capacity limit of three items or the ratio limit to which their numerical capacities are subject. These limits on belief reasoning are likely to be manifest both in terms of the type of content that infants can ascribe and the psychological roles to which they are sensitive. Such limits provide vital clues to the nature of the cognitive processes supporting belief reasoning in infancy (see later). Further studies of infants will, of course, provide informative data on these questions. But as in the case of number, another test for a good account of infants' abilities will be the degree to which it fits with findings from nonhuman animals and human adults, and it is to these findings that we turn next.

Theory of Mind in Nonhuman Animals

Evidence from nonhuman animals is of relevance in the current context because, like human infants, nonhuman animals are distinctly lacking in the linguistic, symbolic, or executive capacities that appear to be necessary for humans to develop the ability to reason flexibly about numbers and beliefs. There is evidence that several nonhuman species enjoy capacities for precise enumeration and numerical estimation analogous to those observed in human infants, but these animals lack the flexible number-reasoning abilities of educated humans (e.g., Feigenson et al., 2004). This is an important piece of converging evidence for the existence of parallel systems for number cognition in humans. Is there similar evidence concerning theory-of-mind abilities?

The most extensive investigation of belief reasoning in nonhuman animals has been conducted in chimpanzees (e.g., Tomasello, Call, & Hare, 2003). Despite much controversy about how to characterize chimpanzee social reasoning, there is broad consensus on two boundaries that are relevant in the current discussion. First, their belief-reasoning abilities appear limited in some of the ways that infants' and younger children's are, for they systematically fail direct tests of false-belief understanding (e.g., Povinelli & Vonk, 2003; Tomasello et al., 2003), and there is no evidence that chimpanzees succeed on tasks that require Level 2 perspective taking (Call & Tomasello, 2005). Second, chimpanzees do have some theory-of-mind abilities. They are sensitive to the direction in which other chimpanzees and humans are looking and follow gaze behind to objects out of view, taking into account opaque barriers much as 18-month-old humans do (Povinelli, 2001, pp. 229–230). They can adapt their strategy for retrieving food depending on what a dominant competitor can see or has seen (Hare, Call, Agnetta, & Tomasello, 2000; Hare, Call, & Tomasello, 2001) and can actively manipulate whether or not a competitor can see them to gain strategic advantage (Hare, Call, & Tomasello, 2006). Whether or not they represent perceptions or beliefs, they are certainly acting in ways that are beneficial in virtue of controlling what others see and believe.

Recent investigation of scrub-jays' caching behaviors provides further converging evidence. When choosing a location to cache food in the presence of a competitor, they prefer far to near, darker to lighter, and occluded to in-view locations (Clayton & Emery, 2007); they also re-cache items frequently in the presence of a competitor but not when alone (Emery & Clayton, 2007). These behaviors are not found when caching nonfood items (Bugnyar, Stöwe, & Heinrich, 2007) or when caching in the presence of a partner (Clayton, Dally, & Emery, 2007, p. 514; Emery & Clayton, 2007). This shows that scrub-jays, like chimpanzees, act in ways that are beneficial because they deny others perceptual experience. More impressive, when recovering food in private, scrub-jays prefer to recover caches that were observed by a competitor over those cached in private, and when recovering food in the presence of a competitor, they prefer to recover food cached in the presence of that competitor to food cached in the presence of another (now absent) competitor (Clayton et al., 2007). We regard these behaviors as manifestations of belief reasoning, because they are beneficial to the agent in virtue of facts about the beliefs of competitors. Although we do not know of any evidence on the limits of scrub-jay's belief reasoning, there are no findings to date that are incompatible with the prediction that scrub-jays' abilities will be limited in ways analogous to those of chimpanzees and infants.

A key focus for controversy is whether chimpanzees or scrub-jays track gaze only in behavioral terms (e.g., Dally, Emery, & Clayton, 2006; Penn & Povinelli, 2007; Povinelli & Vonk, 2003) or whether they form some representation of what is seen when someone looks (e.g., Call & Tomasello, 2005; Emery & Clayton, 2001, 2007). In this section (but not the next), we duck this issue to focus on what everyone agrees about: Somehow or other, these nonhuman animals reliably act in ways that are beneficial, in part, because of facts about beliefs. Thus, there is some convergence between the evidence from nonhuman animals and from infants. In both instances, there is some evidence for belief reasoning, despite very limited resources for language and executive function. And there is evidence that these abilities are limited and limited in similar ways.

Theory of Mind in Adults

Educated adults' everyday number cognition typically includes the ability to count and to perform arithmetic operations over a wide range of numbers. These abilities require the acquisition of a conventional symbolic counting system; they also depend on limited cognitive resources for working memory and executive control. It is important to note that adults also retain the mechanisms used by infants and some nonhuman animals for precise enumeration and numerical estimation, enabling rapid and relatively effortless judgments and intuitions about number. Is there evidence in adults of analogous parallel systems for beliefs?

We take it as established that adults do indeed engage in highly flexible reasoning about beliefs. Thus, our first question is whether such reasoning is indeed cognitively demanding. Direct investigation of this question found evidence that belief reasoning was not automatic and suggested an important role for strategic control in theory-of-mind tasks (Apperly, Riggs, Simpson, Chiavarino, & Samson, 2006; see also Saxe, Schultz, & Jiang, 2006). This conclusion is supported by evidence that variation in adults' performance on different belief-reasoning problems is related to their performance on tests of general processing speed and executive function (e.g., German & Hehman, 2006). Consistent with this, belief reasoning may also be disrupted if adults simultaneously perform a task that interferes with working memory (McKinnon & Moscovitch, 2007; see also Bull, Phillips, & Conway, 2008) or language processing (which may also require working memory; Newton & de Villiers, 2007), or if working memory or other aspects of executive function are impaired as a result of brain injury (for a review, see Apperly, Samson, & Humphreys, 2005). The cognitive demands on belief reasoning are reflected in everyday practice; for example, adults show a tendency for egocentric bias when interpreting the meaning of speakers (e.g., Keysar et al., 2003) and predicting the beliefs of others (e.g., Birch & Bloom, 2007; Mitchell, Robinson, Isaacs, & Nye, 1996), and overcoming this bias is cognitively demanding (e.g., Epley, Keysar, Van Boven, & Gilovich, 2004). In these respects, belief reasoning in adults resembles the number-reasoning abilities that are acquired relatively late and relatively slowly through the learning of a conventional symbol system. In both cases, these abilities are highly flexible but depend on limited cognitive resources for memory and strategic control.

