

Do humans have two systems to track beliefs and belief-like states?

Ian A. Apperly

University of Birmingham, UK

& Stephen A. Butterfill

University of Warwick, UK

*In press in Psychological Review*

This article may not exactly replicate the final version published in the APA journal. It is not the copy of record. Copyright to the American Psychological Association

<http://www.apa.org/journals/rev/submission.html>

Abstract

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 (Wellman, Cross, & Watson, 2001; Wimmer & Perner, 1983), yet infants apparently pass false belief tasks at 13 or 15 months (Onishi & Baillargeon, 2005; Surian, Caldi, & Sperber, 2007). Non-human animals also fail critical tests of belief reasoning but can show very complex social behaviour (e.g., Call & 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., Apperly, Samson & Humphreys, 2005). We interpret these findings by drawing an analogy with the domain of number cognition, where similarly contrasting results have been observed. We propose that the success of infants and non-human 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 later-developing, more flexible but more cognitively demanding theory of mind abilities.

Do humans have two systems to track beliefs and belief-like states?

Introduction

More than twenty five years of research has taught us a great deal about theory of mind, the ability to ascribe mental states such as beliefs, desires and intentions in order to explain, predict and justify behaviour. We have learned much about the age at which children reach developmental milestones, about the abilities of non-human 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 characterise theory of mind in non-human 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 in order 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; compare 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 papers 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 upon 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 will begin. However, the same tensions exist when considering the abilities of non-human animals and human adults, which we discuss in later sections. We will argue that both current views of belief ascription have significant evidence in their favour, 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<sup>1</sup>.

Our central conjecture, that theory of mind involves two systems, has been canvassed in general terms by a variety of theorists 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 & Whitten, 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 paper we examine the cognitive demands of belief reasoning, develop the hypothesis that meeting these demands requires two kinds of cognitive system, we

Two systems for beliefs and belief-like states evaluate this hypothesis in the light of converging evidence from infants, adults, and non-humans, and identify the possible future evidence that could distinguish between alternative two-system solutions. Our project of characterising the cognitive basis of belief reasoning has implications for all of the subject areas where theory of mind has been investigated, including typical and atypical development (e.g., Baron-Cohen, Tager-Flusberg & Cohen, 2000; Doherty, 2008; Wellman et al., 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)<sup>2</sup>. 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 will look for some cheese which was secretly moved while he was sleeping. Although the 3-year-olds incorrectly said that Sam will look where the

Two systems for beliefs and belief-like states  
cheese actually is, they nevertheless appear to show some awareness of false beliefs by looking at the location where a character believes some cheese is hidden when prompted by with 'I wonder where he's going to look' (Clements & Perner, 1994; Garnham & Perner, 2001; Garnham & Ruffman, 2001). Using a modified, non-verbal version of Garnham's procedure, Southgate and colleagues (Southgate, Senju, & Csibra, 2007) have shown similar looking behaviour in 2-year-olds which is also indicative of false belief understanding<sup>3</sup>.

Most strikingly, Onishi & 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 where the actor observed the watermelon's movement (so had a true belief). This and other control conditions suggest that infant's looking times may correlate with whether or not the actor acts in accordance with her beliefs. Related results have since been independently obtained with 13-month-olds (Surian et al., 2007; see also Scott & Baillargeon, 2008)<sup>4</sup>.

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 four years when children first pass standard measures of false belief (Onishi & Baillargeon 2005; Leslie 2005), and 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,

Two systems for beliefs and belief-like states  
others insist that apparent success on theory of mind tasks in infancy can be explained without supposing infants have any understanding of belief at all. For example, some suggest infants' looking times may be explained by their adopting behavioural 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 favours their position (Onishi & Baillargeon 2005, p.257; Perner & Ruffman 2005, p.214). This suggests that considerations of parsimony will not be 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 non-human 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 summarise the evidence suggesting that humans have two kinds of cognitive system for processing number, including converging data from infants, adults and non-human 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 summarise these disagreements in order 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

Two systems for beliefs and belief-like states (e.g., Baroody & Dowker, 2003). On the influential views of Piaget and co-workers (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 behaviour 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, Dehane & Spelke, 2004; Le Corre & Carey, 2008 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



Two systems for beliefs and belief-like states  
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 (aged 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 six months) are able to discriminate between large numerosities, such as 8 versus 16 dots, but they can only do so if the ratio of their discrepancy is large (e.g., 1:2) and perhaps only if the number of items in each collection 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 number are not distinctively human, unlike the more flexible abilities of older children and adults<sup>5</sup>. 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 judgements, or when their ability to use strategies such as counting are disrupted experimentally, they remain able to make precise judgements 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 3 or 4 items observed in infants, and, as in infants, adults' approximate comparison of large sets is limited by the ratio of the two sets, though this

Two systems for beliefs and belief-like states ratio gets smaller with increasing age, allowing progressively more fine-grained approximations (Halberda & Feigenson, 2008).

Thus, much evidence points to the existence of numerical judgements in participants who have limited or no access to language and executive processes and no training in number, and to the distinction between the cognitive systems supporting these abilities and the cognitive systems supporting the additional skills with number and mathematics that many humans acquire through education. There are, of course, a variety of characterisations of the early-developing abilities and we describe these briefly in order to make clear the limits of our analogy with belief reasoning. Some authors have argued that both precise judgements for small numbers and approximate judgements for large numbers can be explained by a single system of analogue number representation that yields high discriminability (and thus high precision) only for 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; Le Corre & Carey, 2007; Feigenson, Dehane and Spelke, 2004). In the latter camp, there is also debate about the nature of the mechanism that yields precise judgements 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 memory (e.g., Vogel, Woodman & Luck, 2001) or that tracks objects via object files (e.g., Kahneman, Triesman & Gibbs, 1992; see e.g., Feigenson, Dehane and Spelke, 2004; Le Corre & Carey, 2007).

Finally, there is debate on how the abilities of infants to make limited judgements 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) argue that the analogue number system

Two systems for beliefs and belief-like states possessed by infants affords simple arithmetic operations (such as addition, subtraction and ordering) and operates over symbolic, analogue number concepts. On their view, learning to count is a process of mapping such concepts and operations into natural language. Other authors argue 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., Dehane, 1997; Wynn, 1992), by representations from the system that allows precise enumeration of small numbers (e.g., Carey, 1994) or by the integration of both systems (e.g., Feigenson, Dehane & Spelke, 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 number, there is considerable agreement on points that are critical for the analogy that 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 judgements. These systems remain present in adults and there is evidence of analogous capacities in some non-human animals. Second, the cognitive efficiency of these systems comes at the cost of distinctive limitations on the kinds of numerical judgement that can be made. These limits are relatively specific to the domain of numerical judgement. 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 (though the 3-4 item limit on precise enumeration may be explained by the limits of a specialised system for visual working memory). Third, these "signature limits" provide key evidence for the existence of distinct systems for processing number (and closely-

Two systems for beliefs and belief-like states related functions) and for the similarity of these systems in human infants, human adults and non-human animals. Fourth, it would be quite wrong to conclude that infants or non-humans understand number 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, Dehane & Spelke, 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 sub-systems) 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 above points provide a powerful analogy for interpreting the existing evidence on belief reasoning and for making novel predictions.