In contrast, only very recently has there been any direct evidence of cognitively efficient belief reasoning in adults. These studies are not yet published but are mentioned here to highlight the future contribution that such studies might make. Samson, Apperly, Braithwaite, and Andrews (2007) presented adult participants with a Level 1 visual perspective-taking task in which they made rapid judgments about the visual perspective of themselves or a computer-generated avatar. Sometimes the participant could see the same number of objects as the avatar, and sometimes they could see more. Consistent with other evidence of an egocentric bias in perspective taking (e.g., Bernstein, Atance, Loftus, & Meltzoff, 2004; Birch & Bloom, 2004, 2007), participants were slower at judging the how many objects the avatar could see when they could see more objects themselves. More surprising, the reverse was also true: When participants judged how many objects they could see, they were slower when the avatar saw fewer objects than when the avatar saw the same number. It is critical that this interference from the avatar's perspective was not eliminated in a second experiment in which participants judged only their own perspective for an entire block of 52 trials. This suggests that, even when there was no reason to work out what the avatar could see and when doing so increased participants' difficulty judging their own perspective, the avatar's perspective was computed nonetheless. This clearly raises the possibility that the avatar's perspective was being computed using cognitive processes that were fast and efficient (fast and efficient enough to produce a representation of what the avatar could see in time for this to interfere with participant's judgments about what they themselves could see) and also resistant to strategic control (in the second experiment, participants did not exploit the fact that processing the avatar's perspective was irrelevant to avoid the costs associated with processing this information). These findings only concerned judgments about the current visual experience of "self" and "other," but preliminary evidence from two other studies (Kovacs & Mehler, 2007; Wang, Apperly, Samson, & Braithwaite, 2007) suggests that similar interference may occur even between recent (but not current) visual experience, that is to say, "belief-like" states (see the following). These studies of fast, efficient, and potentially automatic theory-of-mind processes in adults are clearly in their early stages, but on the current analysis, these abilities and, in particular, the degree to which they are limited to certain kinds of belief are likely to be an interesting avenue for future work. For example, an obvious prediction for a signature limit arising from evidence that neither infants nor chimpanzees appear capable of Level 2 perspective taking (where they must appreciate not only that someone sees something but also how they see it) is that adults might not automatically compute the avatar's perspective if the task involves Level 2 perspective taking.

It is important to note, however, that in addition to these preliminary findings, there are compelling reasons for thinking that adults need fast and efficient belief reasoning. This indirect evidence comes from consideration of the cognitive requirements of communication. It has long been noted that adults' sophisticated moment-by-moment social interaction and their verbal and nonverbal communication seem to depend on keeping track of what other people know and think (Grice, 1989; Sperber & Wilson, 1995). The speed and apparent lack of effort in everyday communication suggests that the necessary theory-of-mind computations must likewise be made quickly and efficiently (e.g., Sperber & Wilson, 2002). This need is clearly at odds with the findings from studies that have actually examined adults' reasoning about beliefs and knowledge (see the preceding text). Most notable, Keysar et al. (2003) showed that adults' interpretations of simple instructions tended to be insensitive to differences in both perspective and belief, although these differences were manifest. If adults struggle to use simple theory-of-mind inferences to guide communication in such uncomplicated cases, it seems unlikely that similar inferences are the principal guide for online interpretation in everyday communication. To the extent that theory-of-mind abilities are needed for everyday communication, adults need a fast and efficient system for theory of mind. In the current analysis, we expect such efficiency to come at the price of flexibility, which will be manifest in signature limits on the ways in which everyday communication can be guided.

Summary

We have reviewed a variety of evidence suggesting that the belief-reasoning abilities of infants and nonhuman animals *could* be limited. Currently, there is positive evidence for only a relatively small set of abilities in these groups, and it is intriguing that there is also evidence of some similar limitations across groups (e.g., it may be that neither infants nor chimpanzees are capable of Level 2 perspective taking). We also argued that there were good reasons for thinking that the abilities of infants and nonhuman animals *should* be limited. As is the case in other domains, such as number, person perception, and general reasoning, the flexibility of older children's and adults' capacity to reason about beliefs is likely to come at the cost of placing heavy demands on language and executive function. Human infants and nonhuman animals lack the linguistic and executive capacities of older children and adults, leading to the suggestion that their belief reasoning is achieved by different cognitive processes that trade flexibility for cognitive efficiency. Finally, an adequate explanation of adults' belief-reasoning abilities seems to require that they have both cognitively efficient processes that are likely to be inflexible and highly flexible processes that are clearly cognitively demanding. By analogy with the case of number, we propose that the cognitively efficient capacity of adults is at least partially underwritten by processes identical or similar to those found in infants and perhaps nonhuman animals. As in the case of number, evidence bearing on this issue will come from careful examination of the signature limits on these cognitively efficient processes, and it is to this that we turn in the following section.

Different Paths to Efficiency Give Rise to Distinct Signature Limits

Supposing that the conflicting needs for efficiency and flexibility are reconciled by the existence of two systems for belief reasoning, what could be the nature of the more efficient system, and what empirical findings would help decide between theoretically possible alternatives? Although something like a two-system account for belief reasoning has been proposed by several authors (e.g., Call & Tomasello, 2008; Doherty, 2006; Gomez, 2007; O'Neil, 1996; Penn et al., 2008; Perner, 1991; Whiten, 1994, 1996), these critical questions have not been adequately addressed. To answer these questions, we first identify factors that make belief reasoning costly, and then consider several ways belief reasoning could be achieved without these factors.

Why is belief reasoning costly? At least part of the cost arises from the type of reason-giving explanation in which beliefs feature. For example,

> She reached for the salt container because she saw the white grains, and—believing them to be sugar—intended to sweeten her pie.

Reason-giving explanations like this one have several features (Davidson, 1980, 1990b). First, they involve complex causal structures: The perceptions influence beliefs, which, together with desires, lead to intentions, which guide action. Note how reason-giving explanations invoke, explicitly or implicitly, multiple interacting causes, some of which may be far removed in time and space from the salient causes of an action. Second, they are abductive: Arriving at them involves inference to the best explanation, where there are no restrictions in principle on what might be relevant to the best explanation. Third, they have a normative dimension: Except in special circumstances, a true explanation reveals how an agent's actions are reasonable in the light of her beliefs and desires. Fourth, they involve ascriptions of states with propositional contents: It is possible to have beliefs involving quantification, modality, and the rest (e.g., it is possible to believe that Noah wasn't the only person who could have survived the flood). These features are all liable to be costly. If anything demands working memory, inhibition, and strategic control, it is surely abductive reasoning about complex causal structures of states individuated by propositional contents and their normative implications.

How could belief reasoning be more efficient? At a minimum, it must not involve explanations with the four features identified above (which means that it cannot be reasoning about beliefs as such; Davidson, 1999). Several possibilities are consistent with this requirement, and more than one may turn out to be actual. In the rest of this section, we evaluate different possible paths to efficiency. We begin with two cases that we do not think are viable explanations for efficient belief reasoning. We then discuss some proposals that may be viable and consider how it might be possible to distinguish between them by considering the nature of the processing limitations—the signature limits—that they would entail.

Accounts That Do Not Explain Efficient Belief Reasoning

Innate belief-reasoning competence. A number of authors have suggested that theory of mind in humans depends upon an innate capacity for parsing mental states from behavior, which is often characterized as a module that may consist of two or more subsystems (e.g., Fodor, 1992; Leslie, 1994a; Leslie, German, & Polizzi, 2005; Luo & Baillargeon, 2007; Onishi & Baillargeon, 2005; Scott & Baillargeon, 2008; Surian et al., 2007). These claims are primarily driven by concerns about the problem of acquisition. By obviating the need for learning, these theories aim to explain how it might be possible for infants to have abstract psychological concepts early in life, possibly before they have the general cognitive resources to learn such concepts or the experiences necessary for such learning. According to such accounts, infants might not be able to use the full range of abilities that their theory-of-mind competence affords because of limitations in the conceptual content available to infant cognition and limitations in their capacity for general processing (e.g., Fodor, 1992) or executive function (e.g., Leslie, 2005). But the complexity of infants' abilities increases as they acquire more diverse conceptual content and new capacities for memory and executive function, culminating in the highly flexible abilities of adults.

Although such theories offer a solution to the problem of acquisition, they do not easily explain how belief reasoning could be simultaneously cognitively efficient and cognitively flexible in adults. This is because the features that explain the superior abilities of adults—greater knowledge, greater memory, and executive control—are the very features that also make adults inefficient at belief reasoning, and on this account, these features are added to the same "one-system" that is present in infants. Innateness, then, does not, in and of itself, explain efficiency. This is not an argument against innateness; our point is simply that these theories, as currently formulated, do not directly address questions about efficiency. More generally, merely describing the capacity to reason about beliefs as modular is inadequate to explain how efficient belief reasoning is possible, because this does not meet the key requirement identified earlier: to show how belief reasoning is possible without abduction over complex causal and normative structures of states individuated by propositions. To stipulate that one form of belief reasoning is innate, tacit or implicit, automatic or modular is not to solve the problem of efficiency but to presuppose that it can be solved.

Reasoning about factual, rather than mental, states. Perner (1991) and Csibra and Gergely (1998, 2007) argued that before children can represent beliefs, they can predict actions by reasoning about facts. To illustrate, consider "James ran toward the bus because it was about to depart." This sentence appears to explain James's behavior by appeal to a fact, rather than a belief and an implicit desire. Although the sentence can be used as shorthand for a belief–desire explanation, it could also be taken literally as explaining James's running in terms of the facts (Gordon, 2000; Stout, 1996). Providing beliefs and desires are largely shared, such explanations will yield the same predictions as belief–desire reasoning does in a useful range of cases. Moreover, Perner suggested that older children and adults may often reason about agents' relations to factual situations, rather than about their beliefs (Perner, 1991, p. 211).

This proposal may be correct, in that infants (and others) may indeed sometimes reason about agents' relations to factual situations as a proxy for belief reasoning. However, it is unable to deal with interpersonal differences in perception or belief and so is inadequate for explaining the full range of infant and nonhuman theory-of-mind reasoning. More importantly, merely shifting from mental states to factual states does not remove the obstacles to cognitive efficiency identified earlier: Whether about facts or beliefs, the reasoning in question still appears to require abduction over multiple states individuated by propositions and subject to the same normative constraints (Csibra, 2003, p. 452; Csibra & Gergely, 1998, p. 258). (Of course, identifying facts may be less costly than identifying beliefs [Apperly, Back, Samson, & France, 2008]; our point is that identifying facts *as potentially explanatory of action* fails to remove some of the cognitively costly problems involved in reasoning about beliefs as such.) Furthermore, switching from mental to factual states does not appear to be necessary for gaining cognitive efficiency. Several highly efficient cognitive processes operative in infancy involve computations over unobservables; these unobservables arguably include intended phonic gestures in speech perception (Jusczyk, 1995; Liberman & Mattingly, 1985; Liberman & Whalen, 2000) and causal relations (Oakes & Cohen, 1990; Saxe & Carey, 2006). Thus, although we think it is plausible that children, adults, and nonhuman animals sometimes reason about agents' relationships to facts rather than beliefs, and although we recognize that reasoning about facts may be a developmental stepping stone toward reasoning about beliefs (e.g., Perner, 1991), we do not think that this alone is a plausible way of achieving cognitive efficiency.