*Systems and concepts.* As noted above, it is a moot point whether infants or non-humans 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 non-human 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. Similarly, our proposal

Two systems for beliefs and belief-like states about theory of mind has two parts that we will 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, non-human 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 where 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 behaviours or of something else. As indicated in our title, we shall argue that it involves representing states which are like beliefs in guiding action but unlike beliefs in not having propositional content and 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), 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, 1986/95). 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, Dehane & Spelke, 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<sup>6</sup>, they are closely tied to developments in language and executive function (Astington & Baird, 2005; Pellicano, 2007; Perner, 1998; Perner & Lang, 1999, 2002;

Two systems for beliefs and belief-like states (Sabbagh, 2006; Zelazo, Jacques, Burack, & Frye, 2002), may be facilitated by explicit training and environmental influences, such as siblings (Clements, Rustin, & McCallum, 2000; Slaughter & Gopnik, 1996) and 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 artefact 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: that later-developing theory of mind abilities involve flexible cognitive processes which, by their very nature, depend on language or executive function; infants' precocious abilities are underwritten by a distinct set of cognitively efficient processes that do not depend upon language and executive function. Importantly, 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 3-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 (that is, 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 or psychological role or both.

In terms of content, all experiments involving infants mentioned so far require only that infants can track attitudes to objects' locations. Other experiments (Moll & Tomasello, 2007; Scott & Baillargeon, 2008) may require that infants and young children understand attitudes to objects that bear certain distinguishing features (including shape or colour). 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 only be represented 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. 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 (for example, when she is facing a wall); they do not expect people to acquire



Two systems for beliefs and belief-like states

beliefs about an object merely in 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, forthcoming; O'Neill, 1996). Nonetheless, children may struggle with level-1 perspective taking before 24 months (Moll and Tomasello, 2006; though 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 instead think of beliefs as independent of each other in much the way that perceptions are. 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 (for example, where someone will reach or walk to). If infants' belief reasoning were shown to be limited in some such ways, we could conclude that 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 emphasise that our aim is not to down-play 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 3 items or the ratio limit to which their numerical capacities are subject. These limits on

Two systems for beliefs and belief-like states 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 below). 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 non-human animals and human adults, and it is to these findings that we turn next.

### *Theory of mind in non-human animals*

Evidence from non-human animals is of relevance in the current context because, like human infants, non-human 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 non-human species enjoy capacities for precise enumeration and numerical estimation analogous to those observed in human infants, but lack the flexible number reasoning abilities of educated humans (e.g., Feigenson et al., 2003). 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 non-human animals has been conducted in chimpanzees (e.g., Tomasello, Call & Hare, 2003). Despite much controversy about how to characterise 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, Call & Hare, 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 and taking into account opaque barriers much as 18-month-olds do (Povinelli, 2001, pp. 229–230). They can adapt their strategy for retrieving food depending upon 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 in order to gain strategic advantage (Hare, Call & Tomasello, 2006). Whether or not they represent perceptions or beliefs, they are certainly acting in ways which are beneficial in virtue of controlling what others see and believe.

Recent investigation of scrub-jays' caching behaviours 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 will also re-cache items frequently in the presence of a competitor but not when alone (Emery & Clayton, 2007). These behaviours are not found when caching non-food 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 which are beneficial because they deny others perceptual experience. More impressively, when recovering food in private scrub-jays prefer to recover caches that were observed by a competitor compared to 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 behaviours as manifestations of belief reasoning because they are beneficial to the agent in virtue of facts about the beliefs of competitors. While 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

Two systems for beliefs and belief-like states 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 behavioural terms (e.g., Dally, Emery & Clayton, 2006; Penn & Povinelli, 2007, 2008; 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 in order to focus on what everyone agrees about: somehow or other these non-human animals reliably act in ways that are beneficial in part because of facts about beliefs. Thus, there is some convergence between the evidence from non-human 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 upon limited cognitive resources for working memory and executive control. Importantly, adults also retain the mechanisms used by infants and some non-human animals for precise enumeration and numerical estimation, enabling rapid and relatively effortless judgements 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

Two systems for beliefs and belief-like states (Apperly, Simpson, Riggs et al., 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 & Moskovitch 2006; 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, Lin and Barr, 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 & Andrews (under submission) presented adult participants with a level-1 visual perspective-taking task in which they made rapid judgements 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,

Two systems for beliefs and belief-like states (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 surprisingly, 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. Critically, 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 in order to avoid the costs associated with processing this information). These findings only concerned judgements about the current visual experience of "self" and "other", but preliminary evidence from two other studies (Kovacs & Mehler, 2007; Wang, Apperly, Samson & Braithwaite, Under submission) suggests that similar interference may occur even between recent (but not current) visual experience, that is to say, "belief-like" states (see below). 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 how they

Two systems for beliefs and belief-like states see it) is that adults might not automatically compute the avatar's perspective if the task involved level-2 perspective taking.

Importantly though, 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 non-verbal communication seems to depend upon keeping track of what other people know and think (Grice, 1989; Sperber & Wilson, 1986/95). 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 above). Most notably, Keysar, Linn & Bar (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 on-line 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. On 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 non-human animals *could* be limited. Currently, there is positive evidence only for a relatively small set of abilities in these groups, and intriguingly, there is

Two systems for beliefs and belief-like states 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). Importantly, we also argued that there were good reasons for thinking that the abilities of infants and non-human 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 upon language and executive function. Human infants and non-human 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. On 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 non-human 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 limitations

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, Holyoak & Povinelli, 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 (for example 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 – “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 behaviour, which is often characterised as a mental “module” that may consist of two or more sub-systems (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 will increase as they acquire more diverse conceptual content and new

Two systems for beliefs and belief-like states 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, we believe that 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 above: 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) argue that before children can represent beliefs, they can predict actions by reasoning about facts. To illustrate, consider “James ran towards the bus because it was about to depart.” This sentence appears to explain James’ behaviour by appeal to a fact rather than a belief and an implicit desire. While the sentence can be used as shorthand for a belief-desire explanation, it could also be taken literally as explaining James’ 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-

Two systems for beliefs and belief-like states desire reasoning does in a useful range of cases. Moreover, Perner suggests that older children and adults may often reason about agents' relations to factual situations rather than 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 non-human theory of mind reasoning. More importantly, merely shifting from mental states to factual states does not remove the obstacles to cognitive efficiency identified above: 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. For 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 non-human animals sometimes reason about agents' relationships to facts rather than beliefs, and although we recognise that reasoning about facts may be a developmental stepping-stone towards reasoning about beliefs (e.g., Perner, 1991), we do not think 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 (for example, 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 behaviour and plans for one's own behaviour, with belief inferences no longer required<sup>7</sup>.

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 only lead to efficient belief reasoning in an organism that has first achieved the capacity to reason about beliefs in a non-automatic 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

Two systems for beliefs and belief-like states abilities of infants and non-human animals (unless we suppose that infants and non-human animals already have non-automatic belief reasoning despite being deficient in language and executive control).

*Behaviour associations and behaviour rules.* A number of authors have suggested that theory of mind abilities in infants and non-human animals are supported by learned associations or (possibly innate) rules that map between observed behaviours (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). On this view, infants and non-human animals exploit statistical regularities in sequences of behaviours such as: head orienting to an object is frequently followed by approaching an object. Where adults may ultimately re-interpret such patterns in folk psychological terms and so use belief reasoning to predict behaviours (e.g., Penn & Povinelli, 2007), it is claimed the same predictions can be achieved by identifying regularities in behaviours alone. On one view, these regularities are identified in something like the way that infants can distinguish non-word from word-like sequences of syllables by discerning transitional probabilities (Gómez & Gerken, 2000; Saffran, Newport, & Aslin, 1996). On another view, these regularities are captured by innate behavioural rules.

The ability to form expectations about a future behaviour based on a behaviour that has just been observed may offer a cognitively efficient method for co-ordinating one's own behaviour with others', but it is an open question whether they explain the full range of phenomena observed in infants, adults and non-human animals. The bold assumptions made by the above authors are doubly conjectural, for it has yet to be investigated both whether appropriate regularities in behaviour 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

Two systems for beliefs and belief-like states on reading statistical patterns in behaviours is only just beginning (Baldwin & Baird, 2001; Byrne, 2003).

Relevant to the possibility that infants and perhaps non-human animals learn associations between behaviours, we so far know that adults can learn to identify regularities in the linear ordering of activities which enable them to distinguish expected from unexpected 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 behaviour 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 behavioural 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 behaviour associations can be discerned by signature limits. Unless behaviour associations are innate, such reasoning will depend on individual learning histories and should be limited to commonly observed behaviours (such as head turning and approach) and not conceptually similar behaviours that are less commonly observed (such as head turning and moving away). Equally, behaviour associations should not be limited to regularities in behaviour that are intelligible in the light of mental states: behavioural 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 non-human animals learn behaviour associations for themselves should be distinguished from the possibility that they are innately endowed with cognitive rules that allow one behaviour to be predicted from observation of another (e.g., Perner, in press). This possibility clearly protects the individual from the vagaries of their

Two systems for beliefs and belief-like states own particular learning environment, thus eliminating one signature limit of associationist accounts. Critically, however, there is at least one further signature limit of behavioural accounts that holds whether we suppose that the individual has behavioural associations or behavioural rules. According to Penn and Povinelli (2007), “The theory of mind debate among comparative researchers [and for current purposes this means any behavioural rule or behavioural 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 733-4. In other words, although behavioural rules or associations link one behaviour 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 behavioural 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., under submission; Wang et al., under submission) 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 non-human animals do indeed have behavioural rules or associations as an efficient way of solving some theory of mind problems. But it does indicate that behavioural 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.



*Specialised processing of belief-like states.* If automatization and behaviour rules or associations alone turn out to be insufficient to explain efficient belief reasoning, what else is there? Several authors have independently attempted to characterise a mode of explanation intermediate between mindless behaviourism and full-blown propositional attitude psychology. For example, Gomez (2007) has suggested 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) uses the notion of an "intervening variable" to explain primitive theory of mind notions and Call (2001) credits 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 behaviour reading and reasoning about propositional attitudes as such.

Start with the notion of a field as a certain region of space centred 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 purposively attempt to manipulate others' encounters: for example, it may be beneficial to prevent others from encountering one's food.

## Two systems for beliefs and belief-like states

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 obtain, since an object may happen not to be where an individual registers it 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 move. 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 based on incorrect registrations and so approximate belief reasoning to such a great extent as to pass some false belief tasks (e.g. Onishi & Baillargeon, 2005)<sup>9</sup>.

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. In order 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 independently 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

Two systems for beliefs and belief-like states 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 from the back or from the side). 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 3 or 4 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 behaviour and develop throughout childhood. The 3-4 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,

Two systems for beliefs and belief-like states (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 judgements. 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 be observed in human adults with the same signature limitations; and we would expect similarly limited abilities (though not necessarily identical) to be observed in at least some non-human animals. Converging evidence from these three sources would provide strong evidence in favour of specialised 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, behavioural 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 that 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 non-symbolic number systems are sufficiently separate that evidence of double dissociations may be found following brain injury (e.g., Lemer, Dehane, 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<sup>10</sup> show similar abilities to perform approximate numerical judgements for numbers that differed in a sufficiently high ratio, whether the numbers were presented non-symbolically (e.g., as dot-patterns) or symbolically (as numerals). The authors suggest that children achieved this by mapping symbolic representations of number onto their approximate representations of numerical quantity. This evidence suggests that even if symbolic and non-symbolic number abilities depend upon 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 on-line 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 (c.f. Leslie, 2000). However, explicit judgements about what someone else thought or knew (i.e., the later-developing system) would receive no direct input from the early-developing system, so would have to

Two systems for beliefs and belief-like states infer such content anew. At the other extreme the later-developing system may depend on the other for its proper operation. Or, on 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 behaviour 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 judgement 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 judgements about beliefs. Moreover, Ruffman et al. (2001) provide 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 behaviour. This finding is 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 trade-offs 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

Two systems for beliefs and belief-like states 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 (contrast 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 assumes 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 only in 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,b, 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

Two systems for beliefs and belief-like states behavioural input. Leslie (1994a) proposes that ToMM consists of two subsystems: Sub-system 1 is available from 6 to 8 months of age and is concerned with processing goal-directed actions; sub-system 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, propose that sub-system 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 sub-systems, any resemblance to our two-systems account is superficial because the two sub-systems discussed by Leslie and Baillargeon are sub-components of a single cognitively efficient theory of mind module. 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 sub-system 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 sub-systems of the theory of mind module, Leslie and colleagues propose that the action of the theory of mind module is augmented by an inhibitory "selection processor" (SP) that selects the appropriate belief content from alternatives computed by ToMM (e.g., Leslie, 1994b; Leslie, German & Polizzi, 2004). 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



Two systems for beliefs and belief-like states reasoning (e.g., German & Hehman, 2006). The ToMM-SP account has been criticised on the grounds that, since 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 behaviour. The ToMM component of ToMM-SP is therefore insufficient for belief reasoning and therefore is not an alternative to the cognitively efficient systems for belief reasoning that is 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, on our account, cognitively efficient systems for solving tasks involving beliefs represent belief-like states which 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 paper, 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 neuro-developmental disorders, Tager-Flusberg and Sullivan (2000) propose a two-systems account for “theory of mind” in the broadest sense. However, their critical distinction is between processes for “social cognition”, which includes belief reasoning, and “social perception”, which include processing of faces and body postures for social information, but do 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 (2000), but neither is it implied by their account.

Gergely and Csibra (2003) propose 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 suppose 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, pp. 290; compare 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 & Gergeley, 2008; Liepelt, Von Crammon & Brass, 2008). One system is in the “mirror network”, which regions of cortex, including the inferior frontal gyrus, that show activity both when the subject performs 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 will be clear from earlier sections that several authors have discussed some form of two-system account where 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, Holyoak & Povinelli, 2008; Perner, 1991; Whiten, 1994, 1996). Such accounts are typically aimed at describing the abilities of infants, children or non-human 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 non-human animals in a distinctive way from the abilities of older children and adults, but to explain how these abilities can be cognitively efficient such that they are within the processing capabilities of infants and non-human 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 non-human animals (which is

Two systems for beliefs and belief-like states (the scope of existing accounts) but is also clearly present in human adults. We hypothesise 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 non-human 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. On analogy with 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 non-human 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 four years. 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 non-human species) show complex social behaviour 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 polarised: infants, non-human animals and on-

Two systems for beliefs and belief-like states line social interaction either employ mental concepts such as perception or belief, or get by exclusively with behavioural rules. The case of number cognition suggests an alternative view.

The key components of this view are as follows. Human infants and some non-human 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 on-line 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 afterwards), and in explicit reasoning about the causes and justifications of mental states (as in everyday practical reasoning, or jurisprudence).

Characterising 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 sub-disciplines 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 non-human

Two systems for beliefs and belief-like states  
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 faced with the problem of operating in complex domains using finite cognitive resources, two systems are often the solution.