Accounts That Might Explain Efficient Belief Reasoning

Automatization. Suddendorf and Whiten (2003) expand on Povinelli and Giambrone's (1999) claim that humans may achieve cognitive efficiency in some theory-of-mind operations, including belief reasoning, via automatization. That is to say, belief reasoning may originally be a hard-won development that is demanding of cognitive resources but becomes efficient in adults through repeated practice. Once again, there is an intriguing analogy with the case of number cognition. Symbolic addition (e.g., computing the sum 10 when presented with the symbol string 4 + 6) is a hard-won development that requires explicit instruction. However, once learned, this may become automatized with practice, leading educated adults to compute 10 when presented with 4 + 6, even when this actually interferes with the task they are trying to perform (e.g., LeFevre, Bisanz, & Markonjic, 1988). If this analogy is mapped directly for the case of belief reasoning, then we should expect that in highly practiced situations (e.g., a poker expert playing poker), automatized processes may infer an agent's beliefs without placing substantial demands on general cognitive processes. An intriguing alternative that we think equally possible is that actions that originally required a belief inference (such as working out when to feint and counter-feint in fencing) may, with practice, be automatized into direct mappings between observations of the opponent's behavior and plans for one's own behavior, with belief inferences no longer required.[7]

We agree with these authors that it is highly plausible that adults and older children achieve some cognitively efficient belief reasoning through automatization. However, as these authors note, automatization can lead to efficient belief reasoning only in an organism that has first achieved the capacity to reason about beliefs in a nonautomatic way that makes significant demands on cognitive resources. Moreover, automatization will necessarily be restricted to well-practiced cases. Thus, automatization cannot explain efficient belief reasoning in novel cases, and it cannot explain the efficient belief-reasoning abilities of infants and nonhuman animals (unless we suppose that infants and nonhuman animals already have nonautomatic belief reasoning, despite being deficient in language and executive control).

Behavior associations and behavior rules. A number of authors have suggested that theory-of-mind abilities in infants and nonhuman animals are supported by learned associations or (possibly innate) rules that map between observed behaviors (Baldwin & Baird, 2001; Byrne, 2002, 2003; Povinelli et al., 2000; for the application to infant false belief tasks, see Perner & Ruffman, 2005; Ruffman & Perner, 2005). In this view, infants and nonhuman animals exploit statistical regularities in sequences of behaviors, such as head orienting to an object being frequently followed by approaching an object. Where adults may ultimately reinterpret such patterns in folk psychological terms and so use belief reasoning to predict behaviors (e.g., Penn & Povinelli, 2007), it is claimed the same predictions can be achieved by identifying regularities in behaviors alone. In one view, these regularities are identified in something like the way that infants can distinguish nonword from word-like sequences of syllables by discerning transitional probabilities (Gómez & Gerken, 2000; Saffran, Newport, & Aslin, 1996). In another view, these regularities are captured by innate behavioral rules (e.g., Perner, in press).

The ability to form expectations about a future behavior on the basis of a behavior that has just been observed may offer a cognitively efficient method for coordinating one's own behavior with others', but it is an open question whether it explains the full range of phenomena observed in infants, adults, and nonhuman animals. The bold assumptions made by the above authors are doubly conjectural, for it has yet to be investigated both whether appropriate regularities in behavior exist and whether subjects can identify such regularities. These questions cannot be decided a priori any more than questions about the existence of phonological structures in language and our sensitivity to them. Research on reading statistical patterns in behaviors is only just beginning (Baldwin & Baird, 2001; Byrne, 2003).

Relevant to the possibility that infants and perhaps nonhuman animals learn associations between behaviors, we so far know that adults can learn to identify regularities in the linear ordering of activities that enable them to distinguish expected from unex-

[7] We are grateful to Josef Perner for suggesting this possibility to us.

pected sequences, even in novel cases (Baldwin, Andersson, Saffran, & Meyer, 2008), and that infants can segment linear sequences of activity into units that match achieving a goal, such as putting a lid on a jar or folding a scarf (Saylor, Baldwin, Baird, & LaBounty, 2007). It seems plausible, then, that parsing regularities in behavior plays a key role in theory-of-mind abilities, a role analogous to parsing phonological structure in linguistic communication. However, if the case of language is any guide, sensitivity to behavioral regularities is essential but falls as far short of generating an approximation to belief reasoning as infant babbling falls short of meaningful conversation.

As Baldwin and colleagues' research exemplifies, belief reasoning based on behavior associations can be discerned by signature limits. Unless behavior associations are innate, such reasoning will depend on individual learning histories and should be limited to commonly observed behaviors (such as head turning and approach) and not conceptually similar behaviors that are less commonly observed (such as head turning and moving away). Equally, behavior associations should not be limited to regularities in behavior that are intelligible in the light of mental states: Behavioral regularities that are unintelligible in terms of mental states should be equally easy to learn and to process (Baldwin et al., 2008).

The hypothesis that infants or nonhuman animals learn behavior associations for themselves should be distinguished from the possibility that they are innately endowed with cognitive rules that allow one behavior to be predicted from observation of another (e.g., Perner, in press). This possibility clearly protects the individual from the vagaries of his or her own particular learning environment, thus eliminating one signature limit of associationist accounts. It is critical, however, that there is at least one further signature limit of behavioral accounts that holds whether we suppose that the individual has behavioral associations or behavioral rules. According to Penn and Povinelli (2007).