References

- Apperly, I. A., Back, E., Samson, D., & France, L. (2008). The cost of thinking about false beliefs: Evidence from adults' performance on a non-inferential theory of mind task. *Cognition*, *106*, 1093-1108.
- Apperly, I.A., Riggs, K.J., Simpson, A., Chiavarino, C. & Samson, D. (2006). Is belief reasoning automatic? *Psychological Science*, *17*(10) 841-844.
- Apperly, I.A., Samson, D., & Humphreys, G.W. (2005). Domain-specificity and theory of mind: Evaluating evidence from neuropsychology. *Trends in Cognitive Sciences*, *9*(12), 572-577.
- Apperly, I. A., Samson, D., & Humphreys, G. W. (2009). Studies of adults can inform account of theory of mind development. *Developmental Psychology*, *45*(1), 190-201.
- Apperly, I.A., & Robinson, E.J. (1998). Children's mental representation of referential relations. *Cognition*, *67*,287-309.
- Apperly, I. A., & Robinson, E. J. (2003). When Can Children Handle Referential Opacity? Evidence for a systematic variation in 5- and 6-year-old children's reasoning about belief and belief reports. *Journal of Experimental Child Psychology*, *85*, 297-311.
- Astington, J., & Baird, J. A. (Eds.). (2005). *Why Language Matters for Theory of Mind*. Oxford: Oxford University Press.
- Baldwin, D., Andersson, A., Saffran, J., & Meyer, M. (2008). Segmenting dynamic human action via statistical structure. *Cognition*, *106*(3), 1382-1407.
- Baldwin, D., & Baird, J. A. (2001). Discerning intentions in dynamic human action. *Trends in Cognitive Sciences*, *5*(4), 171-178.
- Baron-Cohen, S., Leslie, A.M. & Frith (1985) Does the autistic child have a "theory of mind"? *Cognition*, *21*, 37-46.

- Baron-Cohen, S., Tager-Flusberg, H. & Cohen, D.J. (2000) *Understanding other minds. Perspectives from developmental cognitive neuroscience*. 2<sup>nd</sup> Ed. Oxford, Oxford University Press.
- Baroody, A. J. & Dowker, A. (2003) *The Development of Arithmetic Concepts and Skills: Constructing Adaptive Expertise*. Erlbaum, Mahwah, New Jersey.
- Barth, H., Kanwisher, N. & Spelke, E.S. (2003). The construction of large number representations in adults. *Cognition* 86, 201–221.
- Behne, T., Carpenter, M., Call, J., & Tomasello, M. (2005). Unwilling Versus Unable: Infants' Understanding of Intentional Action. *Developmental Psychology*, 41(2), 328-337.
- Behne, T., Carpenter, M., & Tomasello, M. (2005). One-year-olds comprehend the communicative intentions behind gestures in a hiding game. *Developmental Science*, 8(6), 492-499.
- Ben-Yami, H. (1997). Against Characterizing Mental States as Propositional Attitudes. *Philosophical Quarterly*, 47(186), 84-89.
- Bennett, J. (1976). *Linguistic Behaviour*. Cambridge: Cambridge University Press.
- Bernstein, D. M., Atance, C., Loftus, G. R., & Meltzoff, A. (2004). We saw it all along - Visual hindsight bias in children and adults. *Psychological Science*, 15, 264-267.
- Birch, S. A. J. & Bloom, P. (2004). Understanding children's and adults' limitations in mental state reasoning. *Trends in Cognitive Sciences*, 8, 255-260.
- Birch, S.A.J. & Bloom, P. (2007). The curse of knowledge in reasoning about false beliefs. *Psychological Science*, 18(5), 382-386.
- Bloom, P., & Gelman, T. P. (2000). Two reasons to abandon the false belief task as a test of theory of mind. *Cognition*, 77, B25-B31.



- Boysen, S. T., & Berntson, G. G. (1989). Numerical competence in a chimpanzee (*Pan troglodytes*). *Journal of Comparative Psychology*, *103*, 23–31.
- Brandom, R. (1994). *Making It Explicit*. Cambridge, Mass.: Harvard University Press.
- Brannon, E.M. and Terrace, H.S. (1998) Ordering of the numerosities 1-9 by monkeys. *Science* *282*, 746–749
- Brass, M., Schmitt, R.M., Spengler, S. & Gergeley, G. (2008) Investigating action understanding: Inferential processes versus action simulation. *Current Biology*, *17*, 2117-2121.
- Breheny, R., (2006) Communication and Folk Psychology, *Mind & Language*. *21(1)*, 74-107
- Bugnyar, T., Stöwe, M., & Heinrich, B. (2007). The ontogeny of caching in ravens, *Corvus corax* *Animal Behaviour*, *74(4)*, 757-767.
- Bull, R., Philips, L.H. & Conway, C.A. (2008). The role of control functions in mentalizing: Dual task studies of theory of mind and executive function. *Cognition*, *107(2)*, 663-672.
- Butterfill, S.A. (2007) What are modules and what is their role in development? *Mind and Language* *22:4*, 450-473.
- Byrne, R. W. (2002). Parsing behaviour: A mundane origin for an extraordinary ability? In Enfield, N.J. & Levinson, S. (Eds.) *Roots of human sociality. Culture, cognition and interaction*. Berg, Oxford.
- Byrne, R. W. (2003). Imitation as Behaviour Parsing. *Philosophical Transactions: Biological Sciences*, *358(1431)*, 529-536.
- Call, J. (2001). Chimpanzee social cognition. *Trends in Cognitive Sciences*, *5(9)*, 388-393.
- Call, J. & Tomasello, M. (2005). What chimpanzees know about seeing revisited: An explanation of the third kind. In N. Eilan, C. Hoerl, T. McCormack & J. Roessler (eds.).

*Joint Attention: Communication and other Minds* (pp. 45-64). Oxford: Oxford University Press.

Call, J. & Tomasello, M. (2008). Does the chimpanzee have a theory of mind? 30 years later. *Trends in Cognitive Sciences*, 12(5), 187-192.

Campbell, J. (1986). Conceptual Structure. In C. Travis (Ed.), *Meaning and Interpretation* (pp. 127-158). Oxford: Blackwell.

Carey, S. (2002). The Origin of Concepts. In N. L. Stein, P. J. Bauer & M. Rabinowitz (Eds.), *Representation, Memory and Development* (pp. 43-51). London: Lawrence Erlbaum.

Carey, S. (2002). The Origin of Concepts. In N. L. Stein, P. J. Bauer & M. Rabinowitz (Eds.), *Representation, Memory and Development* (pp. 43-51). London: Lawrence Erlbaum.

Carey, S., & Xu, F. (2001). Infants' Knowledge of Objects: Beyond Object Files and Object Tracking. *Cognition*, 80, 179-213.

Carlson, S. M., Moses, L. J., & Hix, H. R. (1998). The role of inhibitory processes in young children's difficulties with deception and false belief. *Child Development*, 69(3), 672-691.

Carpendale, J. I., & Chandler, M. (1996). On the Distinction between False Belief Understanding and Subscribing to an Interpretive Theory of Mind. *Child Development*, 67, 1686-1706.

Carpenter, M., Call, J., & Tomasello, M. (2002). A new false belief test for 36-month-olds. *British Journal of Developmental Psychology*, 20, 393-420.

Clayton, N. S., Dally, J. M., & Emery, N. J. (2007). Social cognition by food-caching corvids. The western scrub-jay as a natural psychologist. *Philosophical Transactions of the Royal Society B*, 362, 507-552.

- Clayton, N. S., & Emery, N. J. (2007). The social life of corvids. *Current Biology*, 17(16), R652-R656.
- Clements, W.A., & Perner, J. (1994). Implicit understanding of belief. *Cognitive Development*, 9, 377-397.
- Clements, W., Rustin, C., & McCallum, S. (2000). Promoting the transition from implicit to explicit understanding: a training study of false belief. *Developmental Science*, 3(1), 81-92.
- Csibra, G. (2003). Teleological and Referential Understanding of Action in Infancy. *Philosophical Transactions: Biological Sciences*, 358(1431), 447-458.
- Csibra, G., & Gergely, G. (1998). The teleological origins of mentalistic action explanations: A developmental hypothesis. *Developmental Science*, 1(2), 255-259.
- Csibra, G., & Gergely, G. (2007). Obsessed with goals': Functions and mechanisms of teleological interpretation of actions in humans. *Acta Psychologica*, 124(1), 60-78.
- Dally, J.M., Emery, N.J. & Clayton, N.S. (2006) Food-caching western scrub-jays keep track of who was watching when. *Science*, 312, 1662-1665.
- Davidson, D. (1980). Towards a Unified Theory of Meaning and Action. *Grazer Philosophische Studien*, 11, 1-12.
- Davidson, D. (1989). The Conditions of Thought. In J. Brandl & W. Gombocz (Eds.), *The Mind of Donald Davidson*. Amsterdam: Rodopi.
- Davidson, D. (1990a). Representation and Interpretation. In K. Mohyeldin Said, W. Newton-Smith, R. Viale & K. Wilkes (Eds.), *Modelling the Mind*. Oxford: Oxford University Press.
- Davidson, D. (1990b). The Structure and Content of Truth. *The Journal of Philosophy*, 87(6), 279-328.

- Davidson, D. (1995). Could there be a science of rationality? *International Journal of Philosophical Studies*, 3(1), 1-16.
- Davidson, D. (1999). The Emergence of Thought. *Erkenntnis*, 51, 7-17.
- Davidson, D. (2003). Responses to Barry Stroud, John McDowell, and Tyler Burge. *Philosophy and Phenomenological Research*, LXVII(3), 691-699.
- Dehaene, S. (1997) *The number sense: How the mind creates mathematics*. Oxford University Press.
- Dehane, S., & Cohen. (1994). Dissociable Mechanisms of Subitizing and Counting: Neuropsychological Evidence From Simulatagnosic Patients. *Journal of Experimental Psychology: Human Perception and Performance*, 20(5), 958-975.
- Dienes, Z., & Perner, J. (1999) A theory of implicit and explicit knowledge. *Behavioural and Brain Sciences*, 22, 735-755.
- Doherty, M.J. (1999). Selecting the wrong processor: a critique of Leslie's theory of mind mechanism-selection processor theory. *Developmental Science*, 2, 81-85.
- Doherty, M. J. (2006). The Development of Mentalistic Gaze Understanding. *Infant and Child Development*, 15, 179-186.
- Doherty, M.J. (2008). *Theory of Mind: How Children Understand Others' Thoughts and Feelings*. Hove, UK: Psychology Press.
- Dretske, F. (1988). *Explaining Behavior*. Cambridge, Mass.: MIT Press.
- Dretske, F. (1981). *Knowledge and the flow of information*. Oxford: Blackwell.
- Dunham, P. J., Dunham, F., & O'Keefe, C. (2000). Two-year-old's Sensitivity to a Parent's Knowledge State: Mind Reading or Contextual Cues? *British Journal of Developmental Psychology*, 18, 519-532.
- Emery, N. J., & Clayton, N. S. (2001). Effects of Experience and Social Context on Prospective Caching Strategies by Scrub Jays. *Nature*, 414, 443-446.

- Emery, N. J., & Clayton, N. S. (2007). How to Build a Scrub-Jay that Reads Minds. In S. Itakura & K. Fujita (Eds.), *Origins of the Social Mind: Evolutionary and Developmental Perspectives*. Tokyo: Springer.
- Epley, N., Keysar, B., Van Boven, L., & Gilovich, T. (2004). Perspective taking as egocentric anchoring and adjustment. *Journal of Personality and Social Psychology*, *87*, 327-339.
- Evans, J. St. B. T. (2003) In two minds: dual-process accounts of reasoning. *Trends in Cognitive Sciences*, *7(10)*, 454-459.
- Fias, W. & Verguts, T. (2004) The mental number line: exact and approximate. *Trends in Cognitive Sciences*, *8(10)*, 447-448.
- Feigenson, L. & Carey, S. (2003) Tracking individuals via object-files: Evidence from infants' manual search. *Developmental Science*, *6*, 568-584.
- Feigenson, L., Dehane, S. & Spelke, E.S. (2004) Core systems of number. *Trends in Cognitive Sciences*, *8(7)*, 307-314.
- Fodor, J. (1975). *The Language of Thought*. Crowell: New York.
- Fodor, J. (1983). *The Modularity of Mind: an Essay on Faculty Psychology*. Cambridge, Mass ; London: MIT Press.
- Fodor, J. (1992). A theory of the child's theory of mind. *Cognition*, *44(3)*, 283-296.
- Frith, U., & Frith, C.D. (2003). Development and neurophysiology of mentalising. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *358*, 459-473.
- Gallese, V. & Goldman, A. (2003) Mirror neurons and the simulation theory of mind-reading. *Trends in Cognitive Sciences*, *2*, 493-501.
- Gallistel, C. R., & Gelman, R. (1992). Preverbal and verbal counting and computation. *Cognition*, *44*, 43-74.

- Gallistel, C. R., & Gelman, R. (2000). Non-verbal numerical cognition: from reals to integers. *Trends in Cognitive Sciences*, 4, 59–65.
- Gelman, R., & Gallistel, C. R. (1978). *The child's understanding of number*. Cambridge, MA: Harvard University Press.
- Garnham, W.A., & Perner, J. (2001) Actions really do speak louder than words – but only implicitly: Young children's understanding of false belief in action. *British Journal of Experimental Psychology*, 19(3), 413-432.
- Garnham, W.A., & Ruffman, T. (2001) Doesn't see, doesn't know: is anticipatory looking really related to understanding of belief? *Developmental Science*, 4(1), 94-100.
- Gergely, G., Nadasky, Z., Csibra, G., & Biro, S. (1995). Taking the Intentional Stance at 12 Months of Age. *Cognition*, 56, 165-193.
- German, T.P. & Hehman, J.A. (2006) Representational and executive selection resources in “theory of mind”: Evidence from compromised belief-desire reasoning in old age. *Cognition*, 101, 129-152.
- Gilbert, D. T. (1998). Ordinary personology. In D. T. Gilbert, S. T., Fiske, & G. Lindzey, (Eds.) *The handbook of social psychology* (4th edition). New York: McGraw Hill.
- Gomez, J.-C. (2007). Pointing Behaviors in Apes and Human Infants: A Balanced Interpretation. *Child Development*, 78(3), 729-734.
- Gómez, R., & Gerken, L. (2000). Infant artificial language learning and language acquisition. *Trends in Cognitive Sciences*, 4(5), 178-186.
- Gopnik, A., & Meltzoff, A. (1997). *Words, Thoughts, and Theories*. Cambridge, Mass.: MIT Press.
- Gordon, R. (2000). Sellars's Ryleans Revisited. *Protosociology*, 14, 102-114.
- Grice, P. (1989). *Studies in the way of words*. Cambridge, Mass ; London: Harvard University Press.