> "The theory of mind debate among comparative researchers [and for current purposes, this includes any behavioral rule or behavioral association account] should turn only around the question of whether, in addition to the representational abilities that any cognitive agent possesses . . . , some particular cognitive system in the agent in question also produces information that is specific to the cognitive perspective of another agent and uses this information to predict the behaviour of the agent" (pp. 733–734).

In other words, although behavioral rules or associations link one behavior of an agent with another, they do not lead to the generation of any content for "what is in the head" of the agent. Thus, any phenomenon that demonstrates interference or confusion between the subject's own perspective and the content of the target agent's perspective would fall outside of what could be explained by behavioral rules or associations. As an example, we note that preliminary evidence of just this kind was reported in our earlier section on theory of mind in adults, where three studies (Kovacs & Mehler, 2007; Samson et al., 2007; Wang et al., 2008) show evidence of interference between self-perspective and automatically generated content corresponding to the perspective of another. Clearly, this in no way undermines the possibility that infants, adults, and nonhuman animals do indeed have behavioral rules or associations as an efficient way of solving some theory-of-mind problems. But it does indicate that behavioral rules or associations may well be insufficient to explain all instances of efficient theory of mind in current and future studies, and it suggests the kind of evidence that may be critical for deciding between these accounts in future work.

Specialized processing of belief-like states. If automatization and behavior rules or associations alone turn out to be insufficient to explain efficient belief reasoning, what else is there? Several authors have independently attempted to characterize a mode of explanation intermediate between mindless behaviorism and full-blown propositional attitude psychology. For example, Gomez (2007) has suggested that we focus on primitive intentional relations to objects established by gaze, O'Neil (1996) and Doherty (2006) have discussed a notion of engagement with objects, Whiten (1994, 1996) used the notion of an "intervening variable" to explain primitive theory-of-mind notions, and Call (2001) credited chimpanzees with a "representational," rather than a "metarepresentational," understanding of seeing. Constructing such an intermediate scheme of explanation is a major challenge (Davidson, 2003, p. 697). Here we attempt to sketch enough of the scheme to illustrate its plausibility and generate predictions capable of distinguishing it from alternative hypotheses, such as behavior reading and reasoning about propositional attitudes as such.

Start with the notion of a field as a certain region of space centered on an individual and define *encountering* as a relation between the individual, an object, and a location, such that the relation obtains when the object is in the individual's field. This definition can be refined. The key requirement is that conditions under which an encounter occurs must be specified without appeal to anything psychological. While meeting this requirement, it is possible to make the conditions under which an object is encountered approximate those under which an object is perceived. For example, we can allow that occluded objects are not encountered unless they are either noisy or moving on a natural trajectory that is not entirely occluded. Given sufficient sophistication, encountering can serve as a proxy for perceiving in a useful range of cases. An agent may intentionally attempt to manipulate others' encounters: For example, it may be beneficial to prevent others from encountering one's food.

The next step is to introduce registration, which is a relation much like encountering except that it continues to obtain even after an object is no longer in one's field. One stands in the registering relation to an object and location if one encountered it at that location and if one has not since encountered it somewhere else. Registrations resemble beliefs in having correctness conditions that may not be obtained: A registration fails to be correct when the object registered is not where it is registered as being. Their interest lies in their connections to action. One can understand registration as an enabling condition for action, so that registering an object and location enables one to act on it later, providing its location does not change. This understanding of registration would be useful to an organism, for example, because it would motivate the organism to move objects a competitor encountered in the past. Further, registration also can be understood as determining which location an individual will direct their actions to when attempting to act on that object. This more sophisticated understanding (which requires the notion of an unsuccessful action) enables one to predict actions on the basis of incorrect registrations and so approximate belief reasoning to such a great extent as to pass some false-belief tasks (e.g., Onishi & Baillargeon, 2005).[8]

Registrations, then, serve as proxies for beliefs both true and false: In a limited but useful range of situations, what someone believes about objects will match what they register. Registration could be made more sophisticated, for example, by allowing properties other than location to be encountered and registered. To meet the requirements for cognitive efficiency identified at the start of this section, two restrictions must be observed: Registrations must be relations to objects and properties, not to propositions; and registrations must have their effects on action by setting parameters for action independently of each other and independent of any psychological states; or, if they do interact, they must do so in ways that are codifiable (unlike beliefs, whose interactions with desires, intentions, and other beliefs are as complex as interactions among reasons). These restrictions are consistent with allowing that reasoning about registrations would enable someone to track beliefs, true and false, in a limited range of situations. At the same time, reasoning about registrations imposes signature limits. It does not permit tracking beliefs that involve quantifiers (no absences, then) or indefinitely complex combinations of properties (perhaps large melons and yellow melons but probably not large yellow melons). Nor does reasoning about registrations allow for a distinction between what is represented and how it is represented (sometimes referred to as mode of presentation or sense), although registrations could, in principle, allow for a weaker type of perspective by including reference to the agent's location. Accordingly, registrations would support Level 1 perspective taking (e.g., appreciating that an agent does not see an object that you see) but not Level 2 perspective taking (e.g., appreciating whether an agent sees an object as a duck or as a rabbit). These and other limitations distinguish registrations from beliefs. We describe registrations as belief-like states because they resemble beliefs insofar as they function to keep an individual's actions in step with relevant information even after such information is no longer immediately accessible.

How could we tell whether, in practice, efficient belief reasoning involves belief-like states such as registrations? By identifying signature limits and seeking converging evidence from different methods and different subject groups. In the case of number, infants' ability to handle precise numerosities appears limited to the representation of three or four items. Moreover, this limit is arbitrary. Nothing about the nature of numbers predicts this limitation. Nor is the limit due to the learning environment to which infants are exposed or to limited development in capacities for general working memory or executive control that support more flexible behavior and develop throughout childhood. The three- to four-item limit is just a fact about the cognitive system that infants use for processing precise numerosity, whether that cognitive system is domain specific for number (e.g., Gallistel & Gelman, 1992, 2000) or whether it is a limited-capacity system for object-based attention (e.g., Trick & Pylyshyn, 1994) or visual working memory (e.g., Vogel, Woodman, & Luck, 2001) that affords numerical judgments. Similarly, reasoning about registration, if it occurs, would be limited in ways that are arbitrary with respect to the nature of belief and inexplicable by appeal to variations in individual's learning history or the capacity of general processing resources. We would expect the capacity observed in infants also to be observed in human adults with the same signature limitations, and we would expect similarly limited abilities (although not necessarily identical) to be observed in at least some nonhuman animals. Converging evidence from these three sources would provide strong evidence in favor of specialized systems for reasoning about belief-like states.