- Halberda, J. & Feigenson, L. (2008) Developmental change in the acuity of the “Number sense”: The approximate number system in 3-, 4-, 5- and 6-year-olds and adults. *Developmental Psychology*, 44(5), 1457-1465.
- Happé, F., & Loth, E. (2002). ‘Theory of Mind’ and Tracking Speakers’ Intentions. *Mind and Language*, 17(1-2), 24-36.
- Hare, B., Call, J., Agnetta, B., & Tomasello, M., (2000). Chimpanzees know what conspecifics do and do not see. *Animal Behaviour*, 59, 771-785.
- Hare, B., Call, J., & Tomasello, M., (2001). Do chimpanzees know what conspecifics know and do not know? *Animal Behaviour*, 61, 139-151.
- Hare, B., Call, J., Tomasello, M. (2006). Chimpanzees deceive a human competitor by hiding. *Cognition*, 101(3), 495-514.
- Harris, P. (1994). Thinking by Children and Scientists. In L. Hirschfeld & S. Gelman (Eds.), *Mapping the Mind: domain specificity in cognition and culture*. Cambridge: Cambridge University Press.
- Harris, P., Johnson, C. N., Hutton, D., Andrews, G., & Cooke, T. (1989). Young children's theory of mind and emotion. *Cognition and Emotion*, 3, 379-400.
- Hauser, M.D. and Carey, S. (2003) Spontaneous representations of small numbers of objects by rhesus macaques: examinations of content and format. *Cognitive Psychology* 47, 367–401.
- Heal, J. (1998). Co-Cognition and Off-Line Simulation: Two Ways of Understanding the Simulation Approach. *Mind and Language*, 13(4), 477-498.
- Hulme, S., Mitchell, P. & Wood, D. (2003). Six-year-olds’ difficulties handling intentional contexts. *Cognition*, 87, 73-99.

- Jusczyk, P. (1995). Language Acquisition: Speech Sounds and the Beginning of Phonology. In J. Miller, L. & P. D. Eimas (Eds.), *Speech, Language and Communication*. San Diego: Academic Press.
- Keysar, B., Lin, S.H., & Barr, D.J. (2003). Limits on theory of mind use in adults. *Cognition*, 98(1). 25-41.
- Koenig, M., Clément, F., & Harris, P. (2004). Trust in Testimony: Children's Use of True and False Statements. *Psychological Science*, 15(10), 694-698.
- Kovacs, A.M. & Mehler, J. (2007) Enhanced executive functions boost performance in theory of mind tasks: the case of bilinguals. Paper presented to the Society for Research in Child Development, Boston, MA. March 29 - April 1.
- Laurence, S., & Margolis, E. (2005). Number and Natural Language. In P. Carruthers, S. Laurence & S. Stich (Eds.), *The Innate Mind* (pp. 272-288). Oxford: Oxford University Press.
- Le Corre, M. & Carey, S. (2008) One, two, there, four, nothing more: An investigation of the conceptual sources of the verbal counting principles. *Cognition*, 105, 395-438.
- LeFevre, J.-A., Bisanz, J. and Mrkonjic, L., 1988. Cognitive arithmetic: Evidence for obligatory activation of arithmetic facts. *Memory and Cognition* 16, 45–53.
- Lemer, C., Dehaene, S., Spelke, E. & Cohen L. (2003) Approximate quantities and exact number words: dissociable systems . *Neuropsychologia* 41 (14), 1942-1958
- Leslie, A. M. (1987). Pretense and representation: The origins of “theory of mind”. *Psychological Review*, 94, 412–426.
- Leslie, A. (1994a). ToMM, ToBY, and Agency: Core Architecture and Domain Specificity. In L. Hirschfeld & S. Gelman (Eds.), *Mapping the Mind: domain specificity in cognition and culture*. Cambridge: Cambridge University Press.



- Leslie, A.M. (1994b). Pretending and believing: Issues in the theory of ToMM. *Cognition*, 50, 211–238.
- Leslie, A.M. (2000). "Theory of Mind" as a Mechanism of Selective Attention. In M. Gazzaniga (Ed.), *The New Cognitive Neurosciences*. Cambridge, Mass: MIT Press.
- Leslie, A.M. (2005). Developmental Parallels in Understanding Minds and Bodies. *Trends in Cognitive Sciences*, 9(10), 459-462.
- Leslie, A.M., German, T. P., & Polizzi, P. (2004). Belief-desire reasoning as a process of selection. *Cognitive Psychology*, 50, 45-85.
- Leslie, A.M., German, T. P., & Polizzi, P. (2005). Belief-desire reasoning as a process of selection. *Cognitive Psychology*, 50, 45-85.
- Leslie, A.M., & Polizzi, P. (1998). Inhibitory processing in the false belief task: Two conjectures. *Developmental Science*, 1(2), 247-253.
- Leslie, A.M., Xu, F., Tremoulet, P. D., & Scholl, B. J. (1998). Indexing and the Object Concept: Developing 'What' and 'Where' Systems. *Trends in Cognitive Sciences*, 2(1) 10-18.
- Liberman, A. M., & Mattingly, I. G. (1985). The Motor Theory of Speech Perception Revised. *Cognition*, 21(1), 1-36.
- Liberman, A. M., & Whalen, D. H. (2000). On the Relation of Speech to Language. *Trends in Cognitive Sciences*, 4(5), 187-196.
- Liepelt, R., Von Crammon, D.Y. & Brass, M. (2008). How do we infer others' goals from non-stereotypic actions? The outcome of context-sensitive inferential processing in right inferior parietal and posterior temporal cortex. *Neuroimage*, 43, 784-792.
- Lillard, A.S. (1998-a). Ethnopsychologies: Cultural variations in theory of mind. *Psychological Bulletin*, 123, 3-30.

- Liszkowski, U., Carpenter, M., Striano, T., & Tomasello, M. (2006). Twelve- and 18-month-olds point to provide information for others. *Journal of Cognition and Development, 7*, 173-187.
- Luo, Y. & Baillargeon, R. (2007) Do 12.5-month-old infants consider what objects others can see when interpreting their actions? *Cognition, 105*, 489-512.
- McDowell, J. H. (1996). *Mind and world : with a new introduction*. Cambridge, Mass ; London: Harvard University Press.
- McGarrigle, J. & Donaldson, M. (1975). Conservation accidents cognition 3(4), 341-350 .
- McKinnon, M.C. & Moscovitch, M. (2007) Domain-general contributions to social reasoning: Theory of mind and deontic reasoning re-explored. *Cognition, 102(2)*, 179-218.
- Millikan, R. (1984). *Language, Thought and Other Biological Categories*. Cambridge, Mass.: MIT Press.
- Millikan, R. (1993). *White Queen Psychology and Other Essays for Alice*. Cambridge, Mass.: MIT Press.
- Mitchell, P., Robinson, E.J., Isaacs, J.E. & Nye, R.M. (1996). Contamination in reasoning about false belief: An instance of realist bias in adults but not children. *Cognition, 59*, 1-21.
- Moll, H., & Tomasello, M. (2006). Level 1 perspective-taking at 24 months of age. *British Journal of Developmental Psychology, 24*, 603-613.
- Moll, H., & Tomasello, M. (2007). How 14- and 18-Month-Olds Know What Others Have Experienced. *Developmental Psychology, 43(2)*, 309-317.
- Newton, A. M., & de Villiers, J. G. (2007). Thinking While Talking: Adults Fail Nonverbal False-Belief Reasoning. *Psychological Science, 18(7)*, 574-579.

- Newton P., Reddy V., Bull R. (2000). Children's everyday deception and performance on false-belief tasks. *British Journal of Developmental Psychology*, Volume 18 (2), pp. 297-317.
- O'Neill, D. K. (1996). Two-year-old Children's Sensitivity to a Parent's Knowledge State When Making Requests. *Child Development*, 67, 659-677.
- O'Neill, D K. & Chong, C. F. (2001). Preschool children's difficulty understanding the types of information obtained through the five senses. *Child Development*, 72, 3, 803-815.
- Oakes, L. M., & Cohen, L. B. (1990). Infant Perception of a Causal Event. *Cognitive Development*, 5(2), 193-207.
- Onishi, K. H., & Baillargeon, R. (2005). Do 15-Month-Old Infants Understand False Beliefs? *Science*, 308(8), 255-258.
- Papineau, D. (1993). *Philosophical Naturalism*. Oxford: Blackwell.
- Peacocke, C. (1992). *A Study of Concepts*. Cambridge, Mass.: MIT Press.
- Pellicano, E. (2007). Links Between Theory of Mind and Executive Function in Young Children With Autism: Clues to Developmental Primacy. *Developmental Psychology*, 43(4), 974-990.
- Penn, D. C., Holyoak, K.J. & Povinelli, D. J. (2008). Darwin's mistake: Explaining the discontinuity between human and nonhuman minds. *Behavioral and Brain Sciences*, 31, 109-178.
- Penn, D. C., & Povinelli, D. J. (2007). On the lack of evidence that non-human animals possess anything remotely resembling a 'theory of mind'. *Philosophical Transactions of the Royal Society B*, 362(1480), 731-744.
- Pepperberg, I.M. (2006) Grey parrot (*Psittacus erithacus*) numerical abilities: addition and further experiments on a zero-like concept. *Journal of Comparative Psychology* 120(1), 1-11.

- Perner, J. (1991). *The Representational Mind*. Brighton: Harvester.
- Perner, J. (1998). The meta-intentional nature of executive functions and theory of mind. In P. Carruthers & J. Boucher (Eds.), *Language and Thought: Interdisciplinary themes*. Cambridge: Cambridge University Press.
- Perner, J., Baker, S. & Hutton, D. (1994). Pre-linguistic: The conceptual origins of belief and pretence. In Lewis, C. & Mitchell, P. (Eds.) *Children's early understanding of mind: Origins and development*. Hove. Lawrence Erlbaum Associates.
- Perner, J. (1998). The meta-intentional nature of executive functions and theory of mind. In P. Carruthers & J. Boucher (Eds.), *Language and Thought: Interdisciplinary themes*. Cambridge: Cambridge University Press.
- Perner, J. (In press). Who took the cog out of cognitive science? Mentalism in an era of anti-cognitivism. In P.A. Frensch et al., (Eds), *International Congress of Psychology – 2008 Proceedings*. Psychology Press.
- Perner, J., & Lang, B. (1999). Development of theory of mind and executive control. *Trends in Cognitive Sciences*, 3(9), 337-344.
- Perner, J., & Lang, B. (2002). What Causes 3-year-olds' Difficulty on the Dimensional Change Card Sorting Task? *Infant and Child Development*, 11, 93-105.
- Perner, J., & Ruffman, T. (2005). Infant's Insight into the Mind: How Deep? *Science*, 308, 214-216.
- Piaget, J. & Szeminska, A. (1952) *The child's conception of number*. London: Routledge & Kegan Paul.
- Pietroski, P. (1992). Intentionality and Teleological Error. *Pacific Philosophical Quarterly*, 73, 267-282.
- Polak, A. & Harris, P.L. (1999). Deception by young children following non-compliance. *Developmental Psychology*, 35(2), 561-568.

- Povinelli, D. J. (2001). On the Possibility of Detecting Intentions Prior to Understanding Tem. In B. F. Malle, L. Moses & D. A. Baldwin (Eds.), *Intentions and Intentionality* (pp. 225-248). Cambridge, MA: MIT Press.
- Povinelli, D. J., Bering, J., & Giambrone, S. (2000). Toward a Science of Other Minds: Escaping the Argument by Analogy. *Cognitive Science*, 24(3), 509-541.
- Povinelli DJ, Eddy TJ (1996) What young chimpanzees know about seeing. *Monographs of the Society for Research in Child Development*, 61 (2, Serial No. 247)
- Povinelli, D.J. & Giambrone, S. (1999). Inferring other minds: Failure of the argument by analogy. *Philosophical Topics*, 27, 167-201.
- Povinelli, D.J. & Vonk, J. (2003) Chimpanzee minds: suspiciously human? *Trends in Cognitive Sciences*, 7(4), 157-160.
- Price, C. (2001). *Functions in Mind*. Oxford: Clarendon Press.
- Reddy, V. & Morris, P. (2004). Participants don't need theories - Knowing minds in engagement. *Theory and Psychology*, 14 (5), 647-665.
- Rizzolati, G. & Craighero, L. (2004). The mirror-neuron system. *Annual Review of Neuroscience*, 27, 169-192.
- Robinson, E. (1994). What People Say, What They Think, and What is Really the Case: Children's Understanding of Utterances as Sources of Knowledge. In C. Lewis & P. Mitchell (Eds.), *Children's Early Understanding of Mind: origins and development*. Hove: Erlbaum.
- Robinson, E., & Apperly, I. A. (2001). Children's difficulties with partial representations in ambiguous messages and referentially opaque contexts. *Cognitive Development*, 16, 595-615.
- Ross-Sheehy, S., Oakes, L., & Luck, S. J. (2003). The development of visual short-term memory capacity in infants. *Child Development*, 74(6), 1807-1822.

- Ruffman, T., Garnham, W., Import, A., & Connolly, D. (2001). Does Eye Gaze Indicate Knowledge of False Belief: Charting Transitions in Knowledge. *Journal of Experimental Child Psychology, 80*, 201-224.
- Ruffman, T. & Keenan, T.R. (1996) The belief-based emotion of surprise: the case for a lag in understanding relative to false belief. *Developmental Psychology, 9*, 89-102.
- Ruffman, T., & Perner, J. (2005). Do infants really understand false belief? *Trends in Cognitive Sciences, 9*(10), 462-463.
- Russell, J. (2007). Controlling core knowledge: conditions for the ascription of intentional states to self and others by children. *Synthese, DOI 10.1007/s11229-007-9203-8*.
- Sabbagh, M. (2006). Executive Functioning and Preschoolers' Understanding of False Beliefs, False Photographs, and False Signs. *Child Development, 77*(4), 1034-1049.
- Saffran, J. R., Newport, E. L., & Aslin, R. N. (1996). Statistical Learning by 8-Month-Old Infants. *Science, 274*(5294), 1926-1928.
- Samson, D., Apperly, I.A., Braithwaite, J. & Andrews, B. (Under submission). Seeing it your way: Evidence for altercentric intrusion effects in visual perspective taking.
- Saxe, R., & Carey, S. (2006). The Perception of Causality in Infancy. *Acta Psychologica, 123*, 144-165.
- Saxe, R., Carey, S., & Kanwisher, N. (2004). Understanding other minds: Linking developmental psychology and functional neuroimaging. *Annual Review of Psychology, 55*, 87-124.
- Saxe, R., Schultz, L.E. & Jiang, Y.V. (2006) Reading minds versus following rules: Dissociating theory of mind and executive control in the brain. *Social Neuroscience 1*(3-4), 284-298.