Summary. To achieve processing efficiency, we need a way of tracking beliefs that does not involve the costly features of reason-giving explanations. This can be achieved in at least three ways: by automatization, behavioral associations, and processing belief-like states. These are not mutually incompatible, and more than one may turn out to be used. Each achieves efficiency at the expense of different signature limitations on the nature and complexity of theory-of-mind processing that can be achieved. Our key point for empirical investigations is therefore that identifying limitations which cannot be explained in terms of a lack of general processing resources or conceptual content indicates that a cognitively efficient process is being employed, and the nature of any limitations can indicate the means by which efficiency is being achieved.

How Could the Two Systems Be Related?

One question not addressed so far is how the two theory-of-mind systems might be related, either in development or in the mature state of adults. In the case of number, understanding the relation between infants' and later-developing abilities is still a major challenge (Carey, 2002; Laurence & Margolis, 2005; Spelke, 1994, 2000), but there is some helpful evidence on the relationship between the number systems of older children and adults. Adults' symbolic and nonsymbolic number systems are sufficiently separate that evidence of double dissociations may be found following brain injury (e.g., Lemer, Dehaene, Spelke, & Cohen, 2003). However, there is also evidence that these systems are not entirely isolated from each another. Gilmore et al. (2007) found that 5- and 6-year-old children[9] showed similar abilities to perform approximate numerical judgments for numbers that differed in a sufficiently high ratio, whether the numbers were presented nonsymbolically (e.g., as dot patterns) or symbolically (as numerals). The authors suggested that children achieved this by mapping symbolic representations of number onto their approximate representations of numerical quantity. This evidence suggests

[8] Understanding registration as explained here appears also to enable one to pass standard false-belief tasks involving unexpected location transfers (e.g., Wimmer, Hogrefe, & Perner, 1988). Because children can indeed pass such tasks if their gaze, rather than verbal responses, is taken to be the relevant measure (Clements & Perner, 1994; Southgate et al., 2007), this is not an objection to our view but, rather, is a genuine puzzle. One possibility is that an early-developing system for tracking registrations is guiding children's eye movements, whereas a later-developing system guides children's explicit judgments about beliefs (see the *How Could the Two Systems Be Related?* section).

[9] In this study, the authors examined children, rather than adults, to have participants who were able to count (could comprehend symbolic number stimuli) but who had no training in formal arithmetic (were unable to answer the estimation problems using symbolic arithmetic operations). Although it would be consistent with this study's findings to hold that symbolic numbers are mapped to nonsymbolic representations only by children, it seems more likely that adults are also able to map symbolic to nonsymbolic number representations.

that even if symbolic and nonsymbolic number abilities depend on distinct functional and neural substrates, they can work in concert.

A two-systems account of belief processing is clearly compatible with a variety of accounts of development and of the mature theory-of-mind system. At one extreme, we might imagine that there is no direct information flow between the early-developing and later-developing systems (see, e.g., Butterfill, 2007, for a discussion of this type of information-processing architecture). The early-developing system might provide constraints for fast online social–cognitive processes such as communication and, in development, might serve to guide young children's attention to cases in which their epistemic perspective diverges from that of someone else (cf. Leslie, 2000). However, explicit judgments about what someone else thought or knew (i.e., the later-developing system) would receive no direct input from the early-developing system and so would have to infer such content anew. At the other extreme, the later-developing system may depend on the other for its proper operation. Or, by analogy with the case of number, it is possible that the two systems work in concert in adults.

There is a surprising lack of evidence bearing directly upon these questions. One intriguing exception is the existence of within-child discrepancies on implicit versus explicit measures of false-belief understanding. As already mentioned, children as young as 24 months may show looking behavior that anticipates the action of a character with a false belief (e.g., Southgate et al., 2007). However, there is evidence that the very same children may respond incorrectly when asked to make an explicit judgment about how the character will act (e.g., Clements & Perner, 1994). These findings are clearly consistent with the possibility that an early-developing system for tracking belief-like states is guiding children's eye movements, and a later-developing system guides children's explicit judgments about beliefs. Moreover, Ruffman, Garnham, Import, and Connolly (2001) provided evidence that children may be highly confident in their incorrect explicit prediction of the character's action (as indexed by their "betting" of counters on a particular outcome), despite correctly anticipating the character's action with their looking behavior. Thus, these findings are also consistent with the possibility that there is no direct information flow between the early-developing and late-developing systems.

Besides these findings, our general line of argument leads us to think that some possible relationships between the two systems are unlikely. Our central claim is that early-developing and late-developing systems for belief processing need to make different and complementary tradeoffs between flexibility and efficiency. If there is an efficient system for ascribing belief-like states, then the efficiency of this system cannot come for free, so there will be restrictions on the kind of input it can take and the kinds of belief-like states it can ascribe. This contrasts starkly with a primary feature of late-developing belief reasoning competence, which is the ability to use all cognitively available facts to ascribe any belief that the subject can themselves entertain. These considerations mean that the early- and late-developing systems cannot be fully continuous with each other (contra Csibra & Gergely, 1998; Russell, 2007; Surian et al., 2007). The early-developing system could not be an implicit homologue of the late-developing system, nor could it supply candidate belief contents to the late-developing system for the significant proportion of cases that were beyond its representational powers (contra Leslie et al., 2005, who assumed continuity between early-developing and later-developing abilities). Moreover, limits on the kind of belief-like states that the early-developing system could represent would mean that many beliefs that could be represented in the late-developing system could never be mapped back into the early-developing system. Of course, future work could prove incompatible with these predictions. Our hope is that by spelling out the implications of our account, we help identify the pressure points that might be particularly important for future investigation.

Comparing the Current Account With Existing Theories

As noted in the introduction, we are not the first to propose that theory of mind may involve more than one type of cognitive system. However, our particular target is the paradigm case of reasoning about beliefs, and in this final section, we make the case for the novelty of our approach to this problem. We suggest that existing accounts either resemble our account in only superficial ways or do not give a two-system account of processing beliefs, or else severely underspecify what a two-system account is supposed to achieve or how the existence of two systems might be studied in a systematic way.

Superficial resemblance. As mentioned in earlier sections, Leslie and colleagues (e.g., Leslie, 1987, 1994a, 1994b, 2000, 2005) have long advocated the view that infants are innately endowed with a mechanism (the *theory of mind module*, or ToMM) that enables them to generate representations of propositional attitudes, such as beliefs, from behavioral input. Leslie (1994a) proposed that ToMM consists of two subsystems: Subsystem 1 is available from 6 to 8 months of age and is concerned with processing goal-directed actions; Subsystem 2 is available from approximately 18 months of age and generates propositional attitude representations. This view has recently been extended by Baillargeon and colleagues (e.g., Onishi & Baillargeon, 2005; Song & Baillargeon, 2008; Song et al., 2008), who, on the basis of the evidence from infants reviewed earlier, proposed that Subsystem 1 is not only concerned with goal-directed actions but also represents the agent's belief, provided that belief is true. However, although these authors discuss two subsystems, any resemblance to our two-systems account is superficial, because the two subsystems discussed by Leslie and Baillargeon are subcomponents of a single cognitively efficient ToMM. The purpose of this module is to explain how infants can reason about mental states like belief, despite lacking either the time or the cognitive resources that might be necessary for the relevant concepts to be acquired. Neither subsystem identified by Leslie and Baillargeon resembles our System 2, which is cognitively flexible and demands general processing resources. This research may therefore be seen as contributing to the case we have made for a cognitively efficient theory-of-mind system, but it does not directly bear on our hypothesis that there is an additional, less efficient but more flexible system, and it does not offer any explanation of how belief reasoning can be both efficient and flexible.

In addition to the two subsystems of the ToMM, Leslie and colleagues proposed that the action of the ToMM is augmented by an inhibitory *selection processor* (SP) that selects the appropriate belief content from alternatives computed by ToMM (e.g., Leslie, 1994b; Leslie et al., 2005). The proposal is that SP develops later than the subsystems of ToMM; immaturity of SP explains why children fail standard false-belief tasks until around 4 years of age; and continuing need for SP explains the involvement of executive function in adults' belief reasoning (e.g., German & Hehman, 2006). The ToMM–SP account has been criticized on the grounds that, because SP needs to "know" which belief content to select from the output of ToMM, SP must itself be capable of belief reasoning, so rendering ToMM redundant (Doherty, 1999). However, such outright objections matter less for our current purposes than whether the ToMM–SP account can explain how belief reasoning can be both cognitively efficient and flexible. On the face of it, the ToMM–SP account may appear to offer an explanation. A single system, ToMM, supplies the representational basis for belief reasoning in infants, 3- to 6-year-old children and adults. The addition of SP makes belief reasoning more cognitively demanding by forcing the involvement of inhibitory processes. Any appearance of an explanation here is illusory, however, for two reasons. First, ToMM supplies multiple alternative beliefs (this is why SP is needed). In general, knowing only that someone has one of multiple alternative beliefs is not sufficient for predicting their behavior. The ToMM component of ToMM–SP is therefore insufficient for belief reasoning and so not an alternative to the cognitively efficient systems for belief reasoning that are proposed here. Second, on our analysis, merely representing beliefs as such is cognitively demanding because beliefs are states individuated by their propositional contents and normative implications. It follows that cognitively efficient systems cannot represent beliefs as such. This is why, in our account, cognitively efficient systems for solving tasks involving beliefs represent belief-like states that serve as proxies for beliefs, and this is also why there is a trade-off between efficiency and flexibility. Leslie and colleagues' ToMM is therefore not an alternative to the cognitively efficient systems for belief reasoning we have proposed because there is no reason to suppose that it could be cognitively efficient. Thus, although originally motivated by concerns related to a subset of our own (see, e.g., Leslie, 1994a), the ToMM–SP account does not address the critical concern for the current article, which is to explain how belief reasoning can be both flexible and cognitively efficient.

Two systems, but not for belief reasoning. On the basis of evidence from neurodevelopmental disorders, Tager-Flusberg and Sullivan (2000) proposed a two-systems account for theory of mind in the broadest sense. However, their critical distinction was between processes for "social cognition," which includes belief reasoning, and "social perception," which includes processing of faces and body postures for social information but does not include processing of any epistemic states, including belief-like states or beliefs. Clearly, the proposal we have developed here is not in conflict with the general account of Tager-Flusberg and Sullivan, but neither is it implied by their account.

Gergely and Csibra (2003) proposed a different kind of account, whereby the ability of infants to process goal-directed actions is explained in terms of reasoning about how a goal state might best be achieved given the physical constraints of the situation. This account concerns intentions, not beliefs, but resembles our own insofar as infants' sensitivity to a propositional mental state is explained without supposing that infants reason about mental states as such. Moreover, the authors also supposed that infants eventually develop into children and adults who do, in addition, reason about mental states as such. However, there is a critical difference between this account and our own, for this account explicitly denies that infants are ascribing anything like mental content to the agents of the goal-directed action. The authors conceive of a "mindblind" creature "that—although unable to represent intentional mental states—could nevertheless have evolved a reality-based interpretational strategy to represent goal-directed actions" (Gergely & Csibra, 2003, p. 290; c.f. Gordon, 2000). For reasons already discussed, we believe that the ability to ascribe simple forms of mental content, at least in the form of belief-like states, may be necessary to explain the full range of phenomena demonstrated by cognitively efficient belief reasoning in infants and adults. Thus, our account has substantial explanatory power beyond the account of Gergely and Csibra (2003).