- Saylor, M. M., Baldwin, D. A., Baird, J. A., & LaBounty, J. (2007). Infants' On-line Segmentation of Dynamic Human Action. *Journal of Cognition and Development, 8*(1), 113-113.
- Scholl, B. J., & Leslie, A. (1999). Explaining the Infant's Object Concept: Beyond the Perception/Cognition Dichotomy. In E. LePore & Z. Pylyshyn (Eds.), *What Is Cognitive Science?* (pp. 26-73). Oxford: Blackwell.
- Slaughter, V., & Gopnik, A. (1996). Conceptual Coherence in the Child's Theory of Mind: Training Children to Understand Belief. *Child Development, 67*, 2967-2988.
- Sodian, B., Thoermer, C. & Metz, U. (2007) Now I see it but you don't: 14-month-olds can represent another person's visual perspective. *Developmental Science 10*(2), 199-204.
- Song, H. & Baillargeon, R. (2008). Infants' reasoning about others' false perceptions. *Developmental Psychology, 44*(6), 1789-1795.
- Song, H., Onishi, K. H., Baillargeon, R., & Fisher, C. (2008). Can an actor's false belief be corrected by an appropriate communication? Psychological reasoning in 18.5-month-old infants. *Cognition, 109*, 295-315.
- Southgate, V., Senju, A., & Csibra, G. (2007). Action Anticipation through Attribution of False Belief By Two-Year-Olds. *Psychological Science, 18*, 587-592.
- Spelke, E. (1994). Initial Knowledge: Six Suggestions. *Cognition, 50*(1-3), 431-445.
- Spelke, E. (2000). Core Knowledge. *American Psychologist, 55*, 1233-1243.
- Spelke, E., & Kinzler, K. D. (2007). Core Knowledge. *Developmental Science, 10*(1), 89-96.
- Sperber, D., & Wilson, D. (1986/95). *Relevance : communication and cognition* (2nd ed ed.). Oxford: Basil Blackwell.
- Sperber, D., & Wilson, D. (2002). Pragmatics, Modularity & Mindreading. *Mind and Language, 17*, 3-23.

- Sprung, M., Perner, J., & Mitchell, P. (2007). Opacity and Embedded Perspectives: object identity and object properties. *Mind and Language*, 22(3), 215-245.
- Starkey, P. & Cooper, R.G. Jr. (1980). Perception of numbers by human infants. *Science*, 210, 1033-1035.
- Stout, R. (1996). *Things That Happen Because They Should*. Oxford: Oxford University Press.
- Surian, L., Caldi, S., & Sperber, D. (2007). Attribution of Beliefs by 13-Month-Old Infants. *Psychological Science*, 18(7), 580-586.
- Suddendorf, T., & Whiten, A. (2003). Reinterpreting the Mentality of Apes. In J. Fitness & K. Sterelny (Eds.), *From Mating to Mentality: Evaluating Evolutionary Psychology* (pp. 173-196): Psychology Press.
- Tager-Flusberg, H. & Sullivan, K. (2000). A componential view of theory of mind: evidence from Williams syndrome. *Cognition*, 76, 59-89.
- Taylor, C. (1964). *The Explanation of Behaviour*. London: Routledge.
- Tomasello, M., Call, J. and Hare, B. (2003) Chimpanzees understand psychological states – the question is which ones and to what extent. *Trends in Cognitive Sciences, Volume 7(4)*, 153-156.
- Trick, L. and Pylyshyn, Z.W. (1994) Why are small and large numbers enumerated differently? A limited capacity preattentive stage in vision. *Psychological Review*, 101, 80–102.
- Vogel, E. K., Woodman, G. F., & Luck, S. J. (2001). Storage of features, conjunctions, and objects in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance*, 27, 92–114.
- Wang, J., Apperly, I.A., Samson, D. & Braithwaite, J.J. (Under submission). Adults infer belief-like states automatically.



- Wellman, Henry (1990). *The Child's Theory of Mind*. Cambridge MA: MIT Press.
- Wellman, H., Cross, D., & Watson, J. (2001). Meta-analysis of Theory of Mind Development: The Truth about False-Belief. *Child Development*, 72(3), 655-684.
- Whiten, A. (1994). Grades of mindreading. In C. Lewis & P. Mitchell (Eds.), *Children's Early Understanding of Mind* (pp. 47–70). Hove: Erlbaum.
- Whiten, A. (1996). When does smart behaviour-reading become mind-reading? In P. Carruthers & P. K. Smith (Eds.), *Theories of Theories of Mind* (pp. 277–292). Cambridge: Cambridge University Press.
- Wimmer, H., & Perner, J. (1983). Beliefs about beliefs: Representation and constraining function of wrong beliefs in young children's understanding of deception. *Cognition*, 13, 103-128.
- Wimmer, H., & Gschaidner, A. (2000). Children's understanding of belief: Why is it important to understand what happened? In P. Mitchell & K. J. Riggs (Eds.) *Children's reasoning and the mind*, (pp. 253-266). Hove. East Sussex: Psychology Press.
- Woodward, A. (1998). Infants Selectively Encode the Goal Object of an Actor's Reach. *Cognition*, 69, 1-34.
- Wynn, K. (1992) Addition and subtraction by human infants. *Nature*, 358, 749-750.
- Wynn, K. (1996) Infants' individuation and enumeration of sequential actions. *Psychological Science*, 7, 164-169.
- Xu, F. (2003). Numerosity Discrimination in Infants: Evidence for Two Systems of Representations. *Cognition*, 89, B15-B25.
- Xu, F., Carey, S., & Quint, N. (2004). The emergence of kind-based object individuation in infancy. *Cognitive Psychology*, 49, 155-190.
- Xu, F. & Spelke, E.S. (2000). Large number discrimination in 6-month old infants. *Cognition*, 74, B1-B11.

Zelazo, P., Jacques, S., Burack, J. A., & Frye, D. (2002). The Relation between Theory of Mind and Rule Use: Evidence from Persons with Autism-Spectrum Disorders. *Infant and Child Development*, 11, 171-195.

Author note

Ian A. Apperly, School of Psychology, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK.

Stephen A. Butterfill, Department of Philosophy, University of Warwick, Coventry, CV4 7AL, UK.

The authors would like to thank Sarah Beck, Hannes Rakoczy, Elizabeth Robinson, James Russell and Dana Samson, who commented on drafts of this manuscript.

Correspondence should be addressed to Ian Apperly, School of Psychology, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK. Email, [i.a.apperly@bham.ac.uk](mailto:i.a.apperly@bham.ac.uk), tel. +44 0121 414 3339, fax. +44 0121 414 4897

1. Some of these 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 will refer to the “two systems” view.
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 in order 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 and colleagues provide evidence that children take into account false beliefs in learning new words (Carpenter, Call, & Tomasello, 2002; see also Happé & Loth, 2002); and there is also a range of evidence on deception-related behaviours (Polak and Harris 1999; Newton, Reddy and Bull, 2000; Reddy and 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 and Tomasello 2007), their own communicative gestures (Liszkowski, Carpenter, et al. 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 non-intentional eye movements and looking times.

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

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.

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, German, & Polizzi, 2004; Leslie & Polizzi, 1998) and the emotional consequences of false beliefs (e.g., Harris, Johnson, Hutton, Andrews & Cooke, 1989; Ruffman & Keenan, 1996).

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

9. 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). Since children can indeed pass such tasks if their gaze rather than verbal responses are taken to be the relevant measure (Clements & Perner, 1994; Southgate et al., 2007), this is not an objection to our view but 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 judgements about beliefs (see section on "How could the two systems be related?").

10. This study examined children, rather than adults, in order to have participants who were able to count (so could comprehend symbolic number stimuli) but had no training in formal arithmetic (so 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 non-symbolic representations only by children, it seems more likely that adults are also able to map symbolic to non-symbolic number representations.