Recent work by cognitive neuroscientists has also shown evidence of dissociable neural systems for action processing (e.g., Brass, Schmitt, Spengler, & Gergely, 2008; Liepelt, Von Crammon, & Brass, 2008). One system is in the *mirror network*, which consists of regions of cortex, including the inferior frontal gyrus, that show activity both when subjects perform an action and when they observe action in others (e.g., Gallese & Goldman, 2003; Rizzolati & Craighero, 2004). The other system is in the *mentalizing network*, which includes regions of medial prefrontal cortex, superior temporal sulcus, and temporal–parietal junction, that shows activity when the subject reasons about the mental states of others (e.g., Frith & Frith, 2003). Once again, however, the claims of these authors pertain to the processing of actions. They do not make claims about the processing of beliefs or belief-like states, and so these accounts are distinct from the one developed here.

Underspecified two-systems accounts. It is clear from earlier sections that several authors have discussed some form of two-system account in which both systems are concerned with enabling the subject to be sensitive to beliefs (e.g., Call & Tomasello, 2008; Doherty, 2006; Gomez, 2007; O'Neil, 1996; Penn et al., 2008; Perner, 1991; Whiten, 1994, 1996). Such accounts typically are aimed at describing the abilities of infants, children, or nonhuman animals in a way that does not require full understanding (or, in some cases, any understanding) of knowledge or beliefs as such. Our account clearly shares these aims, but it has substantial additional motivation and scope and leads to distinctive empirical predictions. In terms of motivation, we have aimed not merely to describe the abilities of infants and nonhuman animals in a way distinctive from the abilities of older children and adults but, rather, have aimed to explain how these abilities can be cognitively efficient such that they are within the processing capabilities of infants and nonhuman animals. In terms of scope, we have stressed that the need for cognitively efficient processing of belief-like states is not confined to infants and nonhuman animals (which is the scope of existing accounts) but is also clearly present in human adults. We hypothesize that one way in which this need is met in human adults is by employing a cognitively efficient capacity for processing belief-like states that has been present since infancy and may be shared with some nonhuman species. In terms of empirical predictions, we expect that cognitively efficient processing of belief-like states will come at the cost of distinctive limits on the complexity of the belief-like states that can be processed. As in the case of number cognition, by identifying such signature limits, it should be possible to tell when a subject is processing belief-like states, rather than full-blown beliefs. And testing for such signature limits offers a way of testing whether similar systems for processing belief-like states are being used by infants, human adults, and nonhuman animals, even though it is often necessary to test these different subject groups on quite different kinds of task. In each of these respects, our account is a substantial advance on existing two-systems accounts.

Conclusion

We began with an apparent contradiction: Infants pass false-belief tasks, yet children first understand false belief at around 4 years of age. Accounting for such findings presents a major puzzle in theory-of-mind research but not the only one. It is also puzzling that chimpanzees (and some other nonhuman species) show complex social behavior but an apparently contradictory pattern of success and failure on perspective-taking tasks in the laboratory (e.g., Call & Tomasello, 2005, 2008). And it is puzzling that human adults seem so quick and efficient in their social interaction and communication—abilities that appear to require theory of mind—yet most direct investigation suggests that adults' belief reasoning is relatively effortful and dependent upon limited cognitive resources for memory and executive control (e.g., Apperly, Samson, & Humphreys, 2009). In the existing literature, debate about these questions tends to be polarized: Infants, nonhuman animals, and online social interaction either employ mental concepts such as perception or belief or get by exclusively with behavioral rules. The case of number cognition suggests an alternative view.

The key components of this view are as follows: Human infants and some nonhuman animals are able to solve some theory-of-mind tasks by virtue of having one or more systems that are cognitively efficient but limited and inflexible. These limitations are only overcome years later when human children acquire psychological concepts such as belief and desire; this development occurs gradually (e.g., Apperly & Robinson, 2003), appears to be related to the development of language (Astington & Baird, 2005) and executive function (Perner & Lang, 1999; Sabbagh, 2006), and may be facilitated by explicit training (Clements et al., 2000; Slaughter & Gopnik, 1996). This equips children with a new system for theory-of-mind reasoning that is highly flexible but cognitively inefficient. In human adults, both systems exist in parallel. The cognitively efficient system plays a central role in guiding online social interaction and communication. The cognitively flexible system enables adults to engage in top-down guidance of social interaction (such as anticipating what the audience of a lecture might know or working out how one misjudged the audience afterward) and in explicit reasoning about the causes and justifications of mental states (as in everyday practical reasoning or jurisprudence).

Characterizing the ability to ascribe beliefs forces us to confront deep theoretical questions about how cognitive systems handle information under different processing constraints. The answers to these questions are of importance in all subdisciplines in which theory of mind is studied, including developmental, cognitive, and comparative psychology and cognitive neuroscience. These questions are not unique to the domain of theory of mind, and research on theory of mind can usefully inherit some of the lessons from other domains, such as number cognition. One lesson from other domains is that it is not always helpful to frame questions in terms of whether or not children or nonhuman animals possess a critical concept, such as number or belief. Unvariegated notions of what it is to have a concept (such as those in Brandom, 1994; Campbell, 1986; Davidson, 1990a; Dretske, 1981; Fodor, 1975; McDowell, 1996; Millikan, 1993) may be inadequate for understanding the complex pattern of phenomena found in cases like number and belief. A second, critical lesson is that, when one is faced with the problem of operating in complex domains using finite cognitive resources, two systems are often the solution.

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